DOI: 10.1002/anie.200703612

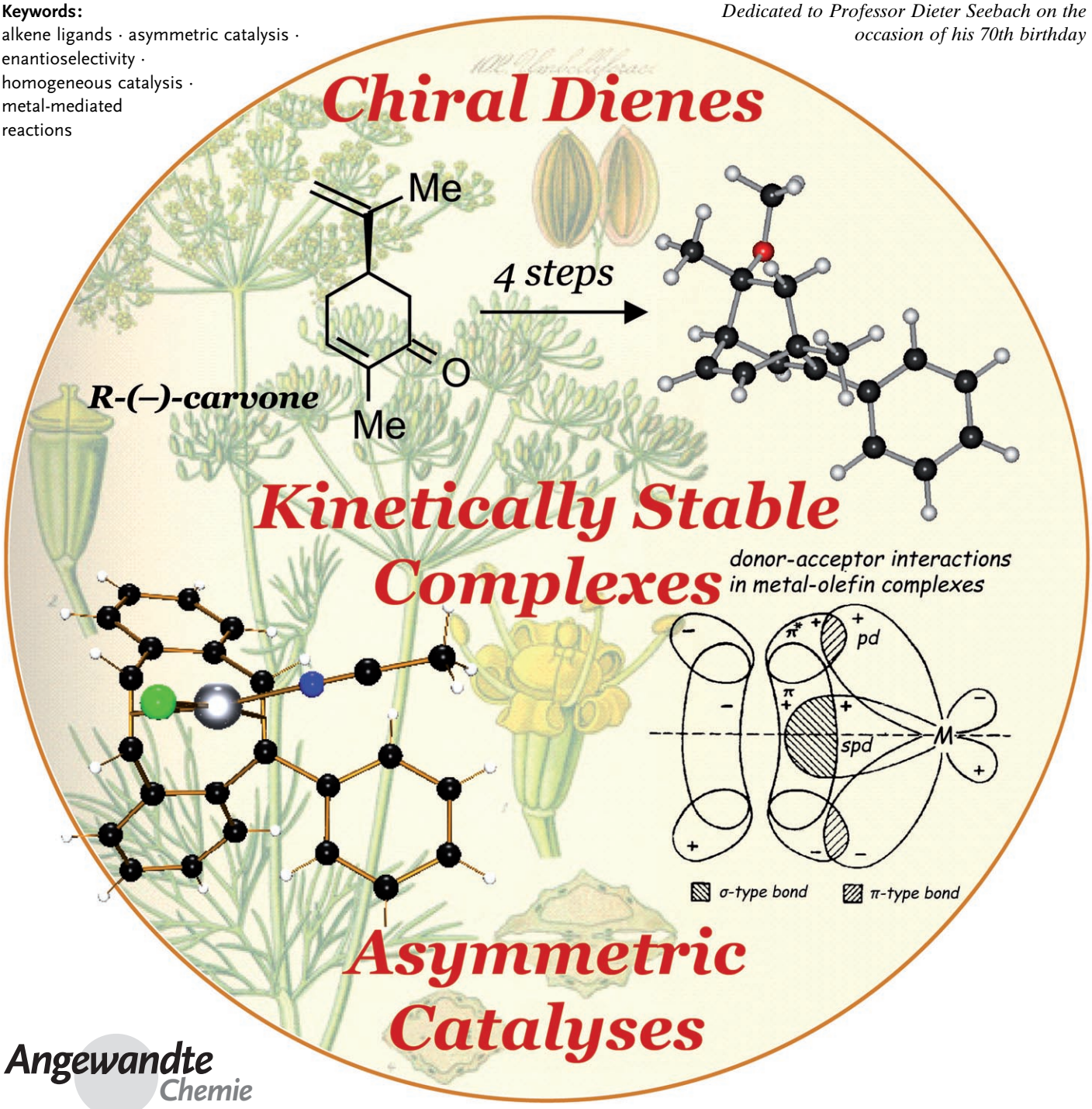
Organic Ligands

Chiral Olefins as Steering Ligands in Asymmetric Catalysis

*Christian Defieber, Hansjörg Grützmacher, and Erick M. Carreira**

Keywords:
alkene ligands · asymmetric catalysis · enantioselectivity · homogeneous catalysis · metal-mediated reactions

Dedicated to Professor Dieter Seebach on the occasion of his 70th birthday



Metal-catalyzed asymmetric processes offer one of the most straightforward ways to introduce stereogenic centers. Hence, the development of novel chiral ligands that can effectively induce asymmetry in reactions is crucial in modern organic synthesis. While many established chiral ligands bind to a metal through heteroatoms, structures that coordinate to metals through carbon atoms have received little attention so far. Here, we highlight the increasing number of such chiral chelating olefin ligands as well as their application in a variety of metal-catalyzed transformations.

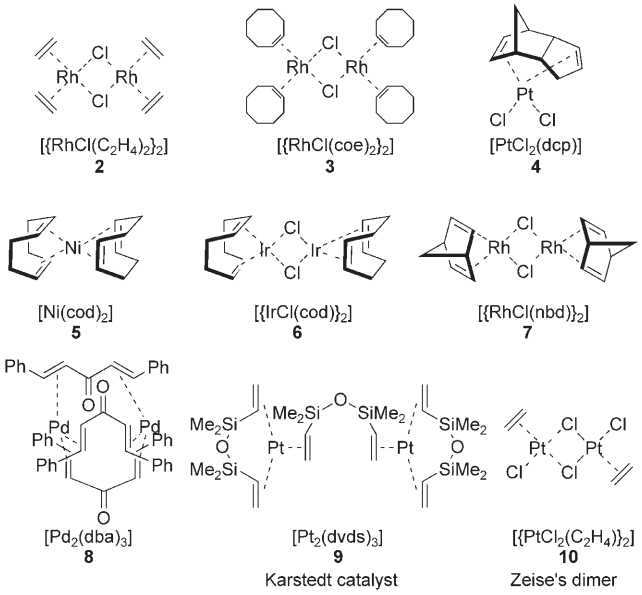
From the Contents

1. Introduction

Olefins have a rich history as ligands in organometallic chemistry.[1] One of the first organometallic complexes reported is Zeise's salt (**1**), a platinum complex coordinated to an ethylene molecule [Eq. (1)].[2] Since 1827, a large

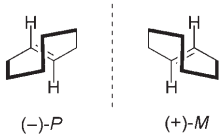
$$K_2[PtCl_4] + C_2H_4 \xrightarrow[60\ bar]{dil.\ HCl} \underset{\mathbf{1}}{K[PtCl_3(C_2H_4)] \cdot H_2O} + KCl \qquad (1)$$

number of olefin complexes have been reported, mostly involving late-transition metals such as Ni, Pd, Pt, Rh, or Ir. These complexes are of great importance in the field of asymmetric catalysis because of the fact that they can be conveniently employed as catalyst precursors to perform ligand exchange reactions with chiral ligands, with the olefin ligands serving as placeholders for vacant coordination sites.[3] Most of the chiral ligands used in asymmetric catalysis are based on heteroatoms, most notably pnictogen atoms such as nitrogen or phosphorus. The lability of olefin ligands, compared to the strong binding affinity of pnictogen-based ligands to transition metals, ensures rapid and quantitative exchange reactions, which allows in situ preparation of optically active catalyst systems. Although some transition-metal–monoolefin complexes are commercially available (Scheme 1, for example, **2**, **3**, and **10**), most of the complexes contain diolefin donor ligands such as 1,5-cyclooctadiene (cod), norbornadiene (nbd), and dicyclopentadiene (dcp).[4] Especially noteworthy is $[Pd_2(dba)_3]$ (**8**), a convenient phosphane-free source of Pd^0, which is often employed as a precursor for cross-coupling reactions.[5,6] The complex $[Pt_2(dvds)_3]$ (**9**), also known as Karstedt's catalyst, serves as a hydrosilylation catalyst for industrial-scale processes.[7]



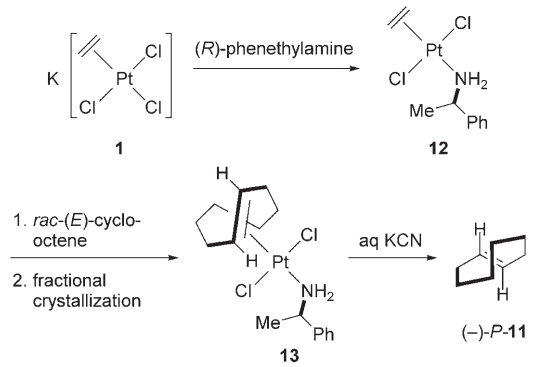
Scheme 1. Selection of commercially available transition-metal olefin complexes. coe: cyclooctene, dcp: *endo*-dicyclopentadiene, cod: 1,5-cyclooctadiene, nbd: norbornadiene, dba: dibenzylideneacetone, dvds: divinyltetramethyldisiloxane.

In pioneering studies on molecular asymmetry of olefins, Cope et al. prepared the first chiral olefin.[8] (*E*)-Cyclooctene (**11**) displays planar chirality as a consequence of restricted rotation of the olefinic bond through the hexamethylene chain,[9] and can be isolated in enantiomerically pure form as shown in Scheme 2. Starting from Zeise's salt (**1**), complexation with a chiral amine resulted in the formation of **12**. Subsequent olefin exchange with *rac*-(*E*)-cyclooctene[10] led to a pair of diastereomeric Pt complexes



11

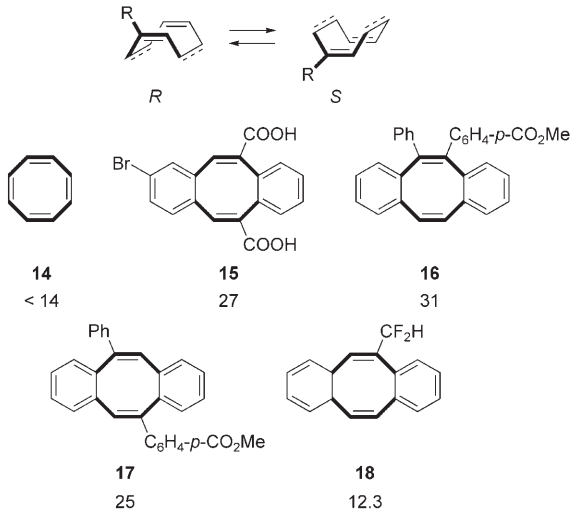
[*] Dr. C. Defieber, Prof. Dr. E. M. Carreira
Laboratorium für Organische Chemie
ETH Zürich
8093 Zürich (Switzerland)
Fax: (+41) 44-632-1328
E-mail: carreira@org.chem.ethz.ch
Prof. Dr. H. Grützmacher
Laboratorium für Anorganische Chemie
ETH Zürich
8093 Zürich (Switzerland)



Scheme 2. Synthesis of chiral (*E*)-cyclooctene ((−)-(*P*)-**11**) according to Cope et al.

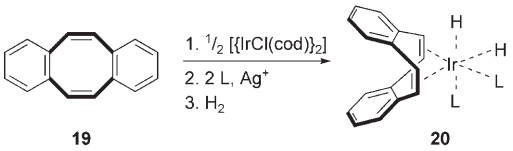
(**13**) which were separated by fractional crystallization. Treatment with KCN liberated the enantiomerically pure chiral olefin **11**, which showed remarkable stability (racemization barrier for (*E*)-cyclooctene: 35.6 kcal mol^{-1}).[11]

The inversion of cyclooctatetraene (**14**)[12] and planar chiral dibenzocyclooctatetraene (dbcot, **19**) derivatives was intensively investigated in the context of electron delocalization in aromatic and antiaromatic molecules (Scheme 3). Resolution by forming the brucine salts allowed Mislow and Perlmutter to separate the enantiomers of the dibenzocyclooctatetraene derivative **15** in 1962.[13] The barrier for inversion via a planar antiaromatic transition state leading to racemization was estimated to be 27 kcal mol^{-1}. Other conformationally stable dbcot derivatives which could be isolated as enantiomerically pure substances are **16** and **17**.[14]



Scheme 3. Inversion barriers ΔG_{inv} of planar chiral cyclooctatetraene derivatives in kcal mol^{-1}.

However, monosubstituted cyclooctatetraene or dbcot derivatives such as **18** are not conformationally stable and racemize at room temperature.[15] Metal complexes were never reported with these ligands, although the parent compound dbcot (**19**) forms remarkably stable complexes. In 1983, Douglas and Crabtree could show that **19** as a ligand in rhodium or iridium complexes such as **20** resists hydrogenation even under forcing conditions [Eq. (2)].[16] Actually, the stability of dbcot complexes is so high that dbcot was employed as a catalyst poison to distinguish between homogeneously and heterogeneously catalyzed reactions.[16b]



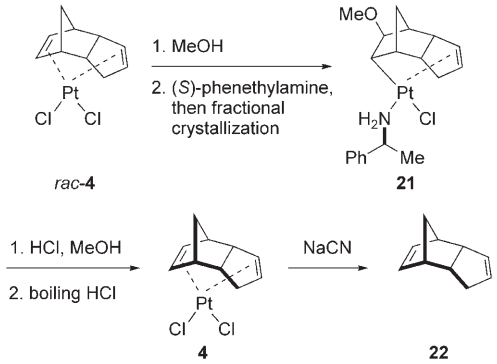
(2)

Diolefin complexes generally exhibit greater stability than monoolefin complexes against decomposition. This feature can be exploited to synthesize diolefin complexes starting from monoolefin complexes. A characteristic feature of metal-bound olefins is the large shift in their spectroscopic parameters as a result of coordination, for example, 100–150 cm^{-1} in the IR ($\nu_{C=C}$) or about 1 ppm in the ^{1}H NMR spectra compared with the free olefins. Ligand exchange reactions can thus be conveniently monitored by observing the corresponding olefin signals. 1,5-Cyclooctadiene (cod) is probably the most common diolefin ligand found in late-transition-metal complexes. These complexes are generally stable. Complexes of *endo*-dicyclopentadiene have only rarely been reported; the bite angle of this ligand is somewhat larger than that of cod: for example, whereas the cod ligand in [$PdCl_2$(cod)] shows a bite angle of 86.3°, the corresponding value for dcp in [$PdCl_2$(dcp)] is 92.5°.[17] Nevertheless, metal–dcp complexes were among the first metal–diene complexes to be isolated. In analogy to the resolution of cyclooctene by Cope et al., Paiaro et al. showed in 1966 that it is possible to resolve *endo*-dicyclopentadiene with the help of [$PtCl_2$(dcp)]

Christian Defieber, born in 1977 in Karlsruhe, Germany, studied chemistry at ETH Zürich, Switzerland, and at the Ecole Polytechnique, Palaiseau, France. In 2003, he completed his diploma thesis in the research group of Carreira, and in 2007 he finished his PhD in the same group. He is currently a DAAD postdoctoral researcher at the California Institute of Technology with Brian M. Stoltz.

Erick M. Carreira was born in Havana, Cuba, in 1963. He received his BSc from the University of Urbana-Champaign working with Scott Denmark, and his PhD from Harvard University working under the direction of David A. Evans. After postdoctoral research at the California Institute of Technology with Peter Dervan, he joined the faculty there. Since 1998, he has been full professor at ETH Zürich.

(**4**, Scheme 4).[18] The reaction of *rac*-**4** with methanol resulted in the stereospecific formation of the *exo*-6-methoxy derivative. Treatment with (*S*)-1-phenethylamine led to a mixture of diastereomeric complexes which were resolved by fractional crystallization. Subsequent treatment with acid removed the chiral amine and eliminated the methoxy group. The resulting optically pure [$PtCl_2$(dcp)] (**4**) was treated with aqueous sodium cyanide to release (+)-dcp (**22**).

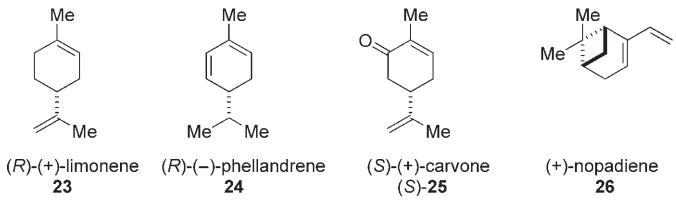


Scheme 4. Resolution of dcp according to Paiaro et al.

Some diene ligands possess smaller bite angles. For example, in norbornadiene (nbd) complexes, the bite angle α towards a coordinating metal can be as small as 70°. Norbornadiene compounds have a bridging carbon atom between the two double bonds, and this ensures a suitable arrangement of the two double bonds for coordination with the metal center. Another salient feature of this bicyclic system is that the central bridge suppresses delocalization and isomerization of the two double bonds to form the more stable conjugated system. Thus, metal complexes with 1,4-cyclohexadiene are very sensitive and tend to readily isomerize to 1,3-cyclohexadiene metal complexes. However, benzoquinone is known to form stable complexes with various metals because isomerization is not possible.[19] An impressive demonstration of the very different stabilities of cod and nbd complexes was obtained when [Rh(P∩P)(cod)]BF_4 and [Rh(P∩P)(nbd)]BF_4 were tested as catalyst precursors in hydrogenations (P∩P = chelating bisphosphane ligand): the nbd complexes had three orders of magnitude shorter induction times, thus indicating a higher lability.[20]

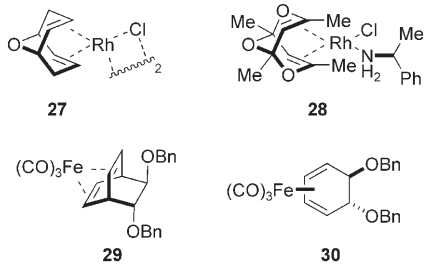
Hansjörg Grützmacher, born 1959 in Hamburg, studied and earned his degree in Chemistry at the University of Göttingen with Herbert W. Roesky. He worked with Guy Bertrand at the Laboratoire de Chimie de Coordination in Toulouse, was nominated Privatdozent at the University of Heidelberg, and joined the faculty of the University of Freiburg before he was appointed at the ETH, where he has been full professor since 2001.

Naturally occurring dienes, including chiral dienes, are also capable of forming complexes with transition metals (Scheme 5). In this respect, Lewis and co-workers generated [{RhCl(diene*)}$_2$] dimers which were treated in situ with TlC_5H_5 to obtain the corresponding (π-cyclopentadienyl)rhodium complexes as orange oils (diene* = **23**, **24**, (*S*)-**25**).[21] ^{1}H NMR spectroscopic measurements demonstrated that both double bonds are coordinated to the transition metal. Schurig and co-workers obtained an X-ray structure of [RhCp((*S*)-**25**)] (Cp = cyclopentadienyl), which unambiguously established complexation to both olefin moieties.[22] Salzer et al. prepared [RhCp(**26**)], a complex containing a chiral diene derived from the monoterpene (−)-myrtenal.[23]



Scheme 5. Natural common chiral dienes used for the formation of Rh^I and Ir^I complexes.

Early investigations were also aimed at designing and synthesizing non-natural chiral dienes and examining their coordination capabilities with various metals. Noteworthy in this respect is the synthesis of Rh complex **27**, which contains a chiral analogue of cyclooctadiene (Scheme 6).[24] Panunzi and co-workers reported the synthesis of the chiral diene 1,3,5,8-tetramethyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene (tond) and its complexation to form **28**,[25] which enabled resolution of its enantiomers. Iron complexes incorporating a chiral bicyclo[2.2.2]octadiene **29**[26] as well as cyclohexa-1,3-diene **30**[27] were also disclosed. However, these studies were restricted to examining the coordination chemistry and the associated reactivity of the metal-bound olefins. No investigations were carried out to explore the potential of these complexes as catalysts for asymmetric synthesis. In the conclusion to their studies on metal–diamine complexes for enantioselective transfer hydrogenation of ketones in 1998, Lemaire, Sautet, and co-workers suggested that the investigation of chiral diene complexes could prove fruitful.[28] However, this kernel of an idea was not followed up.

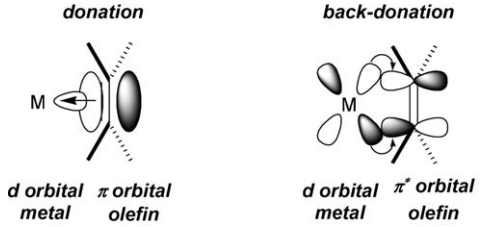


Scheme 6. Rh^I and Fe^0 complexes containing non-natural chiral dienes as ligands.

2. Theory of Metal–Olefin Bonding

This Review focuses on the application of olefins as steering ligands in complexes of late-transition metals for homogeneous catalysis. To illustrate their potential, we will briefly discuss some fundamental theoretical concepts which highlight the properties of olefins as ligands.

The elucidation of the electronic structure of olefin complexes can be considered as being at the cutting edge between classical organic and coordination chemistry. Some 60 years ago, Walsh established the formulation of the metal–alkene bond as a Lewis acid/Lewis base interaction.[29] This view was refined by Dewar[30] by employing molecular orbital concepts and the symmetry properties of the involved orbitals to develop a qualitative bonding model. According to this model, a σ bond is formed by donation of a pair of electrons in the π_{2p} orbital on the olefin to an empty hybrid orbital on the metal (L→M donation, defined as *d*). This is complemented by π back-donation of electron density from a filled hybrid orbital on the metal to the initially empty π^*_{2p} (antibonding) orbital on the olefin (M→L back-donation, defined as *b*). These two types of interactions are synergistic (Scheme 7).



Scheme 7. Dewar–Chatt–Duncanson (DCD) model for metal–olefin binding.

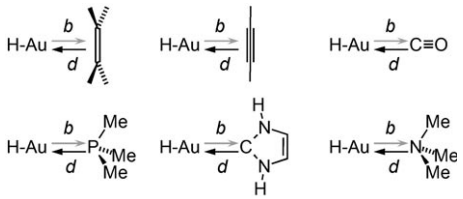
By studying a variety of metal–alkene complexes, Chatt and Duncanson[31] realized very early that even structurally similar alkenes possess different metal–alkene binding energies. Specifically, this was recognized with the limiting cases of $[Ag(alkene)]^+$ and $[PtX_3(alkene)]^-$ complexes. While the bonding interaction in the former is mainly due to L→M donation, the latter owe their stability to significant M→L back-donation. Remarkably, only recently was the first homoleptic silver–ethene complex, $[Ag(C_2H_4)_3][Al\{OC(CF_3)_3\}_4]$ isolated and structurally characterized.[32] This compound owes its stability to the very weakly coordinating anion, which is fully in accord with Chatt's notion that silver–alkene complexes become more stable the more ionized the silver salt is.[31b]

It is generally accepted that back-donation increases with the principal quantum number of the metal center, and frequently the stabilities of the complexes of a specific alkene follow the same trend. Increasing back-donation causes an increasing hybridization of the coordinated olefinic carbon center from sp^2 to sp^3, whereby the NMR resonance for this carbon atom is shifted to a lower frequency. It is generally accepted that the coordination shift $\Delta\delta = (\delta_{complex} - \delta_{free\ ligand})$ measures the degree of back-donation, and serves as a first estimate for the stability of a given olefin complex.[33] This is nicely demonstrated with the Zeise-type anions $[M(C_6F_5)_3(C_2H_4)]^-$ (M = Pd, Pt) with $\delta(^{13}C) = 97.6$ ppm for Pd and 78.9 ppm for Pt.[34] In the same study the isolation of the analogous nickel complexes and a theoretical study of the complexes $[MCl_3(C_2H_4)]^-$ (M = Ni, Pd, Pt) were reported. The Pt complexes were in both cases (C_6F_5 and Cl complexes) significantly more stable and can be easily isolated and stored. It is, however, a priori difficult to estimate the relative importance of L→M donation and M→L back-donation for the stability of a complex.

Modern theoretical approaches make use of energy and charge decomposition schemes such as the extended transition state (ETS) method as promoted by Ziegler and Rauk[35] or the charge decomposition analysis (CDA) developed by Frenking et al. for the electronic analysis of bonding in organometallic compounds.[36] Examples of such analyses are given in Tables 1 and 2 for the binding of some relevant ligands to an AuH metal fragment.[37] The CDA method may be regarded as a "quantified" DCD model that just provides information about the above-mentioned quantities, that is, donation, back-donation, and repulsive interactions. The following orbital contributions to the charge distributions are inspected: a) mixing of the occupied orbitals of the ligand and the empty orbitals of the metal complex fragment to give an electron-donation term *d*, b) mixing of the unoccupied orbitals of the ligand with the filled orbitals of the metal complex fragment to result in back donation *b*; c) interaction between the occupied orbitals of the ligand and the occupied orbitals of the metal complex fragment, thereby leading to the repulsive polarization *r*. Finally, the nonclassical term *Δ* resulting from the mixing of unoccupied orbitals on the two fragments should be virtually zero in a donor–acceptor complex, because all interactions between the fragments should arise from the mixing of occupied and unoccupied orbitals. If it turns out not to be zero, the metal–ligand complex might not be appropriately described by the DCD model; *Δ* thus serves as a control term.

Although some care must be taken with respect to generalizations, the data in Table 1 show that olefins are quite good donors ($d = 0.36$), similar to the fashionable N-heterocyclic carbenes (NHCs, $d = 0.36$)[38] and stronger than

Table 1: CDA analyses for some HAu-L complexes (DFT, B3LYP, basis set II[36b])



L	*d*	*b*	*d*/*b*
C_2H_4	0.36	0.13	2.9
C_2H_2	0.16	0.12	1.3
CO	0.27	0.22	1.2
PMe_3	0.53	0.16	3.3
imidazol-2-ylidene	0.36	0.12	3.0
NMe_3	0.20	0.01	32.7

CO. As expected, phosphanes are especially strong, while amines and acetylenes are especially weak donors. Since the accepting properties of olefins are very similar to those of NHCs, the *d*/*b* ratio of the two ligand classes is very similar. Phosphanes (PR_3) are not only remarkably good donors, they also serve as good acceptors (see below) by interaction of the unoccupied P-R σ* orbitals with filled (d,s,p) hybrid orbitals at the metal center. Amines, on the other hand, are not only weak donors they are especially weak acceptors, with the net effect that the *d*/*b* ratio becomes very large (32.7 for NMe_3).

An estimate of the intrinsic binding energy ΔE_{int}, that is, the binding energy between the metal complex fragment $[X_nM]^*$ and the ligand L* (the asterisks designate that both fragments have the same structural parameters as in the complex $[MX_nL]$), can be obtained according to the ETS scheme. The bonding energy between the two fragments is described by the three interaction terms shown in Equation (3). The first term ΔE_{Pauli} quantifies the Pauli repulsion

$$\Delta E_{int} = \Delta E_{Pauli} + \Delta E_{elstat} + \Delta E_{orb} \quad (3)$$

between the electrons on the two fragments; the electrostatic attraction between the two fragments is ΔE_{elstat}; and ΔE_{orb} represents the orbital interaction term, which quantifies the energy gain upon mixing the orbitals of the two fragments. Table 2 lists these energies for the HAu-L complexes shown in Table 1.

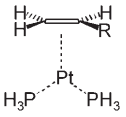
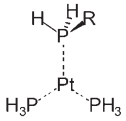
Table 2: ETS analyses for HAu-L complexes (DFT, B3LYP, basis set II[36b]). All energies are in kcal mol^{-1}.

L	ΔE_{int}	ΔE_{Pauli}	ΔE_{elstat}	ΔE_{orb}
C_2H_4	−27.6	116.5	−90.9	−53.2
C_2H_2	−26.6	118.5	−91.4	−53.8
CO	−34.2	154.2	−120.3	−68.1
PMe_3	−43.8	153.5	−144.3	−53.0
imidazol-2-ylidene	−52.7	174.1	−173.3	−53.5
NMe_3	−29.9	82.5	−81.7	−30.7

This analysis clearly shows that care must be taken when orbital interactions alone are discussed in the context of complex stabilities, since the ΔE_{orb} value does not differ significantly within the series HAu-L, except for the amine complex $[HAu(NMe_3)]$. The repulsive term ΔE_{Pauli} plays an unfavorable role for ligands with rather extended occupied π orbitals such as C_2H_4, C_2H_2, and CO, and is not counterbalanced by a strong electrostatic interaction ΔE_{elstat}. This latter term is especially large for NHC complexes and completely neutralizes the ΔE_{Pauli} contribution, thus making NHCs the strongest ligands, along with phosphanes, in this series, which is in accord with experimental observations.

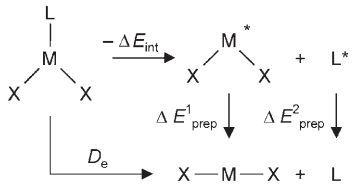
Some interesting trends were computed with the series of $[Pt(PH_3)_2(L)]$ complexes with respect to the binding (L = olefin or phosphane; Table 3).[39] For olefins, particularly for the electron-poor acrylonitrile, the contribution from back-donation becomes important.[40] On the other hand, in phosphanes, particularly for electron-rich phosphanes, electron donation makes a significant contribution to the binding.

Table 3: CDA and ETS analyses of Pt–olefin and Pt–phosphane complexes (DFT, B3LYP, basis set II[36b]). All energies are in kcal mol^{-1}.

	R	*d*	*b*	*d*/*b*	D_e	ΔE_{int}
	H	0.51	0.38	1.33	15.4	−56.9
	CN	0.47	0.42	1.13	17.6	−62.8
	F	0.51	0.40	1.27	11.9	−58.9
	NH_2	0.51	0.38	1.35	6.6	−54.7
	OH	0.50	0.37	1.37	9.9	−53.9
	H	0.38	0.23	1.67	9.7	−28.3
	CN	0.35	0.29	1.20	11.4	−30.1
	F	0.46	0.34	1.35	19.6	−44.3
	NH_2	0.49	0.27	1.78	14.2	−35.8
	OH	0.47	0.30	1.53	16.3	−38.7

Variation of the substituents R has a larger effect in the phosphane complexes, thus indicating that the electronic properties of a transition-metal complex may be more easily controlled by changing the substituent of a coordinated phosphane than in an olefin complex.

Apart from the intrinsic interaction energy, it is instructive to inspect the adiabatic dissociation energy D_e (Scheme 8). The energy D_e is required to dissociate any given complex



Scheme 8. Graphical illustration of the adiabatic dissociation energy D_e, the preparation energies ΔE^1_{prep}, ΔE^2_{prep}, and intrinsic interaction energy ΔE_{int}.

$[MX_2L]$ into the fragments $[MX_2]$ and L, both in their ground-state structures, and is a more realistic measure than the intrinsic dissociation energy $-\Delta E_{int}$ (see above). The value of D_e is always smaller than ΔE_{int} by the sum of the energies ΔE^1_{prep} and ΔE^2_{prep}—the energies spent preparing the two fragments, $[MX_2]$ and L, sterically and electronically for bond formation—that is, $D_e = -\Delta E_{int} - (\Delta E^1_{prep} + \Delta E^2_{prep})$.

Frequently, the value of D_e does not differ too much from that of ΔE_{int}; for example, when only small deviations in the angle are required to prepare the ground-state structures MX_2 and L in their excited "ready-to-bind" states MX_2* and L*. The preparation energies ΔE^2_{prep} are especially large for olefins, and thus lead to a considerable difference between D_e and ΔE_{int}. The reason for the large ΔE^2_{prep} value upon binding an olefin to a metal center is the energy which must be paid for elongation of the strong C–C double bond and the rehybridization of the carbon atoms from an sp^2 towards an sp^3 valence electron configuration. This large value turns olefins into relatively weakly bound ligands.

As early as 1969, Hogeveen and co-workers examined the relative stabilities of various rhodium–diene complexes[41] and studied their relative rates of ligand exchange.[42] The addition of an appropriate amount of a chelating diene to a solution of

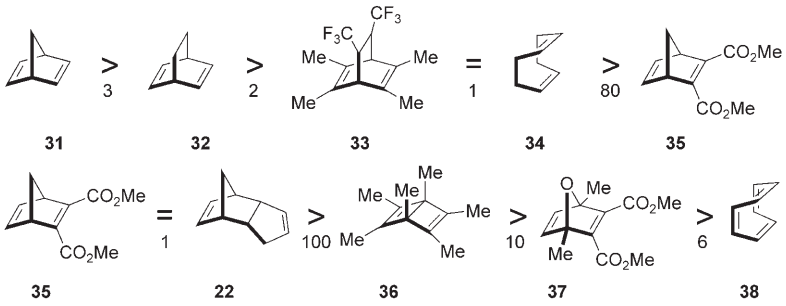
a rhodium complex of a different diene gives rise to a displacement reaction according to Equation (4). The equi-

$$2\,\text{diene}_A + [\{RhCl(\text{diene}_B)\}_2] \overset{K}{\rightleftharpoons} 2\,\text{diene}_B + [\{RhCl(\text{diene}_A)\}_2] \quad (4)$$

librium constant K for the reaction is given by Equation (5).

$$K = \frac{[\text{diene}_B]^2[\{RhCl(\text{diene}_A)\}_2]}{[\text{diene}_A]^2[\{RhCl(\text{diene}_B)\}_2]} \quad (5)$$

The extent of the displacement was measured by integration of suitable NMR signals of the four components in the reaction mixtures. Equilibration was generally rapid at room temperature. The numbers in Scheme 9 indicate the equilibrium constant K between the next nearest neighbors diene_A and diene_B.



Scheme 9. Comparison of the stabilities of rhodium complexes with various chiral diene ligands.

The relative order in coordination stabilities is a result of a) the geometry of the diene and b) the nature of the substituents. The most stable complexes are those of bicyclo[2.2.1]hepta-2,5-diene (**31**) and bicyclo[2.2.2]octa-2,5-diene (**32**) which have a similar bite angle and no steric hindrance around the double bonds. Apart from the chelate effect, which is exerted by the two olefin units located in proximity, an additional factor of these strained scaffolds might be taken into account: Particularly strong bonds are formed upon η^2 coordination with the metal center, as pyramidalization at the ligating carbon atoms occurs. Quantum-chemical calculations of simple model complexes with specified pyramidalization angles revealed a significant strengthening of the metal–alkene bond relative to that in complexes of the planar alkenes.[36c,43] The major electronic effects resulting from pyramidalization of the double bond is a) to lower the energy of the π^* LUMO, thus making it a better acceptor of electron density from the metal, and b) to lower the energy ΔE^2_{prep} for binding of the olefin (see Scheme 8).

(+)-Dcp (**22**) possesses—in comparison to **31** and **32**—drastically reduced binding affinity towards a metal center. It is presumed that the nonparallel location of the diene system and the large distance (3.12 Å) between the two double bonds are responsible for the diminished affinity of **22**. Compared to the bicyclic compounds **31** and **32**, 1,5-cyclooctadiene (**34**) as well as cylcooctatetraene (**38**) are flexible molecules. Although their bite angles seem to be optimal for coordination with a metal center, their coordination involves a considerable loss of entropy compared to that of the free diene, thus making complex formation unfavorable. However, the similar distance between the complexed double bonds in $[\{RhCl(cod)\}_2]$ and the free diene (2.87 and 2.8 Å, respectively) suggest that cod can bind relatively strongly to the metal center despite the unfavorable entropy effect.[44] The instability of the cyclooctatetraene complex is probably due to the large distance between the nonconjugated double bonds (3.12 Å) combined with the unfavorable entropy effect. In general, electron-withdrawing substituents stabilize metal–olefin complexes; the opposite is found for electron-donating substituents. This characteristic property can be rationalized with the DCD model (see Table 3). However, steric effects have to be superimposed on the electronic effects. Electron-donating substituents such as in **33** or **36** lead to destabilization relative to the unsubstituted **32**. The lower stabilities of the complexes of the symmetrically substituted dienes **35** and **37** are rather surprising when the electron-withdrawing character of the methoxycarbonyl group is taken into account. It may well be that the favorable electronic effect is entirely counterbalanced by a large steric hindrance of the substituents.

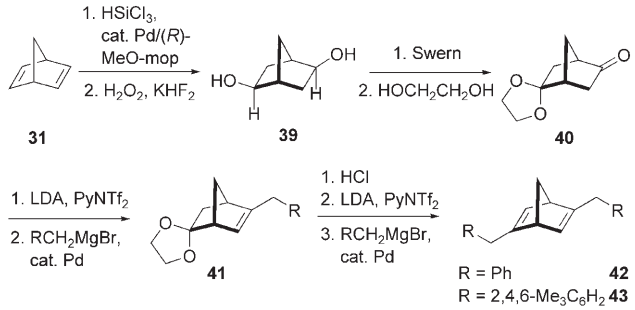
In summarizing this section: The intrinsic interaction energies ΔE_{int} for the binding of olefins do not disfavor them over other ligands. It is the high energy for the preparation of binding ΔE^2_{prep} and the rather high Pauli repulsion term ΔE_{Pauli} which make simple olefins only weakly bound ligands. However, structurally preorganized olefins and especially dienes may be excellent steering ligands, either because a rigid ligand backbone stabilizes the complex kinetically or alternatively because electron-withdrawing substituents or pyramidalization of the carbon atoms in the ground state of the free olefin stabilize the complex electronically. As a further consequence of these reflections, one may propose the use of unsaturated p-block-element analogues of olefins such as silaethenes ($R_2Si{=}CR_2$), disilenes ($R_2Si{=}SiR_2$), and phosphaalkenes ($RP{=}CR_2$) as ligands for homogeneous transition-metal catalysts because they bind more strongly to transition metals.[45] These ideas remain largely to be tested, but the stage is set for the use of olefins as steering ligands in catalysis.

3. Synthesis of Chiral Dienes

Despite the large number of investigations on the coordination chemistry of metal–olefin complexes, applications of these complexes in catalysis are scarce.[28] This might be attributed to the general notion that such complexes possess only limited stability. Chiral coordinating olefins might be envisaged to easily dissociate in the course of a catalytic cycle, thereby resulting in only moderate asymmetric induction. The lability of metal–olefin complexes must certainly be taken into account when considering a catalytic application; however, a large number of asymmetric processes have been efficiently catalyzed by chiral olefins since their

first disclosure by Carreira and Hayashi.[46] In some cases, chiral olefins even outperformed conventional ligands such as phosphanes. In Sections 3 to 5 the synthesis of the various ligand scaffolds will be briefly outlined and discussed; Sections 6 and 7 highlights the applications of chiral olefins in catalysis.

The synthesis of a chiral bicyclo[2.2.1]heptadiene that serves as a ligand in an asymmetric process (the addition of phenylboronic acid to cyclohex-2-enone) was disclosed by Hayashi et al. (Scheme 10).[47] The synthesis starts with the

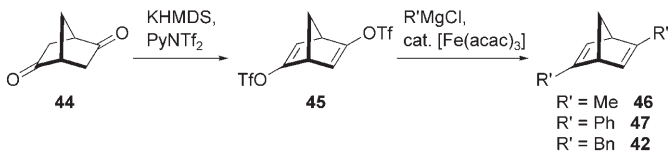


Scheme 10. Synthesis of the chiral bicyclo[2.2.1]heptadienes **42** and **43** according to Hayashi et al. MeO-mop: 2-diphenylphosphanyl-2′-methoxy-1,1′-binaphthyl, LDA; lithium diisopropylamide, $PyNTf_2$: *N*-(pyrid-2-yl)bis(trifluoromethanesulfonyl)imide.

catalytic asymmetric hydrosilylation of nbd (**31**) in the presence of Pd/(*R*)-MeO-mop to provide optically active diol **39** with 99% *ee*.[48] Swern oxidation and protection of one of the carbonyl groups as an acetal gave acetal ketone **40**. Formation of an alkenyl triflate followed by cross-coupling with BnMgBr in the presence of $[PdCl_2(dppf)]$ (dppf: 1,1′-bis(diphenylphosphanyl)ferrocene) and repetition of the sequence for the other carbonyl group gave (1*R*,4*R*)-2,5-dibenzylbicyclo[2.2.1]hepta-2,5-diene (**42**; the sterically encumbered ligand **43** was synthesized in the same way).

The sequential introduction of the two side chains limits the efficiency of this synthetic route. The simultaneous introduction of both substituents was not viable at first because of difficulties encountered with the isolation of bistriflate **45** (see Scheme 11). However, an optimized process was recently disclosed which enabled the simultaneous introduction of Me, Ph, or Bn substituents (Scheme 11).[49]

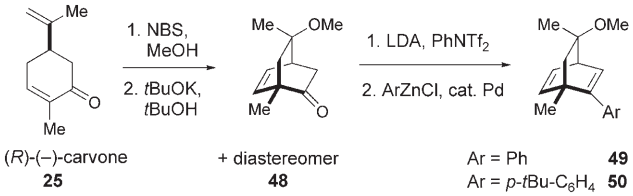
A disadvantage of the bicyclo[2.2.1]heptadiene **47** is its limited lifetime. A sample of **47** decomposes in $CDCl_3$ in less than 24 h. The origin of the instability in this case is presumably due to the presence of a styrene moiety in a strained bicyclic[2.2.1] core. This structural unit effectively



Scheme 11. Optimization of the synthesis of chiral bicyclo[2.2.1]heptadienes. KHMDS: potassium hexamethyldisilazide, acac: acetylacetonate.

lowers the energy of the π* orbital of the alkene relative to that of the nonconjugated olefin, thus rendering it highly reactive and prone to radical- and acid-catalyzed decomposition. Although the phenyl substituent causes the inherent instability of the ligand, this property is key for increasing the stability of the complex $[\{RhCl(\mathbf{47})\}_2]$ relative to the complexes of other bicyclo[2.2.1]heptadienes.

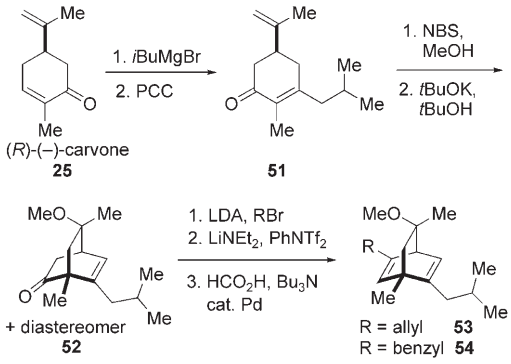
The synthesis of a chiral diene, a bicyclo[2.2.2]octadiene, was described by Carreira and co-workers (Scheme 12).[50] The synthesis commences with (−)-carvone (**25**), an inexpensive terpene which is available in both enantiomeric



Scheme 12. Synthesis of the chiral bicyclo[2.2.2]octadienes **49** and **50** according to Carreira and co-workers. NBS: *N*-bromosuccinimide.

forms. Bromination of the more electron-rich double bond, trapping of the bromonium ion with methanol, and subsequent enolization gave rise to the bicyclic ketone **48**. The subsequent formation of the vinyl triflate allows the introduction of a wide variety of aryl substituents (for example, R = Ph in **49** and R = *p*-C_6H_4-*t*Bu in **50**). Since the stereogenic centers are already set by the chiral starting material, it is possible to scale-up the synthesis without encountering any problems.

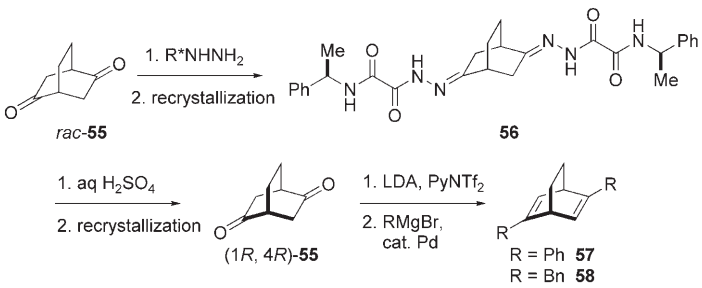
A second substituent at the bicyclic olefin scaffold can be conveniently introduced by a slight modification of the original synthetic route (Scheme 13).[51] Thus, a Grignard addition to carvone followed by PCC oxidation formed enone **51**, which was then submitted to identical cyclization conditions as described in Scheme 12. The ensuing bicyclic ketone **52** can be substituted by using a variety of different alkylating agents, for example, benzyl bromide. Formation of the vinyl triflate followed by its Pd-catalyzed reduction gave rise to a family of chiral bicyclo[2.2.2]octadienes with differ-



Scheme 13. Synthesis of the chiral disubstituted bicyclo[2.2.2]octadienes **53** and **54** according to Carreira and co-workers. PCC: pyridinium chlorochromate.

ent substituents (for example, **53** and **54**). It is easy to scale-up the synthesis, and the most successful member of this ligand class (**54**) is commercially available in both enantiomeric forms under the name diolefin.[52]

Alternative ligands based on the bicyclo[2.2.2]octadiene scaffold were later introduced (Scheme 14).[53] The racemic

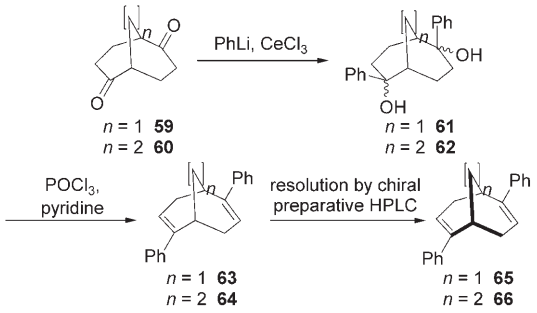


Scheme 14. Synthesis of the chiral bicyclo[2.2.2]octadienes **57** and **58** according to Hayashi and co-workers.

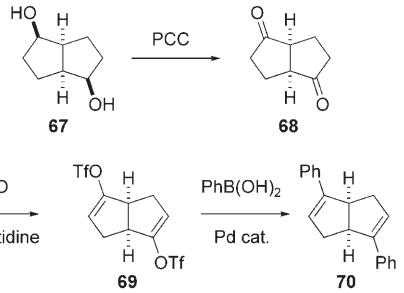
diketone **55** was resolved through fractional recrystallization of the hydrazone **56** formed on treatment with (*R*)-5-(1-phenylethyl)semioxamazide. Enantiomerically pure (1*R*,4*R*)-bicyclo[2.2.2]octa-2,5-dione (**55**) was first first converted into a ditriflate and then cross-coupled with BnMgBr or PhMgBr to give the 2,5-disubstituted bicyclooctadienes **57** and **58**, respectively. The major drawback of the synthesis is the low yield for the resolution of the key intermediate (1*R*,4*R*)-**55** (0.5% based on *rac*-**55**). Alternatively, the dienes can be resolved by preparative HPLC on a chiral stationary phase.[54]

The synthesis of ligands based on bicyclo[3.3.1] and bicyclo[3.3.2] scaffolds have also been documented (Scheme 15).[55] The racemic diketone **59** was treated with a phenylcerium reagent. Dehydration of the resulting diol **61** provided 2,6-diphenyl-substituted bicyclo[3.3.1]nona-2,6-diene. Separation of the enantiomers was carried out by preparative HPLC on a chiral stationary phase.

The exploration of various bicyclic ligand backbones was completed by the recent synthesis of a chiral bicyclo[3.3.0]octadiene by Lin and co-workers (Scheme 16).[56] Starting from enantiomericially enriched diol **67**, which was obtained by resolution in the presence of lipase, a short reaction sequence of oxidation, vinyl triflate formation, and Pd-catalyzed Suzuki coupling enabled the synthesis of chiral diene **70**.

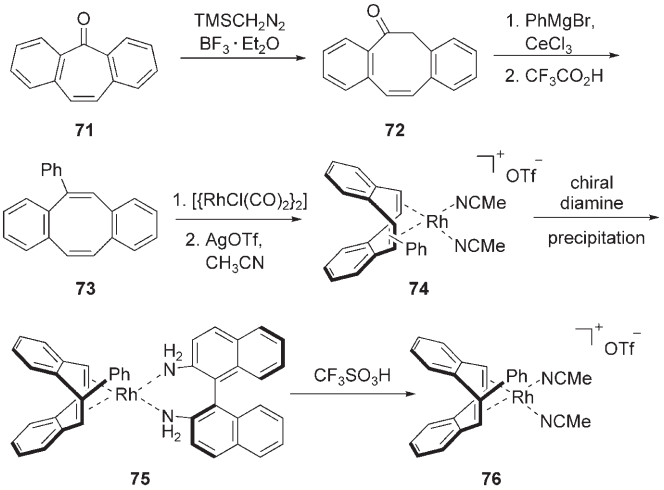


Scheme 15. Synthesis of the chiral dienes **65** and **66** with a bicyclo-[3.3.1]nonadiene framework according to Hayashi and co-workers.



Scheme 16. Synthesis of a chiral bicyclo[3.3.0]octadiene **70** according to Lin and co-workers.

A major challenge in the preparation of chiral dienes is the separation of the enantiomers at some point in the synthesis. Asymmetric catalysis, classical resolution of the intermediates, or chromatographic separation of the enantiomers by HPLC on a chiral stationary phase provide solutions to this problem. Grützmacher and co-workers employed, however, an alternative approach: an organometallic method in which the enantiomers were resolved by formation of diastereomeric complexes of the racemic diene followed by the addition of a chiral diamine and subsequent crystallization (Scheme 17).[57] The synthesis of **76** started from commercially

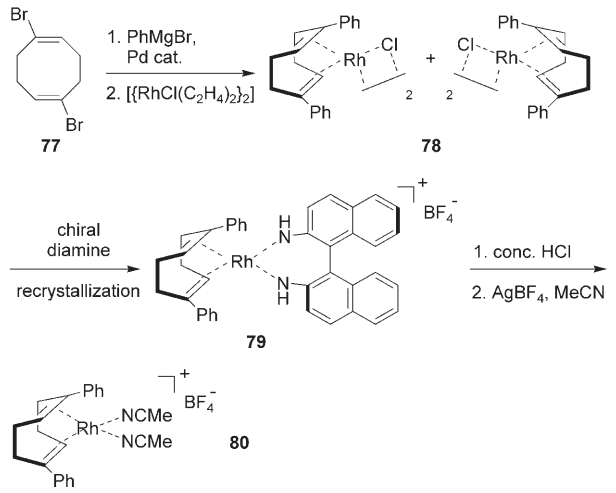


Scheme 17. Resolution of a substituted dibenzocyclooctatetraene by complextion with a chiral diamine according to Grützmacher and co-workers. TMS: trimethylsilyl.

available dibenzosuberone (**71**). Ring expansion by treatment with $TMSCHN_2$, subsequent addition of a phenylcerium reagent, and dehydration provided **73**. Complexation with Rh^I and ligand exchange with optically pure (+)-1,1′-binaphthyl-2,2′-diamine yielded a mixture of diastereomeric complexes, which could be precipitated from a mixture of EtOH and hexanes to give the diastereomerically pure **75**. The chiral diamine could then be removed by treatment with triflic acid.

The same concept was adapted by Hayashi and co-workers to resolve a 1,5-disubstituted diphenyl-1,5-cyclo-

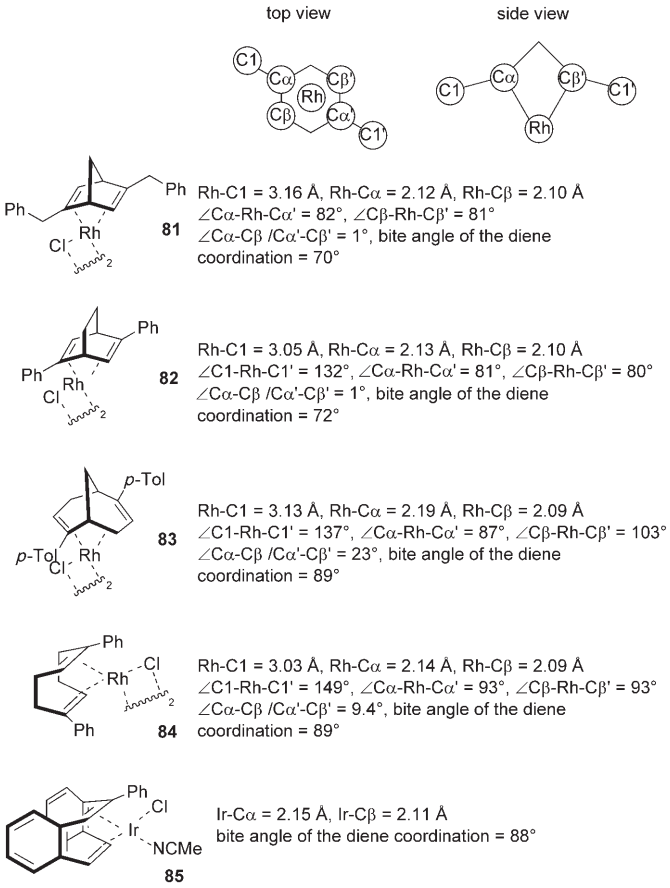
octadiene through formation of complex **78** (Scheme 18).[58] Starting from 1,5-dibromo-1,5-cyclooctadiene (**77**), a palladium-catalyzed cross-coupling reaction with PhMgBr afforded the 1,5-diphenylcyclooctadiene which was treated



Scheme 18. Resolution of a substituted cyclooctadiene by complexation with a chiral diamine according to Hayashi and co-workers.

with $[\{RhCl(C_2H_4)_2\}_2]$ to give **78**. This mixture was resolved into its diastereomerically pure complexes by coordination with (+)-1,1′-binaphthyl-2,2′-diamine and recrystallization to give **79**. Acid treatment liberated the rhodium dimer (not shown), which was treated with $AgBF_4$ in acetonitrile to give **80**. The rhodium dimer was used as the catalyst precursor in the rhodium-catalyzed 1,4-addition of phenylboronic acid to cyclohex-2-enone. The authors found that the enantiomeric purity of the 1,4-adduct is strongly dependent on the progress of the reaction: the lower the conversion, the higher the enantioselectivity. When the reaction was stopped after 20 min, optically enriched product was obtained in 91% *ee*, but only 3% yield; after 6 h reaction time the 1,4-adduct was isolated in 90% yield, but only 43% *ee*. A possible explanation for this finding is the racemization of the catalyst under the reaction conditions, that is, dissociation of the diene from the rhodium center and recoordination on the other enantiotopic face.

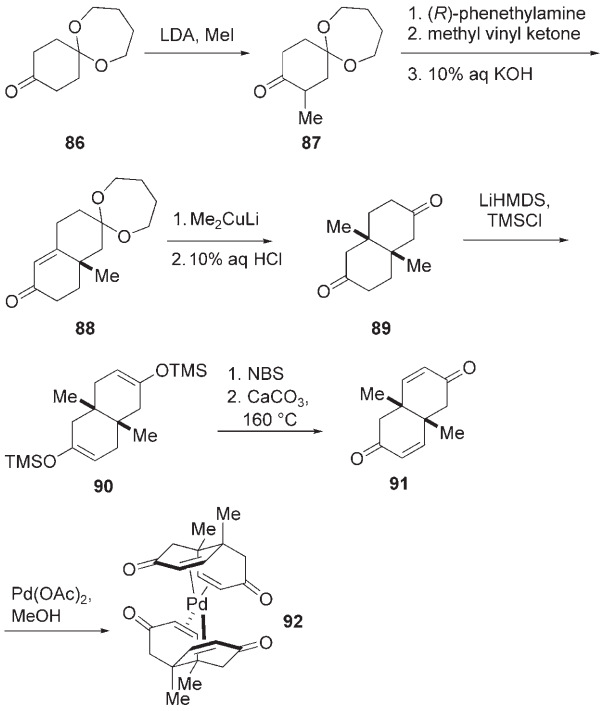
A comparison of X-ray structural data reveals some interesting properties of the different rhodium–diene complexes (Scheme 19). As expected, the rhodium–diene complexes based on the bicyclo[2.2.1]- and bicyclo[2.2.2] scaffolds **81** and **82** show similar structural data. Both scaffolds have a bite angle for diene coordination of approximately 70°; this contrasts with the bicyclo[3.3.1]nonadiene catalyst **83** which has a much larger bite angle of 89°. Moreover, the Rh–C1 distance in **83** is slightly larger than that in **82** (3.13 versus 3.05 Å). In complex **83**, the two double bonds (Cα=Cβ and Cα'=Cβ') coordinated to the rhodium center are not parallel to each other but twisted by 23°. As a result, the angles Cα-Rh-Cα' and Cβ-Rh-Cβ' are very different (87° versus 103°). These coordination properties are very different from those of unsubstituted cyclooctadiene complexes such as $[\{RhCl(cod)\}_2]$ where the two double bonds are parallel to



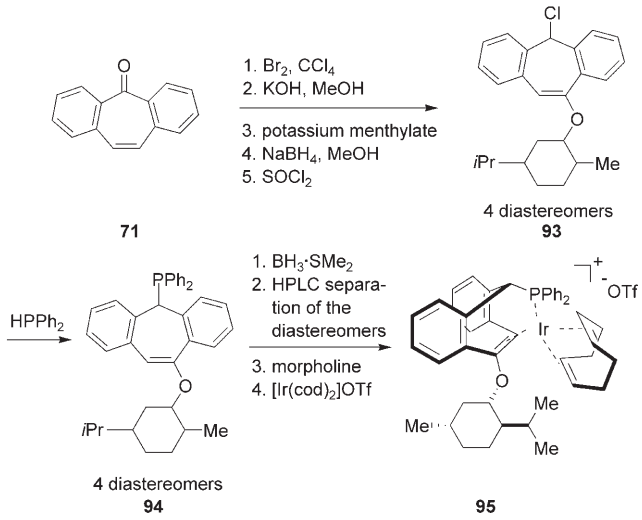
Scheme 19. Structural parameters of various chiral metal–diene complexes.

one another. The twisted coordination is probably caused by the minimization of torsion in the bridging backbone. In contrast, the 1,4-cyclohexadiene framework in **82** is highly symmetric, and the two double bonds coordinated to the rhodium center are almost parallel (1°). An inspection of the 1,5-diphenylcyclooctadiene complex **84** reveals that the Rh–Cα distance is longer than the Rh–Cβ distance (2.14 and 2.09 Å, respectively). The two double bonds are once again not parallel to each other, but slightly twisted by 9.4°.

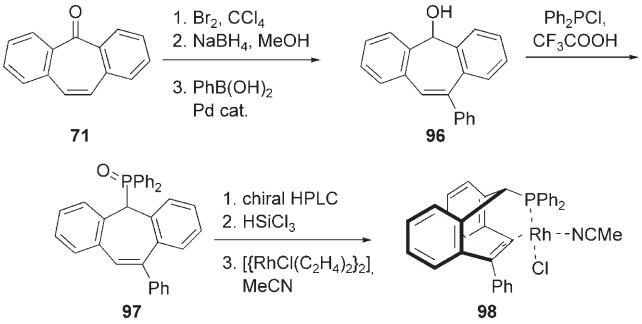
An innovative approach to make use of the well-known coordination chemistry of dibenzylideneacetone (dba) was reported by Trauner and co-workers.[59] A molecular modeling study led to the synthesis of bicyclic bis(enone) **91**, which forms stable complexes with Pd^0 (Scheme 20). The synthesis of bicyclic ketone **91** was straightforward and involved enolate alkylation of cyclohexanone **86** followed by formation of a chiral imine, which subsequently directed the cuprate addition of methyl vinyl ketone. Hydrolysis of the imine and Robinson annulation gave rise to bicyclic ketone **88**. Cuprate addition and unmasking of the ketone group led to intermediate **89**, which was treated with LiHMDS and TMSCl to obtain **90**. A bromination and dehydrobromination sequence provided bis(enone) **91** in good yield. Thus, the formation of the air- and moisture-insensitive, stable Pd^0 complex **92** was readily accomplished. The stability of this complex was ascribed to the increased back-donation caused by the



Scheme 20. Synthesis of a bis(enone) complex **92** according to Trauner and co-workers.



Scheme 21. Synthesis of a complex with a chiral phosphane-olefin ligand according to Grützmacher and co-workers.



Scheme 22. Example of the optimization of the synthesis of a complex with a chiral phosphane-olefin ligand.

electron-withdrawing carbonyl substituents on the double bonds. However, complex **92** showed no asymmetric induction in a Pd-catalyzed enyne cyclization.

4. Chiral Phosphane-Olefin Ligands

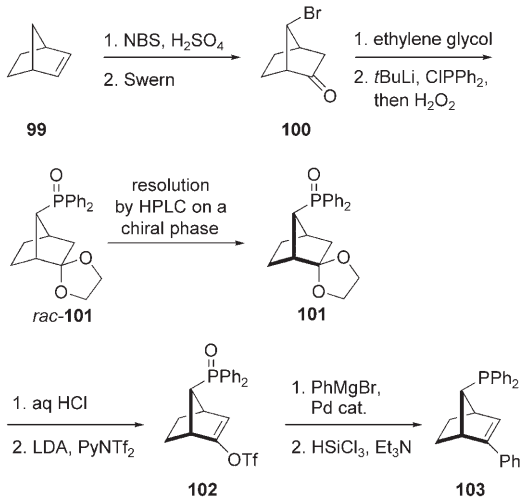
Recently, the design, synthesis, and application of phosphane-olefin hybrid ligands has revealed a new promising class of ligands. The beneficial effects of different types of donors are thus combined in a single ligand framework: the phosphorus atom ensures strong binding to the transition metal because of its increased coordination ability compared to an olefin (better σ donor), while an olefin provides the opportunity to create a chiral environment in proximity to the transition metal.

A first representative ligand of this class was reported by the research group of Grützmacher (Scheme 21).[60] Bromination and dehydrobromination of dibenzosuberone (**71**) followed by treatment with potassium menthylate and subsequent reduction of the ketone to the corresponding alcohol resulted in the formation of a diastereomeric mixture that was chlorinated to give **93**. A phosphorus donor was introduced by substitution with $HPPh_2$. The resulting four diastereomers **94** were separated by column chromatography after protection of the phosphorus atom as a phosphane-borane adduct. The resulting ligands were applied in an iridium-catalyzed hydrogenation reaction and displayed moderate levels of enantioselectivity (24–86% *ee*).

The synthesis of hybrid phosphane-alkene ligands was significantly simplified by using a Suzuki cross-coupling approach (Scheme 22).[61] Alcohol **96** underwent an Arbuzov-like rearrangement to provide phosphane oxide **97**. The enantiomers were resolved by preparative HPLC on a chiral stationary phase. Reduction of **97** with $HSiCl_3$ gave ready access to the phosphanyl- and phenyl-substituted dibenzocycloheptatriene. The application of this ligand in rhodium-catalyzed conjugate additions (see Section 6.1) as well as in iridium-catalyzed hydrogenations led to moderate levels of enantioselectivity (30–67% *ee*, see Section 7).

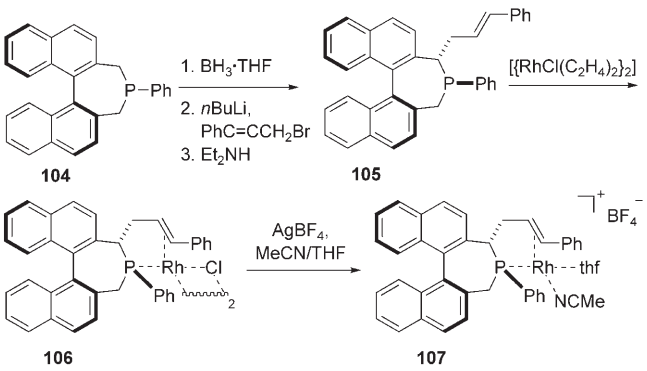
Hayashi and co-workers have also reported the synthesis of the mixed phosphane-olefin ligand **103** (Scheme 23).[62] Treatment of norbornene (**99**) with hypobromous acid followed by a Swern oxidation led to the selective formation of **100**. A sequence of ketalization and exchange of the bromine for a phosphanyl substituent gave rise to bicyclic phosphane oxide *rac*-**101**. The enantiomers were separated by preparative HPLC on a chiral stationary phase. The enantiopure **101** was then deprotected and the ketone was converted into alkenyl triflate **102**. A palladium-catalyzed cross-coupling reaction allowed the introduction of an aromatic substituent in place of the triflate group. The final reduction of the phosphane oxide with $HSiCl_3$ resulted in the formation of the hybrid ligand **103**.

Widhalm and co-workers recently reported the synthesis of a different phosphane-olefin ligand and its coordination to



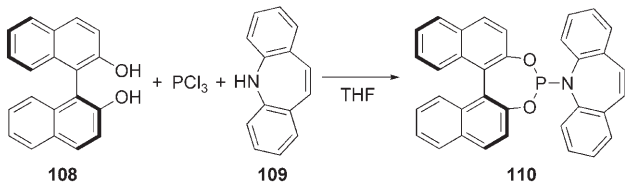
Scheme 23. Synthesis of a chiral phosphane-olefin ligand according to Hayashi and co-workers.

rhodium (Scheme 24).[63] Starting from dinaphthophosphepine **104**, the side chain containing the olefin functionality was selectively introduced after appropriate protection of the phosphane moiety as a borane adduct. Deprotection of the phosphane and complexation with Rh^I afforded complex **107**, the X-ray structure of which unequivocally established that binding occurred between the double bond and the phosphorus atom.



Scheme 24. Synthesis of a chiral phosphane-olefin ligand and its coordination to rhodium according to Widhalm and co-workers.

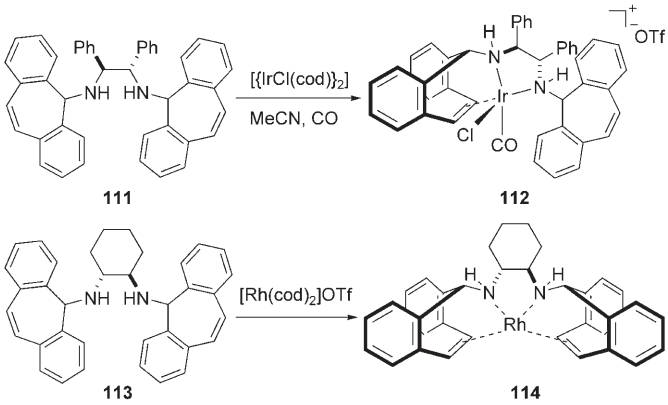
Easy and straightforward synthetic access to novel ligand systems is a necessary prerequisite for their widespread application in organic synthesis. Carreira and co-workers reported a one-step synthesis of the phosphor-olefin hybrid ligand **110** starting form (*S*)-binol (**108**), PCl_3, and *5H*-dibenzo[*b*,*f*]azepine (**109**; Scheme 25).[64] The bent structure of **110** reduces the amount of conjugation and renders the olefin unit more susceptible to coordination with a transition metal. A nonchiral aminophosphane-olefin ligand with **109** as the olefin donor had been previously employed in the rhodium-catalyzed hydroformylation of various olefins, and showed remarkable selectivity in favor of the branched aldehydes.[65]



Scheme 25. Synthesis of a phosphoramidite-olefin ligand according to Carreira and co-workers.

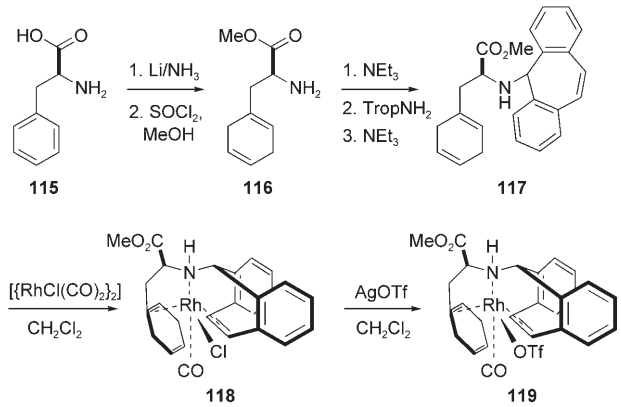
5. Chiral Amine-Olefin Ligands

Unlike their phosphorus-based analogues, amine-olefin hybrid ligands cannot be easily oxidized. This advantageous property was exploited by Grützmacher and co-workers in their straightforward synthesis of metal–olefin complexes **112** and **114**, wherein a chiral diamine backbone is linked to two tropylideneamine units (Scheme 26).[66] X-ray structure analysis established unequivocally that the transition metal was bound to the nitrogen atom as well as to the olefinic bonds.



Scheme 26. Synthesis of complexes with an amino-olefin ligand according to Grützmacher and co-workers.

Grützmacher et al. also disclosed the synthesis of a monoamine-diolefin hybrid ligand **117** and its incorporation in the rhodium complex **119** (Scheme 27).[67] The ligand **117**

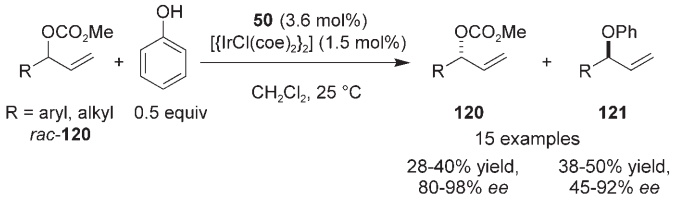


Scheme 27. Synthesis of a monoamine-diolefin ligand and its application in the formation of complexes according to Grützmacher et al.

was obtained by a Birch reduction of (*S*)-phenylalanine (**115**) followed by formation of a methyl ester and coupling with tropylideneamine.

6. Chiral Dienes as Ligands in Asymmetric Catalysis

One of the first applications of a chiral diene in asymmetric catalysis was the Ir/diene-catalyzed kinetic resolution of allylic carbonates **120** with phenol (Scheme 28).[50]

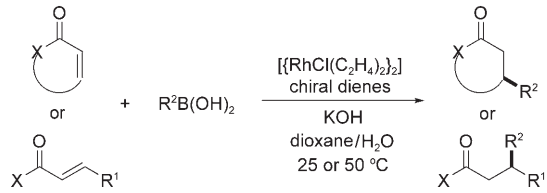


Scheme 28. Ir/diene-catalyzed kinetic resolution of allylic carbonates.

The method allowed the allylic carbonates to be isolated in high enantiomeric purity, and thus served as a proof of concept that chiral dienes are indeed able to induce asymmetry.

6.1. Rhodium/Diene-Catalyzed Asymmetric Conjugate Addition of Arylboronic Acids to α,β-Unsaturated Carbonyl Compounds

The Rh-catalyzed conjugate addition of aryl- and alkenylboronic acids to α,β-unsaturated carbonyl compounds constitutes not only one of the first reactions wherein the proof-of-concept of chiral olefins as ligands for asymmetric transition-metal catalysis was established by Hayashi and co-workers, but also the largest field of application for chiral diene ligands reported so far (Scheme 29).[68] It has turned out

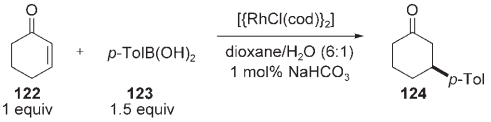


Scheme 29. Rh/diene-catalyzed asymmetric conjugate addition of aryl- and alkenylboronic acids to α,β-unsaturated carbonyl compounds.

that these ligands are ideally suited for this transformation, and in certain cases even outperform traditional phosphane-based ligands.

In 2001 Miyaura and co-workers reported that a {Rh(cod)} complex is a highly active catalyst for the conjugate addition of *p*-tolylboronic acid (**123**) to cyclohex-2-enone (**122**; Table 4).[69] Importantly, Rh^I complexes of cyclooctene, ethylene, and norbornadiene are not effective in catalyzing

Table 4: Investigation of Rh/diene catalysis by Miyaura and co-workers; TON: turnover number.

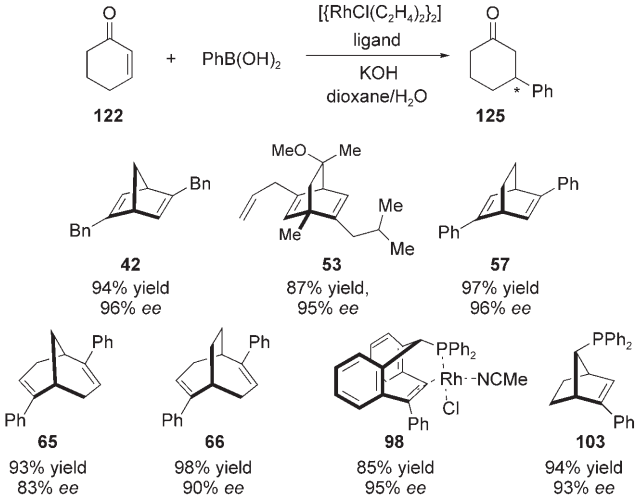


Entry	Mol % catalyst	*T* [°C]	*t* [h]	Yield [%]	TON
1	0.01	90	16	98	9800
2	0.005	90	24	67	13400
3	0.005	90	36	97	18400
4	0.001	100	36	97	97000
5	0.0005	100	36	96	192000
6	0.0002	100	36	75	375000

the reaction. Intrigued by these preliminary results, further investigations were carried out to lower the catalyst loadings and improve the turnover numbers. With as little as 0.0002 mol% Rh catalyst, the 1,4-adduct **124** could be isolated in 75% yield after 36 h reaction time.

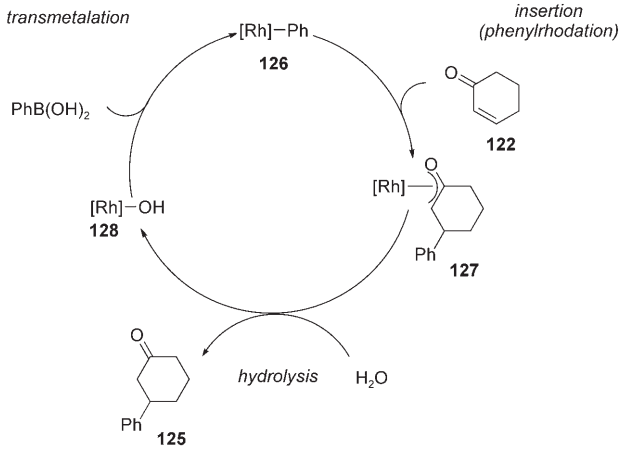
These impressive results highlight the importance of dienes as ligands. Furthermore, they indicate that the generation of a chiral Rh/phosphane catalyst by mixing a {Rh(cod)} catalyst precursor with a chiral phosphane ligand may cause lower enantioselectivity if the ligand exchange is incomplete. An optically active diene would thus be an optimal ligand for this transformation. Since the first application of chiral diene ligand **42** in the addition of phenylboronic acid to cyclohex-2-enone by Hayashi and co-workers,[47] a variety of bicyclic diene scaffolds[51,54,55] as well as phosphane-olefin hybrids[61,62] have been successfully applied (Scheme 30). The most significant feature of the rhodium/diene system is its high catalytic activity. For example, 0.005–0.01 mol% of Rh/**57** can catalyze asymmetric 1,4-additions in high yields without loss of enantioselectivity (TOF up to 14000 h^{-1}).[70]

Intermediates in the catalytic cycle were identified by NMR spectroscopy,[71] and a series of experiments were



Scheme 30. Activity of various olefin ligands in the Rh-catalyzed addition of phenylboronic acid to **122**. In the case of compound **98**, the Rh complex and not the ligand is shown.

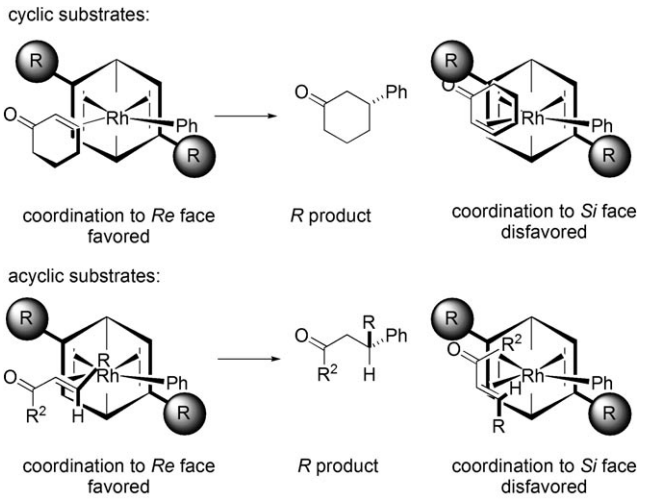
carried out to investigate the kinetics of the reaction (Scheme 31).[72] The kinetic data obtained by the use of a reaction calorimeter were analyzed by the method of reaction progress kinetic analysis developed by Blackmond and co-



Scheme 31. Mechanism of the Rh-catalyzed conjugate addition of arylboronic acids to enones.

workers.[73] The catalyst activity is strongly dependent on the nature of the ligand employed. The reaction proceeded about 20-times faster at 50 °C with $[\{Rh(OH)(cod)\}_2]$ as the catalyst than with $[\{Rh(OH)(binap)\}_2]$, which was attributed to a large rate constant for the rate-determining transmetalation step.

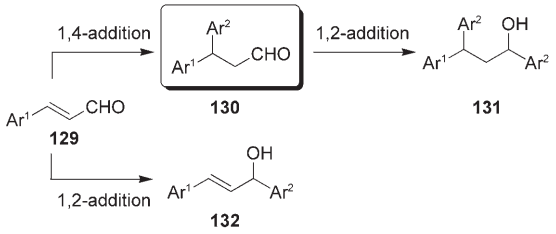
The mode of space differentiation is very different with chiral dienes compared to conventional ligands such as binap. In bisphosphanes, chirality is frequently controlled by the face/edge orientations of the aryl substituents on the phosphorus atoms, while in dienes, chirality is controlled by the size of the substituents attached to the double bonds. Consequently, a model was postulated that predicts the stereochemical outcome of the addition reaction (Scheme 32).[47,53,54,62a]



Scheme 32. Stereochemical model of Hayashi and co-workers to predict the configuration of the product from an addition reaction.

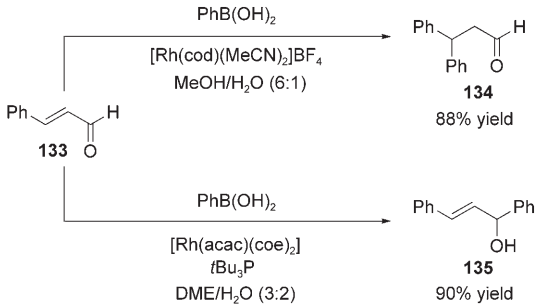
6.1.1. α,β-Unsaturated Aldehydes as Acceptors

In 2005 Carreira and co-workers disclosed a Rh/diene-catalyzed enantioselective conjugate addition of arylboronic acids to enals, a traditionally challenging class of acceptor.[74] Although 1,2-addition of boronic acids to aldehydes has been studied extensively,[75] a general, reliable enantioselective conjugate addition protocol was lacking. This might be attributed to the fact that any effort could be thwarted by a 1,2-addition either in competition with (to give **132** instead of **130**) or after the 1,4-addition (further reaction of **130** to give **131**; Scheme 33). The influence of the ligand on the selectivity



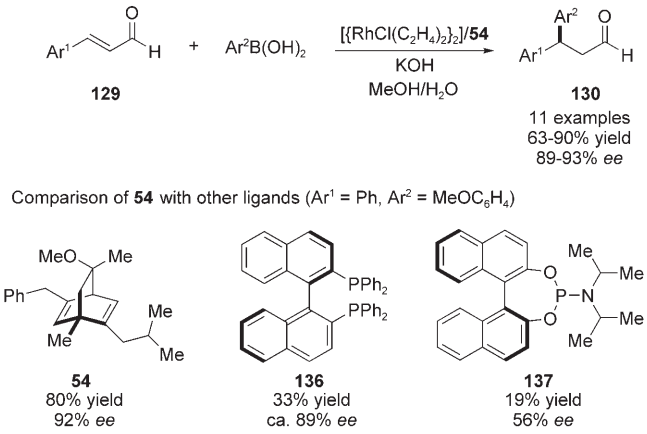
Scheme 33. Competing reaction pathways in the Rh-catalyzed conjugate addition of arylboronic acids to enals.

of the transformation is shown in Scheme 34:[76] whereas phosphane catalysis of the addition of phenylboronic acid to cinnamaldehyde **133** led selectively to the allyl alcohol **135**, the diene-catalyzed process resulted in the formation of the desired 1,4-adduct **134**.



Scheme 34. 1,4- or 1,2-Addition—Effect of the ligand. DME = dimethoxyethane

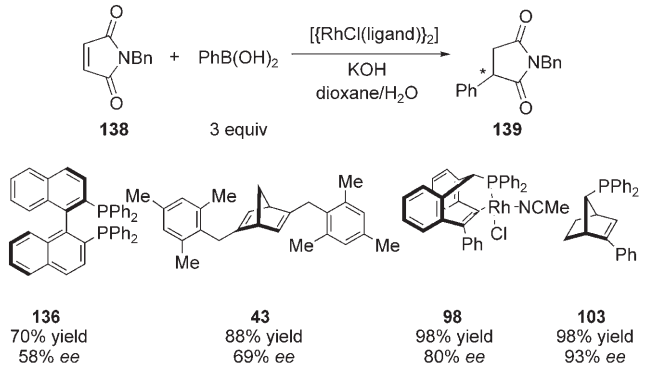
The use of chiral diene **54** in combination with methanol as the reaction solvent were optimal for the formation of a wide range of enantiomerically highly enriched 3,3-diarylpropanals (Scheme 35). This method not only results in the otherwise difficult to set stereogenic centers with two aryl substituents (found in numerous pharmaceuticals and natural products[77]), aldehydes—a convenient handle for further synthetic modification—were also released. The inferior results obtained with conventional ligands such as (*R*)-binap (**136**) or phosphoramidite **137** (see Scheme 35) further illustrate the importance of the use of chiral dienes.



Scheme 35. Rh/diene-catalyzed asymmetric conjugate addition of arylboronic acids to enals.

6.1.2. *Maleimides as Acceptors—Control of the Regioselectivity*

Maleimides also fall into the class of traditionally challenging substrates for conjugate additions. However, the products of the 1,4-additions, namely, α-substituted succinimides, are of synthetic interest because of their biological activity.[78] As is evident from Scheme 36, conventional

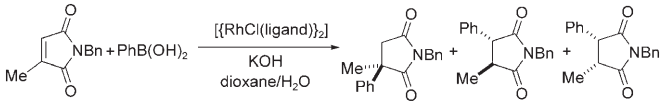


Scheme 36. Activity of different ligands in the Rh-catalyzed addition of phenylboronic acid to maleimide (**138**). In the case of compound **98**, the Rh complex and not the ligand is shown.

phosphane-based ligands such as (*R*)-binap (**136**) only lead to moderate enantioselectivity. First generation chiral dienes such as **43** showed increased reactivity,[79] but enantioselectivity remained low. A breakthrough was achieved with the use of phosphorus-olefin hybrid ligands with which excellent yields and enantioselectivities were obtained (complex **98**,[61] ligand **103**[62]).

There are very few examples of conjugate additions to β,β-disubstituted α,β-unsaturated carbonyl compounds.[80] During examination of the use of substituted maleimides, Hayashi and co-workers discovered that the regioselectivity of the addition is a function of the employed ligand (Table 5).[81] Whereas Rh/binap-catalyzed processes preferably give rise to 1,4-adducts with a quaternary stereogenic center, Rh/diene catalysts lead to *cis/trans* mixtures of **142**.

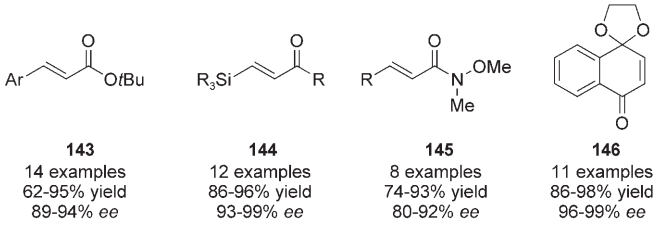
Table 5: Ligand-dependent regioselectivity in the asymmetric 1,4-addition of arylboronic acids to maleimides, with imide **140** used as an example.



Ligand	Yield [%]	**141**/**142** (*trans*/*cis*)	*ee* of **141** [%]	*ee* of *trans*-**142**, *cis*-**142** [%]
136	99	75:25 (2.1:1)	95	0, 96
57	94	11:89 (1:1.4)	93	79, 99
103	99	17:83 (1:1.2)	77	95, >99

6.1.3. *Other Synthetically Useful Compounds as Acceptors*

The scope of synthetically interesting acceptors that can be used in the Rh/diene-catalyzed conjugate addition has been considerably expanded in the meantime (Scheme 37).

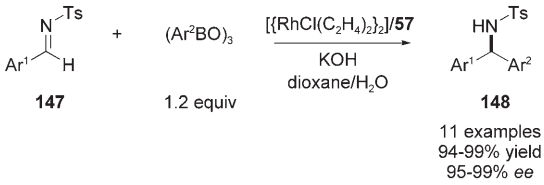


Scheme 37. Synthetically useful acceptors in Rh/diene-catalyzed 1,4-additions.

These comprise not only α,β-unsaturated esters **143** which are particularly well suited for heterocyclic-substituted substrates,[82] but α,β-unsaturated Weinreb amides **145** have also found wide application.[83] Both classes of acceptors allow the straightforward modification of the resulting adducts. The use of β-silyl-substituted α,β-unsaturated carbonyl compounds **144** as acceptors is of special interest since these compounds can be transformed to β-hydroxyketones by Tamao–Fleming oxidation.[84] Recently, Tokunaga and Hayashi reported on a Rh/diene-catalyzed 1,4-addition of organoboron reagents to quinone monoketals **146**, which gave rapid access to α-arylated tetralones in high yield and stereoselectivity.[85]

6.1.4. *Imines as Acceptors*

Chiral diarylmethylamines and -alcohols are important structural motifs that are encountered in many pharmaceuticals and natural products.[86] A direct 1,2-addition of arylboronic acids to imines or aldehydes, respectively, represents one of the most straightforward ways to access these molecules in high yield and stereoselectivity. Although there are examples of asymmetric catalysis induced by chiral phosphane ligands, often only a narrow range of substrates is tolerated.[87] Hayashi and co-workers used ligand **57** for a highly enantioselective 1,2-addition of a wide range of arylboroxines to *N*-tosylarylimines (Scheme 38).[53] However, a drawback of the

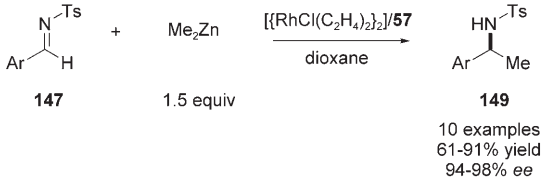


Scheme 38. Rh/diene-catalyzed asymmetric 1,2-addition of arylboroxines to *N*-tosylarylimines. Ts: tosyl(*p*-toluenesulfonyl).

initially reported protocol was the difficult removal of the tosyl protecting group. An optimization of the process was disclosed in 2005: The tosyl group could be replaced by a readily cleavable nitrobenzenesulfonyl (nosyl) group, and the use of chiral diene **65** led to the yields and enantioselectivities remaining superb.[55]

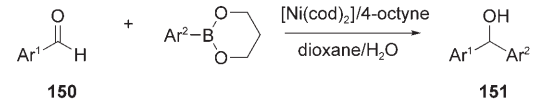
Lin and co-workers used chiral diene **70** for the direct 1,2-addition of arylboronic acids to imines, obviating the need for arylboroxines which need to be synthesized prior to use.[56] The bicyclo[3.3.0]diene **70** seems to be ideally suited for this transformation as the addition proceeds in excellent yield and with a very narrow range of high enantioselectivity (20 examples, 98–99% *ee*).

The enantioselective addition of dimethylzinc to *N*-tosylarylimines was also made possible by using chiral diene **57** (Scheme 39).[88] The tosyl group was reported to be readily removed by treatment of the adducts with lithium in liquid ammonia.



Scheme 39. Rh/diene-catalyzed asymmetric 1,2-addition of dimethylzinc to *N*-tosylarylimines.

The asymmetric 1,2-addition of arylboronic acids to aldehydes remains challenging. Although several protocols are available to perform the racemic reaction, an analogous general asymmetric version is still lacking. However, an interesting observation by Shirakawa and co-workers is worth mentioning.[89] During examination of the nickel-catalyzed addition of arylboronates to aldehydes, they discovered that alkynes act as activators in the process (Scheme 40). The exact mechanistic role of these additives is still a matter of investigation. However, the use of an optically active alkyne as ligand induces low levels of asymmetry in the addition of phenylboronic acid to α,β-unsaturated carbonyl compounds

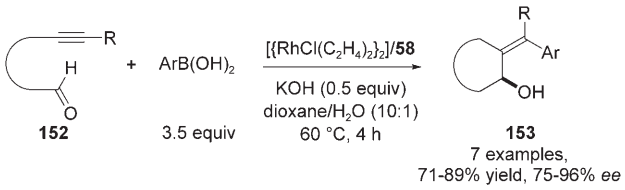


Scheme 40. Ni/alkyne-catalyzed 1,2-addition of arylboronates to aldehydes.

(7% *ee*).[90] Although this result is far from being optimal, it reveals the potential of using alkynes as chiral ligands in asymmetric catalysis.

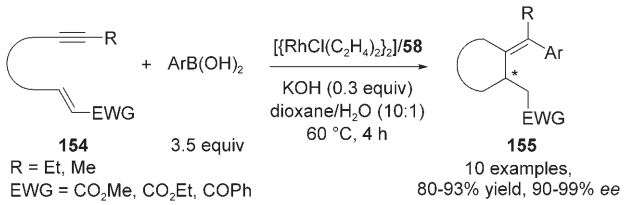
6.2. Rhodium/Diene-Catalyzed Formation of Carbocycles through Sequential Carborhodation

Organorhodium species generated through transmetalation between a rhodium catalyst and an organoboron reagent can act as effective nucleophiles in a number of transformations. Cascade reactions can be envisaged when several electrophilic sites are present at appropriate positions in the same molecule.[91] For example, alkynals **152** have been employed as substrates. The organorhodium moiety first undergoes *syn* addition across the triple bond and subsequently cyclizes by intramolecular attack on the aldehyde (Scheme 41).[92] The resulting cycloalkanols **153** were obtained in high yield and enantioselectivity.



Scheme 41. Rh/diene-catalyzed arylative cyclization of alkynals.

Remarkable chemoselectivity is also observed when alkyne-tethered electron-deficient olefins **154** are employed (Scheme 42). Rhodium/diene catalysis leads to a preferred

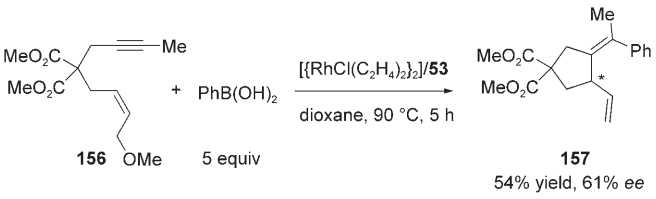


Scheme 42. Rh/diene-catalyzed arylative cyclization of alkynes with electron-deficient double bonds.

carborhodation of the alkyne followed by 1,4-addition of the α,β-unsaturated moiety to provide adducts **155** in high yield and excellent enantioselectivity.[93] The difference between phosphanes and chiral dienes as ligands in this reaction setting is striking: Whereas Rh-bisphosphanes catalyze the 1,4-addition to α,β-enoates more effectively than the arylation of alkynes, Rh/diene catalysts favor the arylation of alkynes over the 1,4-addition. In these reactions the active catalyst, a Rh-OR species, is regenerated in the termination step by proto-demetalation under the aqueous reaction conditions. Murakami and co-workers proposed β-oxygen elimination as an alternative termination step.[94] Rhodium/diene catalysts efficiently cyclize enynes **156** to give adducts **157** after

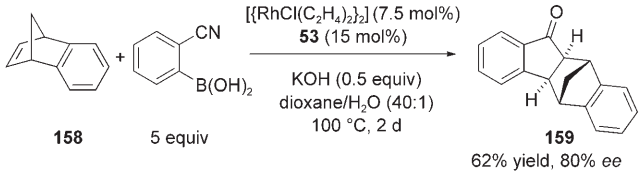
carborhodation of the alkyne and subsequent β-oxygen elimination from the allylic ether moiety (Scheme 43).

Electrophilic sites in appropriate positions of the arylboronic acid moiety also react. For example, (2-cyanophenyl)-



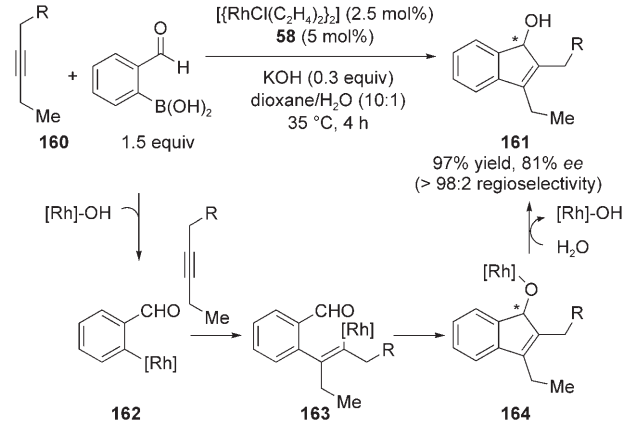
Scheme 43. Rh/diene-catalyzed arylative cyclization followed by β-oxygen elimination.

boronic acid undergoes facile transmetalation with rhodium/diene catalysts. The resulting organorhodium species attacks the strained alkene **158**, and then a CN group is added. In situ hydrolysis releases the annulated adduct **159** in 62 % yield and 80 % *ee* (Scheme 44).[95] Along the same lines, the reaction



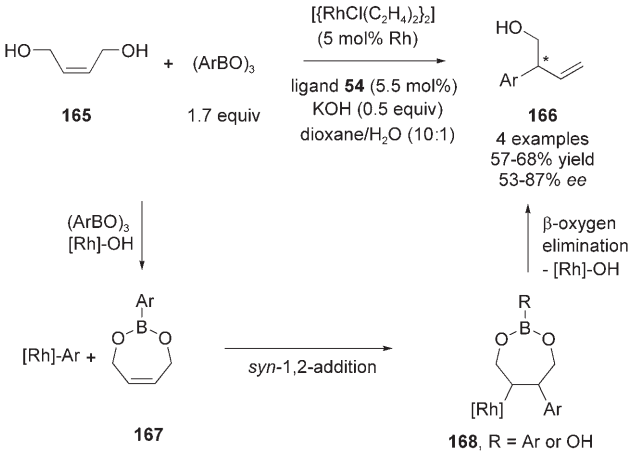
Scheme 44. Rh/diene-catalyzed annulation of (2-cyanophenyl)boronic acid with a strained alkene.

between (2-formylphenyl)boronic acid and alkyne **160** delivered a straightforward access to optically active 2-indenol **161** (Scheme 45).[96] Transmetalation is followed by carborhodation of the triple bond and a ring closure through 1,2-addition to the aldehyde. Both the chemo- and enantioselectivity are remarkable when rhodium/diene catalysts are used.



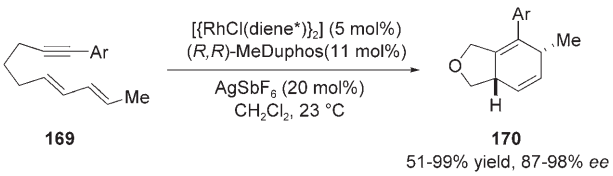
Scheme 45. Rh/diene-catalyzed synthesis of an indenol. R: $C(Me)(CO_2Me)_2$.

An innovative approach towards the synthesis of enantiomerically enriched 2-arylbut-3-enols **166** makes use of *cis*-allyldiol **165** and arylboroxines (Scheme 46).[97] Under the reaction conditions, the readily formed cyclic arylboronic esters **167** serve as acceptors for a *syn*-1,2-carborhodation to give **168**. A subsequent β-oxygen elimination regenerates the rhodium catalyst and releases the optically active alcohols **166**.



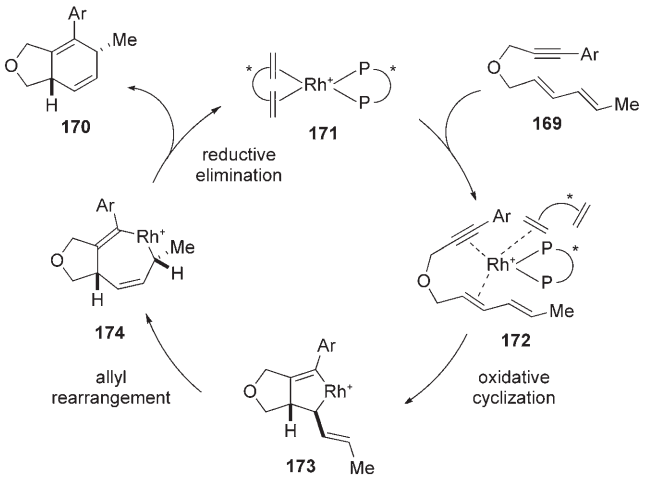
Scheme 46. Rh/diene-catalyzed substitutive arylation of a *cis*-allylic diol with arylboroxines.

Chiral dienes often display opposing catalytic performance to conventional phosphanes in reactions. Mikami and co-workers recently disclosed an impressive example wherein dienes and phosphanes exert a considerable synergistic effect (Scheme 47).[98] Neither ligand alone was able to reach optimal yields and enantioselectivities in the cationic Rh^I-catalyzed intramolecular [4+2] cycloaddition of dienynes **169**.



Scheme 47. Rh/diene-catalyzed intramolecular [4+2] cycloaddition.

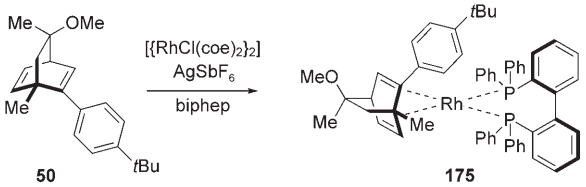
However, the combination of chiral diene **49** or **50** (diene*) and Me-duphos enabled the formation of cycloadducts **170** in high yields and selectivities. A plausible rationale is depicted in Scheme 48. After formation of substrate-coordinated intermediate **172**, an oxidative cyclization affords the metallacyclopentene **173**. Subsequently, an allyl rearrangement takes place, followed by a reductive elimination to form the desired cyclization product **170**. Another possible intermediate, where both the chiral diene and bisphosphane coordinate to the rhodium center in a bidentate fashion was excluded. Chiral dienes must coordinate to the rhodium center in a monodentate fashion in the enantiodetermining step.



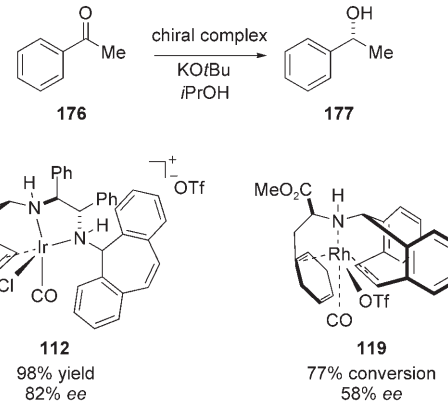
Scheme 48. Plausible reaction mechanism for the reaction shown in Scheme 47.

7. Other Applications of Chiral Dienes

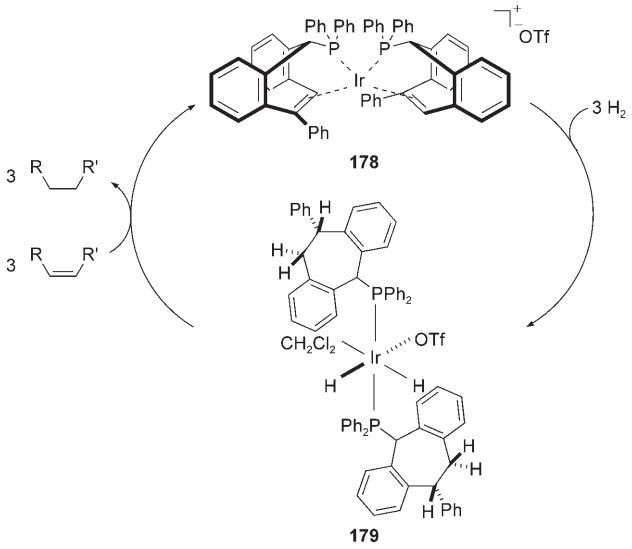
Faller and Wilt described the use of chiral diene **50** for the resolution of the bisphosphane biphep which racemizes at room temperature.[99] After abstraction of the chloride ion from the rhodium–diene species, complexation with biphep occurred (Scheme 49). The resolved enantomerically pure ligand was then employed in the hydroboration of styrene.



Scheme 49. Resolution of configurationally unstable biphep by using the chiral diene **50**.



Scheme 50. Transfer hydrogenation with amine-olefin ligands.

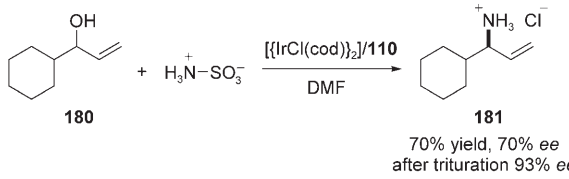


Scheme 51. Ir/phosphane-olefin catalyzed hydrogenation of external olefins.

The chiral amine-olefin complexes **112** and **119** developed by Grützmacher and co-workers were employed in the transfer hydrogenation of acetophenone (**176**) and acetophenone derivatives (Scheme 50).[66,67] Although the reported *ee* values are not yet optimal, it is important to point out that the transfer hydrogenations proceed with high TONs even with sterically hindered substrates at ambient temperature.

A remarkable reservoir function of olefin ligands has been demonstrated by Grützmacher and co-workers in an iridium-catalyzed hydrogenation with the phosphane-olefin ligand derived from **98** (see Scheme 22).[61] At room temperature under an atmosphere of 1 bar H_2, the iridium complex **178** takes up three equivalents of dihydrogen to yield the remarkable Ir^{III}–dihydride complex **179** (Scheme 51) in which the previously coordinated olefins are hydrogenated. The addition of three equivalents of an external olefin fully regenerates the starting complex **178**. Under catalytic conditions, turnover frequencies up to 4000 h^{-1} and moderate enantioselectivities were reached (30–67 % *ee*).

Carreira and co-workers reported on the use of ligand **110** in the iridium-catalyzed allylic substitution for the direct transformation of allylic alcohols into allylic amines (Scheme 52).[64] Sulfamic acid served as the nitrogen source in this process to give allylamine **181** in 70 % yield and 70 % *ee*. When the saturated analogue of ligand **110** was employed, the reaction only proceeded with 20 % conversion, again highlighting the importance of the involved phosphor-olefin complex.



Scheme 52. Ir/phosphoramidite-catalyzed synthesis of an allylamine from an allyl alcohol.

8. Conclusions

Since the first implementation of chiral dienes as steering ligands for metal-catalyzed reactions, an impressive research effort has been directed towards developing efficient syntheses of various bicyclic diene scaffolds. In the meantime, applications go far beyond proof of concept and include various synthetically useful processes that give rise to high value added building blocks. However, it is striking that most of the methods are centered around rhodium- and iridium-catalyzed reactions. Future work will thus primarily aim at employing different metals, which will considerably expand the scope of olefins as ligands. To ensure wide acceptance of these ligand systems, an easy and straightforward synthetic access to chiral dienes is of prime importance. Consequently, further optimizations of the various synthetic routes are necessary. A ligand design wherein olefins are combined with heteroatoms such as phosphorus or nitrogen for coordination to the metal has shown promising first results. Further investigations in this direction will allow the best design elements of every ligand class to be united to create highly active and selective hybrid ligands.

Financial support from ETH Zürich and the Swiss National Science Foundation is gratefully acknowledged.

Received: August 8, 2007
Published online: May 5, 2008

[1] a) M. A. Bennett, *Chem. Rev.* **1962**, *62*, 611 – 652; b) E. O. Fischer, H. Werner, *Angew. Chem.* **1963**, *75*, 57 – 70; *Angew. Chem. Int. Ed. Engl.* **1963**, *2*, 80 – 93; c) R. Jones, *Chem. Rev.* **1968**, *68*, 785 – 806; d) F. R. Hartley, *Angew. Chem.* **1972**, *84*, 657 – 667; *Angew. Chem. Int. Ed. Engl.* **1972**, *11*, 596 – 606; e) S. D. Ittel, J. A. Ibers, *Adv. Organomet. Chem.* **1976**, *14*, 33 – 61; f) I. Omae, *Angew. Chem.* **1982**, *94*, 902 – 915; *Angew. Chem. Int. Ed. Engl.* **1982**, *21*, 889 – 902; g) D. M. P. Mingos in *Comprehensive Organometallic Chemistry I* (Eds.: E. W. Abel, F. G. A. Stone, G. Wilkinson), Pergamon, Oxford, **1982**, chap. 19; h) C. Elschenbroich, *Organometallics*, Wiley-VCH, Weinheim, **2005**, 3rd ed., chap. 15; i) R. H. Crabtree, *The Organometallic Chemistry of the Transition Metals*, Wiley, Hoboken, NJ, **2005**, 4th ed., chap. 6.

[2] a) W. C. Zeise, *Poggendorffs Ann. Phys.* **1827**, *9*, 632 – 633; b) for a neutron diffraction study of this complex, see R. A. Love, T. F. Koetzle, G. J. B. Williams, L. C. Andrews, R. Bau, *Inorg. Chem.* **1975**, *14*, 2653 – 2657.

[3] For certain reactions, olefins are known to fulfil more complex functions than just being spectator ligands: for example, olefins are known to facilitate reductive elimination in cross-coupling reactions, see a) T. Yamamoto, A. Yamamoto, S. Ikeda, *J. Am. Chem. Soc.* **1971**, *93*, 3350 – 3359; b) R. Sustmann, J. Lau, M. Zipp, *Tetrahedron Lett.* **1986**, *27*, 5207 – 5210; c) A. E. Jensen, P. Knochel, *J. Org. Chem.* **2002**, *67*, 79 – 85; for the acceleration of oxidative addition, see J. B. Johnson, E. A. Bercot, J. M. Rowley, G. W. Coates, T. Rovis, *J. Am. Chem. Soc.* **2007**, *129*, 2718 – 2725; moreover, olefins are often used as additives to prevent agglomeration, see d) T. Nishimura, K. Ohe, S. Uemura, *J. Am. Chem. Soc.* **1999**, *121*, 2645 – 2646; e) R. Kuwano, Y. Kondo, *Org. Lett.* **2004**, *6*, 3545 – 3547; f) I. Nakamura, Y. Mizushima, Y. Yamamoto, *J. Am. Chem. Soc.* **2005**, *127*, 15022 – 15023; g) C. S. Scarborough, S. S. Stahl, *Org. Lett.* **2006**, *8*, 3251 – 3254; olefins can also act as hemilabile ligands and thus stabilize complexes or catalytic intermediates: recent examples include: h) M. E. Krafft, M. Sugiura, K. A. Abboud, *J. Am. Chem. Soc.* **2001**, *123*, 9174 – 9175; i) N. Nomura, K. Tsurugi, T. V. RajanBabu, T. Kondo, *J. Am. Chem. Soc.* **2004**, *126*, 5354 – 5355; j) K. M. Miller, T. Luanphaisarnnont, C. Molinaro, T. F. Jamison, *J. Am. Chem. Soc.* **2004**, *126*, 4130 – 4131; k) K. M. Miller, T. F. Jamison, *J. Am. Chem. Soc.* **2004**, *126*, 15342 – 15343; l) R. M. Moslin, K. M. Miller, T. F. Jamison, *Org. Lett.* **2006**, *8*, 455 – 458; m) R. M. Moslin, K. M. Miller, T. F. Jamison, *Tetrahedron* **2006**, *62*, 7598 – 7610; n) J. B. Johnson, T. Rovis, *Angew. Chem.* **2008**, *120*, 852 – 884; *Angew. Chem. Int. Ed.* **2008**, *47*, 840 – 871.

[4] For an excellent review on diolefin donor ligands, see I. Omae, *Coord. Chem. Rev.* **1983**, *51*, 1 – 39.

[5] Various Pd/dba ratios are often quoted for these types of complexes. It should be noted that in solution these complexes are dimeric; the precise stoichiometry depends on whether the compound has been recrystallized to give $[Pd_2(dba)_3]$·solvent, and either used as is or vacuum dried to give $[Pd_2(dba)_3]$. Otherwise, the complex is $[Pd_2(dba)_3]$·dba. The latter complex is commonly referred to as $[Pd(dba)_2]$, which is structurally incorrect based on ^1H and ^2H NMR studies in solution, see a) R. Ukai, H. Kawazura, Y. Ishii, J. J. Bonnet, J. A. Ibers, *J. Organomet. Chem.* **1974**, *65*, 253 – 266; b) H. Kawazura, H. Tanaka, K. Yamada, T. Takahashi, Y. Ishii, *Bull. Chem. Soc. Jpn.* **1978**, *51*, 3466 – 3468; c) K. Selvakumar, M. Valentini, M. Wörle, P. S. Pregosin, A. Albinati, *Organometallics* **1999**, *18*, 1207 – 1215.

[6] For the role of dba in the reactivity of Pd^0 complexes generated in situ from mixtures of $[Pd(dba)_2]$ and phosphanes, see a) C. Amatore, A. Jutand, *Coord. Chem. Rev.* **1998**, *178–180*, 511 – 528; b) I. J. S. Fairlamb, A. R. Kapdi, A. F. Lee, G. P. McGlacken, F. Weissburger, A. H. M. de Vries, L. Schmieder-van de Vondervoort, *Chem. Eur. J.* **2006**, *12*, 8750 – 8761.

[7] a) B. D. Karstedt, U.S. Patent 3775452, **1973**; b) P. B. Hitchcock, M. F. Lappert, N. J. W. Warhurst, *Angew. Chem.* **1991**, *103*, 439 – 441; *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 438 – 440; c) see also: J. Krause, G. Cestaric, K.-J. Haack, K. Seevogel, W. Storm, K.-R. Pörschke, *J. Am. Chem. Soc.* **1999**, *121*, 9807 – 9823.

[8] a) A. C. Cope, C. F. Howell, A. Knowles, *J. Am. Chem. Soc.* **1962**, *84*, 3190 – 3191; b) A. C. Cope, C. R. Ganellin, H. W. Johnson, Jr., *J. Am. Chem. Soc.* **1962**, *84*, 3191 – 3192; c) A. C. Cope, C. R. Ganellin, H. W. Johnson, Jr., T. V. van Auken, H. J. S. Winkler, *J. Am. Chem. Soc.* **1963**, *85*, 3276 – 3279.

[9] M. Nakazaki, K. Yamamoto, K. Naemura, *Top. Curr. Chem.* **1984**, *125*, 1 – 23.

[10] A. C. Cope, R. A. Pike, R. F. Spencer, *J. Am. Chem. Soc.* **1953**, *75*, 3212 – 3215.

[11] Selected direct syntheses of enantiopure (*E*)-cyclooctenes: a) E. J. Corey, J. I. Shulman, *Tetrahedron Lett.* **1968**, *9*, 3655 – 3658; b) D. Bourgeois, A. Pancrazi, L. Ricard, J. Prunet, *Angew. Chem.* **2000**, *112*, 741 – 744; *Angew. Chem. Int. Ed.* **2000**, *39*, 725 – 728; c) D. C. Braddock, G. Cansell, S. A. Hermitage, A. J. P. White, *Tetrahedron: Asymmetry* **2004**, *15*, 3123 – 3129.

[12] a) F. A. L. Anet, *J. Am. Chem. Soc.* **1962**, *84*, 671 – 672; b) F. A. L. Anet, A. J. R. Bourn, Y. S. Lin, *J. Am. Chem. Soc.* **1964**, *86*, 3576 – 3577.

[13] K. Mislow, H. D. Perlmutter, *J. Am. Chem. Soc.* **1962**, *84*, 3591 – 3592.

[14] a) L. E. Salisbury, *J. Org. Chem.* **1978**, *43*, 4987 – 4991; b) L. E. Salisbury, *J. Org. Chem.* **1978**, *43*, 4991 – 4995.

[15] a) A. C. Cope, J. E. Meili, *J. Am. Chem. Soc.* **1967**, *89*, 1883 – 1886; b) G. H. Senkler, D. Gust, P. X. Riccobono, K. Mislow, *J. Am. Chem. Soc.* **1972**, *94*, 8626 – 8627.

[16] a) A. R. Douglas, R. H. Crabtree, *Organometallics* **1983**, *2*, 621 – 627; b) A. R. Douglas, R. H. Crabtree, *Organometallics* **1983**, *2*, 855 – 859.

[17] a) For [$PdCl_2$(cod)], see M. F. Rettig, R. M. Wing, G. R. Wiger, *J. Am. Chem. Soc.* **1981**, *103*, 2980 – 2986; b) for [$PdCl_2$(dcp)], see K. A. Hofmann, J. von Narbutt, *Ber. Dtsch. Chem. Ges.* **1908**, *41*, 1625 – 1628.

[18] a) G. Paiaro, A. Panunzi, A. De Renzi, *Tetrahedron Lett.* **1966**, *7*, 3905 – 3908; b) A. Panunzi, A. De Renzi, G. Paiaro, *Inorg. Chim. Acta* **1967**, *1*, 475 – 478; c) G. Paiaro, *Organomet. Chem. Rev. Sect. A* **1970**, *6*, 319 – 335.

[19] J. A. Reingold, S. U. Son, S. B. Kim, C. A. Dullaghan, M. Oh, P. C. Frake, G. B. Carpenter, D. A. Sweigart, *Dalton Trans.* **2006**, 2385 – 2398. For application of these complexes as catalysts in Rh-catalyzed additions of arylboronic acids to aldehydes and α,β-unsaturated carbonyl compounds, see a) S. U. Son, S. B. Kim, J. A. Reingold, G. B. Carpenter, D. A. Sweigart, *J. Am. Chem. Soc.* **2005**, *127*, 12238 – 12239; b) W. C. Trenkle, J. L. Barkin, S. U. Son, D. A. Sweigart, *Organometallics* **2006**, *25*, 3548 – 3551.

[20] H.-J. Drexler, W. Baumann, A. Spannenberg, C. Fischer, D. Haller, *J. Organomet. Chem.* **2001**, *621*, 89 – 102, and references therein.

[21] B. F. G. Johnson, J. Lewis, D. J. Yarrow, *J. Chem. Soc. Dalton Trans.* **1974**, 1054 – 1058.

[22] a) W. Winter, B. Koppenhöfer, V. Schurig, *J. Organomet. Chem.* **1978**, *150*, 145 – 155; b) for the corresponding complex with Ir^I, see L. A. Oro, *J. Less-Common Met.* **1977**, *53*, 289 – 290.

[23] A. Salzer, H. Schmalle, R. Stauber, S. Streiff, *J. Organomet. Chem.* **1991**, *408*, 403 – 424.

[24] A. Takahashi, M. Aso, M. Tanaka, H. Suemune, *Tetrahedron* **2000**, *56*, 1999 – 2006.

[25] a) A. De Renzi, A. Panunzi, L. Paolillo, A. Vitagliano, *J. Organomet. Chem.* **1977**, *124*, 221 – 228; b) V. G. Albano, M. Monari, A. Panunzi, G. Roviello, F. Ruffo, *J. Organomet. Chem.* **2003**, *679*, 93 – 100.

[26] A. Watanabe, M. Aso, H. Suemune, *Org. Biomol. Chem.* **2003**, *1*, 1726 – 1729.

[27] A. Watanabe, T. Kamahori, M. Aso, H. Suemune, *J. Chem. Soc. Perkin Trans. 1* **2002**, 2539 – 2543.

[28] M. Bernard, V. Guiral, F. Delbecq, F. Fache, P. Sautet, M. Lemaire, *J. Am. Chem. Soc.* **1998**, *120*, 1441 – 1446.

[29] A. D. Walsh, *Nature* **1947**, *159*, 712 – 713.

[30] a) M. J. S. Dewar, *Bull. Chem. Soc. Fr.* **1951**, *18*, C71 – C79; b) M. J. S. Dewar, H. C. Longuet-Higgins, *Proc. Royal Acad. Sci. Ser. A* **1952**, *214*, 482 – 493.

[31] a) J. Chatt, *Chem. Rev.* **1951**, *48*, 7 – 43; b) J. Chatt, L. A. Duncanson, *J. Chem. Soc.* **1953**, 2939 – 2947; c) for a critical review on the history of the Dewar–Chatt–Duncanson model and a discussion concerning the scientific contributions of the specific scientists to it, see D. M. P. Mingos, *J. Organomet. Chem.* **2001**, *635*, 1 – 8.

[32] I. Krossing, A. Reisinger, *Angew. Chem.* **2003**, *115*, 5903 – 5906; *Angew. Chem. Int. Ed.* **2003**, *42*, 5725 – 5728.

[33] B. E. Mann, B. E. Taylor, *^{13}C NMR Data for Organometallic Compounds*, Academic Press, London, **1981**, p. 16.

[34] J. Forniés, A. Martín, L. F. Martín, B. Menjón, *Organometallics* **2005**, *24*, 3539 – 3546.

[35] T. Ziegler, A. Rauk, *Inorg. Chem.* **1979**, *18*, 1558 – 1565.

[36] a) S. Dapprich, G. Frenking, *J. Phys. Chem.* **1995**, *99*, 9352 – 9362; for applications of CDA to transition-metal–alkene bonding, see b) G. Frenking, I. Antes, M. Böhme, S. Dapprich, A. W. Ehlers, V. Jonas, A. Neuhaus, M. Otto, R. Stegmann, A. Veldkamp, S. F. Vyboishchikov in *Reviews in Computational Chemistry*, *Vol. 8* (Eds.: K. B. Lipkowitz, D. B. Boyd), VCH, New York, **1996**, pp. 63 – 144; c) G. Frenking, U. Pidun, *J. Chem. Soc. Dalton Trans.* **1997**, 1653 – 1662; d) J. Uddin, S. Dapprich, G. Frenking, B. F. Yates, *Organometallics* **1999**, *18*, 457 – 465; e) G. Frenking, *J. Organomet. Chem.* **2001**, *635*, 9 – 23; f) C. Massera, G. Frenking, *Organometallics* **2003**, *22*, 2758 – 2765.

[37] G. Frison, H. Grützmacher, G. Frenking, unpublished results. The linear AuH fragment was chosen because the resulting HAu-L complexes contain at least a mirror plane which allows the σ and π contributions of the orbital terms to be separated.

[38] D. Bourissou, O. Guerret, F. P. Gabbaï, G. Bertrand, *Chem. Rev.* **2000**, *100*, 39 – 92.

[39] G. Frison, H. Grützmacher, *J. Organomet. Chem.* **2002**, *643*, 285 – 291.

[40] For a review on the chemistry of tetrafluorobenzobarrelenes and their complexes with Rh and Ir, see M. E. Esteruelas, L. A. Oro, *Coord. Chem. Rev.* **1999**, *193–195*, 557 – 618.

[41] For a review on thermodynamic data of metal—olefin complexes, see F. R. Hartley, *Chem. Rev.* **1973**, *73*, 163 – 189.

[42] H. C. Volger, M. M. P. Gaasbeek, H. Hogeveen, K. Vrieze, *Inorg. Chim. Acta* **1969**, *3*, 145 – 150; for a related study involving the relative stabilities of rhodium–monoolefin complexes, see R. Cramer, *J. Am. Chem. Soc.* **1967**, *89*, 4621 – 4626.

[43] a) K. Morokuma, W. T. Borden, *J. Am. Chem. Soc.* **1991**, *113*, 1912 – 1914; b) A. Nicolaides, J. M. Smith, A. Kumar, D. M. Barnhart, W. T. Borden, *Organometallics* **1995**, *14*, 3475 – 3485; c) B. F. Yates, *J. Organomet. Chem.* **2001**, *635*, 142 – 152; d) F. A. Theophanous, A. J. Tasiopoulos, A. Nicolaides, X. Zhou, W. T. G. Johnson, W. T. Borden, *Org. Lett.* **2006**, *8*, 3001 – 3004.

[44] J. A. Ibers, R. G. Snyder, *J. Am. Chem. Soc.* **1962**, *84*, 495 – 496.

[45] For reviews on this topic, see a) T. P. Fehlner, *J. Organomet. Chem.* **2001**, *635*, 92 – 99; b) L. Weber, *Angew. Chem.* **2002**, *114*, 583 – 592; *Angew. Chem. Int. Ed.* **2002**, *41*, 563 – 572; c) L. Weber, *Coord. Chem. Rev.* **2005**, *249*, 741 – 763.

[46] For a highlight on the early work of chiral dienes as novel ligands in asymmetric catalysis, see F. Glorius, *Angew. Chem.* **2004**, *116*, 3444 – 3446; *Angew. Chem. Int. Ed.* **2004**, *43*, 3364 – 3366.

[47] T. Hayashi, K. Ueyama, N. Tokunaga, K. Yoshida, *J. Am. Chem. Soc.* **2003**, *125*, 11508 – 11509.

[48] Y. Uozumi, S.-Y. Lee, T. Hayashi, *Tetrahedron Lett.* **1992**, *33*, 7185 – 7188.

[49] G. Berthon-Gelloz, T. Hayashi, *J. Org. Chem.* **2006**, *71*, 8957 – 8960.

[50] C. Fischer, C. Defieber, T. Suzuki, E. M. Carreira, *J. Am. Chem. Soc.* **2004**, *126*, 1628 – 1629.

[51] C. Defieber, J.-F. Paquin, S. Serna, E. M. Carreira, *Org. Lett.* **2004**, *6*, 3873 – 3876.

[52] Ligand **54** is commercially available in both enantiomeric forms from Sigma–Aldrich.

[53] N. Tokunaga, Y. Otomaru, K. Ueyama, R. Shintani, T. Hayashi, *J. Am. Chem. Soc.* **2004**, *126*, 13584 – 13585.

[54] Y. Otomaru, K. Okamoto, R. Shintani, T. Hayashi, *J. Org. Chem.* **2005**, *70*, 2503 – 2508.

[55] a) Y. Otomaru, N. Tokunaga, R. Shintani, T. Hayashi, *Org. Lett.* **2005**, *7*, 307 – 310; b) Y. Otomaru, A. Kina, R. Shintani, T. Hayashi, *Tetrahedron: Asymmetry* **2005**, *16*, 1673 – 1679.

[56] Z.-Q. Wang, C.-G. Feng, M.-H. Xu, G.-Q. Lin, *J. Am. Chem. Soc.* **2007**, *129*, 5336 – 5337.

[57] F. Läng, F. Breher, D. Stein, H. Grützmacher, *Organometallics* **2005**, *24*, 2997 – 3007.

[58] A. Kina, K. Ueyama, T. Hayashi, *Org. Lett.* **2005**, *7*, 5889 – 5892.

[59] M. A. Grundl, J. J. Kennedy-Smith, D. Trauner, *Organometallics* **2005**, *24*, 2831 – 2833.

[60] P. Maire, S. Deblon, F. Breher, J. Geier, C. Böhler, H. Rüegger, H. Schönberg, H. Grützmacher, *Chem. Eur. J.* **2004**, *10*, 4198 – 4205.

[61] E. Piras, F. Läng, H. Rüegger, D. Stein, M. Wörle, H. Grützmacher, *Chem. Eur. J.* **2006**, *12*, 5849 – 5858.

[62] a) R. Shintani, W.-L. Duan, T. Nagano, A. Okada, T. Hayashi, *Angew. Chem.* **2005**, *117*, 4687 – 4690; *Angew. Chem. Int. Ed.* **2005**, *44*, 4611 – 4614; b) R. Shintani, W.-L. Duan, K. Okamoto, T. Hayashi, *Tetrahedron: Asymmetry* **2005**, *16*, 3400 – 3405;

c) W.-L. Duan, H. Iwamura, R. Shintani, T. Hayashi, *J. Am. Chem. Soc.* **2007**, *129*, 2130 – 2138.
[63] P. Kasák, V. B. Arion, M. Widhalm, *Tetrahedron: Asymmetry* **2006**, *17*, 3084 – 3090.
[64] C. Defieber, M. A. Ariger, P. Moriel, E. M. Carreira, *Angew. Chem.* **2007**, *119*, 3200 – 3204; *Angew. Chem. Int. Ed.* **2007**, *46*, 3139 – 3143.
[65] G. Mora, S. van Zutphen, C. Thoumazet, X. Le Goff, L. Ricard, H. Grützmacher, P. Le Floch, *Organometallics* **2006**, *25*, 5528 – 5532.
[66] P. Maire, F. Breher, H. Schönberg, H. Grützmacher, *Organometallics* **2005**, *24*, 3207 – 3218.
[67] H. Grützmacher, T. Büttner, P. Maire, M. Ramseier, D. Scheschkewitz, T. Zweifel, DE 102004027771, **2006**; EP 05011539.3.
[68] For the first reported Rh/phosphane-catalyzed 1,4-addition, see a) M. Sakai, H. Hayashi, N. Miyaura, *Organometallics* **1997**, *16*, 4229 – 4231; for the first reported asymmetric Rh/phosphane-catalyzed 1,4-addition, see b) Y. Takaya, M. Ogasawara, T. Hayashi, M. Sakai, N. Miyaura, *J. Am. Chem. Soc.* **1998**, *120*, 5579 – 5580; for general reviews, see c) K. Fagnou, M. Lautens, *Chem. Rev.* **2003**, *103*, 169 – 196; d) T. Hayashi, K. Yamasaki, *Chem. Rev.* **2003**, *103*, 2829 – 2844; e) T. Hayashi, *Pure Appl. Chem.* **2004**, *76*, 465 – 475; f) T. Hayashi, *Bull. Chem. Soc. Jpn.* **2004**, *77*, 13 – 21; g) K. Yoshida, T. Hayashi in *Modern Rhodium-Catalyzed Organic Reactions* (Ed.: P. A. Evans), Wiley-VCH; Weinheim, **2005**, chap. 3; h) K. Yoshida, T. Hayashi in *Boronic Acids* (Ed: D. G. Hall), Wiley-VCH, Weinheim, **2005**, chap. 4; i) Y. Yamamoto, T. Nishikata, N. Miyaura, *J. Synth. Org. Chem. Jpn.* **2006**, *64*, 1112 – 1121.
[69] R. Itooka, Y. Iguchi, N. Miyaura, *Chem. Lett.* **2001**, 722 – 723.
[70] F.-X. Chen, A. Kina, T. Hayashi, *Org. Lett.* **2006**, *8*, 341 – 344.
[71] T. Hayashi, M. Takahashi, Y. Takaya, M. Ogasawara, *J. Am. Chem. Soc.* **2002**, *124*, 5052 – 5058.
[72] A. Kina, Y. Yasuhara, T. Nishimura, H. Iwamura, T. Hayashi, *Chem. Asian J.* **2006**, *1*, 707 – 711; for a kinetic study of the Rh/bisphosphane-catalyzed version, see A. Kina, H. Iwamura, T. Hayashi, *J. Am. Chem. Soc.* **2006**, *128*, 3904 – 3905.
[73] a) D. G. Blackmond, *Angew. Chem.* **2005**, *117*, 4374 – 4393; *Angew. Chem. Int. Ed.* **2005**, *44*, 4302 – 4320; b) J. S. Mathew, M. Klussmann, H. Iwamura, F. Valera, A. Futran, E. A. C. Emanuelsson, D. G. Blackmond, *J. Org. Chem.* **2006**, *71*, 4711 – 4722.
[74] J.-F. Paquin, C. Defieber, C. R. J. Stephenson, E. M. Carreira, *J. Am. Chem. Soc.* **2005**, *127*, 10850 – 10851; for a different in which chiral dienes were employed, see T. Hayashi, N. Tokunaga, K. Okamoto, R. Shintani, *Chem. Lett.* **2005**, *34*, 1480 – 1481; for a Rh/bisphosphane-catalyzed version, see N. Tokunaga, T. Hayashi, *Tetrahedron: Asymmetry* **2006**, *17*, 607 – 613.
[75] a) C. Moreau, C. Hague, A. S. Weller, C. G. Frost, *Tetrahedron Lett.* **2001**, *42*, 6957 – 6960; b) A. Fürstner, H. Krause, *Adv. Synth. Catal.* **2001**, *343*, 343 – 350; c) K. Suzuki, T. Arao, S. Ishii, Y. Maeda, K. Kondo, T. Aoyama, *Tetrahedron Lett.* **2006**, *47*, 5789 – 5792.
[76] M. Ueda, N. Miyaura, *J. Org. Chem.* **2000**, *65*, 4450 – 4452.
[77] Some natural products with stereogenic diarylmethine centers: a) podophyllotoxin: R. C. Andrews, S. J. Teague, A. I. Meyers, *J. Am. Chem. Soc.* **1988**, *110*, 7854 – 7858; b) mimosifoliol: K. Tuttle, A. A. Rodriguez, T. R. R. Pettus, *Synlett* **2003**, 2234 – 2236; some pharmaceuticals containing this motif: c) sertraline: H. M. L. Davies, D. G. Stafford, T. Hansen, *Org. Lett.* **1999**, *1*, 233 – 236; d) CDP840: J. E. Lynch, W.-B. Choi, H. R. O. Churchill, R. P. Volante, R. A. Reamer, R. G. Ball, *J. Org. Chem.* **1997**, *62*, 9223 – 9228; e) SB-209670: W. M. Clark, A. M. Tickner-Eldridge, G. K. Huang, L. N. Pridgen, M. A. Olsen, R. Mills, I. Lantos, N. H. Baine, *J. Am. Chem. Soc.* **1998**, *120*, 4550 – 4551.
[78] M. L. Curtin, R. B. Garland, H. R. Heyman, R. R. Frey, M. R. Michaelides, J. Li, L. J. Pease, K. B. Glaser, P. A. Marcotte, S. K. Davidsen, *Bioorg. Med. Chem. Lett.* **2002**, *12*, 2919 – 2923.
[79] R. Shintani, K. Ueyama, I. Yamada, T. Hayashi, *Org. Lett.* **2004**, *6*, 3425 – 3427.
[80] For some recent examples involving Cu-catalyzed conjugate additions, see a) J. Wu, D. M. Mampreian, A. H. Hoveyda, *J. Am. Chem. Soc.* **2005**, *127*, 4584 – 4585; b) A. W. Hird, A. H. Hoveyda, *J. Am. Chem. Soc.* **2005**, *127*, 14988 – 14989; c) M. d'Augustin, L. Palais, A. Alexakis, *Angew. Chem.* **2005**, *117*, 1400 – 1402; *Angew. Chem. Int. Ed.* **2005**, *44*, 1376 – 1378; d) E. Fillion, S. Wilsily, *J. Am. Chem. Soc.* **2006**, *128*, 2774 – 2775.
[81] R. Shintani, W.-L. Duan, T. Hayashi, *J. Am. Chem. Soc.* **2006**, *128*, 5628 – 5629.
[82] J.-F. Paquin, C. R. J. Stephenson, C. Defieber, E. M. Carreira, *Org. Lett.* **2005**, *7*, 3821 – 3824.
[83] R. Shintani, T. Kimura, T. Hayashi, *Chem. Commun.* **2005**, 3213 – 3214.
[84] R. Shintani, K. Okamoto, T. Hayashi, *Org. Lett.* **2005**, *7*, 4757 – 4759.
[85] N. Tokunaga, T. Hayashi, *Adv. Synth. Catal.* **2007**, *349*, 513 – 516.
[86] For a recent review, see F. Schmidt, R. T. Stemmler, J. Rudolph, C. Bolm, *Chem. Soc. Rev.* **2006**, *35*, 454 – 470.
[87] a) M. Sakai, M. Ueda, N. Miyaura, *Angew. Chem.* **1998**, *110*, 3475 – 3477; *Angew. Chem. Int. Ed.* **1998**, *37*, 3279 – 3281; b) T. Focken, J. Rudolph, C. Bolm, *Synthesis* **2005**, 429 – 436; c) H.-F. Duan, J.-H. Xie, W.-J. Shi, Q. Zhang, Q.-L. Zhou, *Org. Lett.* **2006**, *8*, 1479 – 1481; d) R. B. C. Jagt, P. Y. Toullec, J. G. de Vries, B. L. Feringa, A. J. Minnaard, *Org. Biomol. Chem.* **2006**, *4*, 773 – 775; e) S. L. X. Martina, R. B. C. Jagt, J. G. de Vries, B. L. Feringa, A. J. Minnaard, *Chem. Commun.* **2006**, 4093 – 4095; f) K. Suzuki, K. Kondo, T. Aoyama, *Synthesis* **2006**, 1360 – 1364; g) T. Arao, K. Suzuki, K. Kondo, T. Aoyama, *Synthesis* **2006**, 3809 – 3814.
[88] T. Nishimura, Y. Yasuhara, T. Hayashi, *Org. Lett.* **2006**, *8*, 979 – 981.
[89] G. Takahashi, E. Shirakawa, T. Tsuchimoto, Y. Kawakami, *Chem. Commun.* **2005**, 1459 – 1461.
[90] E. Shirakawa, Y. Yasuhara, T. Hayashi, *Chem. Lett.* **2006**, *35*, 768 – 769.
[91] For a review, see T. Miura, M. Murakami, *Chem. Commun.* **2007**, 217 – 224.
[92] R. Shintani, K. Okamoto, Y. Otomaru, K. Ueyama, T. Hayashi, *J. Am. Chem. Soc.* **2005**, *127*, 54 – 55; for a Rh/bisphosphane-catalyzed version of this reaction, see T. Miura, T. Sasaki, H. Nakazawa, M. Murakami, *J. Am. Chem. Soc.* **2005**, *127*, 1390 – 1391.
[93] R. Shintani, A. Tsurusaki, K. Okamoto, T. Hayashi, *Angew. Chem.* **2005**, *117*, 3977 – 3980; *Angew. Chem. Int. Ed.* **2005**, *44*, 3909 – 3912.
[94] T. Miura, M. Shimada, M. Murakami, *J. Am. Chem. Soc.* **2005**, *127*, 1094 – 1095; for an asymmetric version of this reaction, see T. Miura, M. Shimada, M. Murakami, *Chem. Asian J.* **2006**, *1*, 868 – 877.
[95] T. Miura, M. Murakami, *Org. Lett.* **2005**, *7*, 3339 – 3341.
[96] R. Shintani, K. Okamoto, T. Hayashi, *Chem. Lett.* **2005**, *34*, 1294 – 1295; for a racemic version of this reaction, see T. Matsuda, M. Makino, M. Murakami, *Chem. Lett.* **2005**, *34*, 1416 – 1417.
[97] T. Miura, Y. Takahashi, M. Murakami, *Chem. Commun.* **2007**, 595 – 597.
[98] K. Aikawa, S. Akutagawa, K. Mikami, *J. Am. Chem. Soc.* **2006**, *128*, 12648 – 12649.
[99] J. W. Faller, J. C. Wilt, *J. Organomet. Chem.* **2006**, *691*, 2207 – 2212.

