Chemical Reviews

Volume 89, Number 8 December 1989

Synthetic Applications of Enantioselective Organotransition-Metal-Mediated Reactions

SHERI L. BLYSTONE

Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6022

Received March 15, 1988 (Revised Manuscript Received April 25, 1989)

Contents

Sheri L. Blystone received her B.S. degree from Gannon University in 1983. She then attended Case Western Reserve Univerity in Cleveland, OH, where in 1988 she received a Ph.D. degree in organic chemistry under Professor Anthony J. Pearson. Currently she is working with Dr. F. F. Knapp, Jr., in the Nuclear Medicine group at the Oak Ridge National Laboratory under a Department of Energy Postgraduate Fellowship. While attending CWRU, she received the Standard Oil of Ohio Graduate Fellowship in 1985. Her research interests include the development of new methodology for the construction of organic molecules of medical or biological interest.

I. Introduction

The field of organometallic chemistry has, in recent years, developed into a large and diversified discipline and has been the subject of many texts.[1] The application of organotransition metals to organic synthesis has been a very active area of this discipline, particularly the use of iron,[2-8] molybdenum,[9-12] manganese,[13-15] chromium,[16-18] cobalt,[19,20] and palladium[21-28] complexes to effect the regio- and/or stereospecific construction of organic molecules.

The application of these procedures toward enantioselective organic synthesis has become an ever growing concern. This review is intended to highlight the achievements that have been accomplished in this field thus far. It is concerned with those transition-metal reactions in which a new bond (i.e., carbon–carbon, carbon–hydrogen, or carbon–halogen) is formed and does not deal with such areas as transition-metal-mediated asymmetric isomerizations.[29] Asymmetric homogeneous catalysis (primarily hydrogenations) is a large part of this field with extensive coverage in the literature.[30] It is included again here primarily for its importance to the field as well as to introduce concepts vital to the other topics discussed. In addition, some newer references in this area are included. This review covers references from the seventies through early 1988, focusing primarily on the group 6–10 transition metals and their application to asymmetric organic synthesis. It is intended to be a reference point for those organometallic methodologies that have proven to be, or are potentially, synthetically valuable. The field of asymmetric oxidations, particularly the Sharpless epoxidations, suitable for a separate review, is not specifically addressed.

The studies in the area covered by this review can be grouped into three general categories. The first involves diastereoselective reactions involving a complex in which a chiral auxiliary has been incorporated. The chiral auxiliary in these cases may be either the organic

0009-2665/89/0789-1663$06.50/0

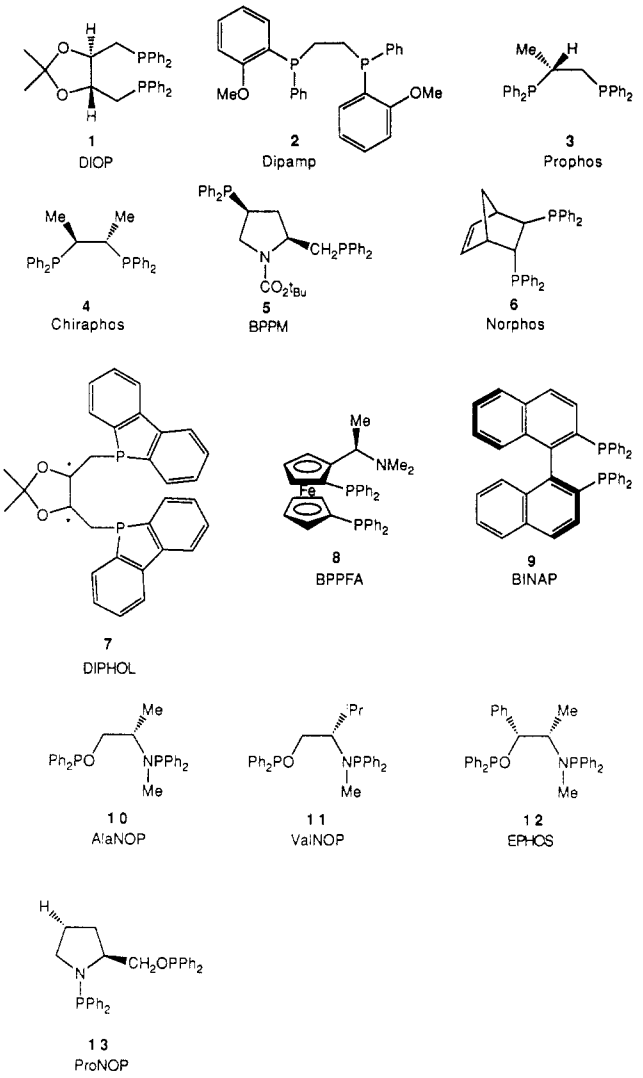


Figure 1. Some chiral phosphine ligands.

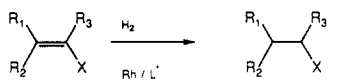
ligand of interest itself or other ligands on the metal. In the latter case, this is generally a chiral phosphine. Alternatively, the metal itself may be considered chiral by virtue of having different ligands attached. The second category involves the enantioselective addition of a nucleophile to an organometallic complex where the olefin, by having the metal complexed to one face of the π system, becomes the center of chirality. Finally, in a new extension of this area, a chiral nucleophile can be added diastereoselectively to an achiral organometallic complex.

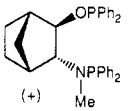
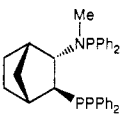
II. Asymmetric Homogeneous Catalysis

A. Hydrogenations and Hydrosilylations

One of the most successful applications of transition metals in asymmetric organic synthesis has been in homogeneous catalysis—hydrogenations, hydrosilylations, hydroformylations, and coupling reactions. In 1968, the first instance of enantioselectivity was seen during the hydrogenation of a prochiral olefin with a Wilkinson-type rhodium catalyst that incorporated a chiral phosphorus monodentate ligand.[31] It was soon discovered, however, that the degree of optical induction could be greatly enhanced by the use of chiral phosphine bidentate ligands.[32] With these types of ligands, some of which are shown in Figure 1, hydrogenated

TABLE 1. Asymmetric Catalytic Hydrogenation of Olefins



R_1	R_2	R_3	X	L*	%e.e. (config)	Ref.
H	Ph	CO_2H	NHCOMe	12	80 (R)	(a)
H	Ph	CO_2Me	NHCOMe	12	75 (R)	(a)
H	H	Ph	CH_2CO_2H	12	64 (S)	(a)
H	H	CO_2H	CCOMe	12	24 (R)	(a)
H	Ph	CO_2H	NHCOMe	 (+)	85 (R)	(b)
H	Ph	CO_2Me	NHCOMe		87 (R)	(b)
H	H	CO_2H	NHCOMe		89 (R)	(b)
H	Ph	CO_2H	NHCOMe	 (-)	85 (S)	(b)
H	Ph	CO_2Me	NHCOMe		87 (S)	(b)
H	H	CO_2H	NHCOMe		89 (S)	(b)
H	Ph	CO_2H	NHCOPh	9 (R)	100 (S)	(c)
Ph	H	CO_2H	NHCOPh	9 (S)	87 (S)	(c)
H	Ph	CO_2Me	NHCOPh	9 (S)	93 (R)	(c)
H	Ph	CO_2H	NHCOMe	9 (S)	84 (R)	(c)
H	H	CO_2H	NHCOPh	9 (S)	98 (R)	(c)

[a] Pracejus, G.; Pracejus, H. *J. Mol. Catal.* **1984**, *24*, 227. [b] Dobler, C.; Kreuzfeld, H.-J.; Pracejus, H. *J. Organomet. Chem.* **1988**, *344*, 89. [c] Miyashita, A.; Takaya, H.; Souchi, T.; Noyori, R. *Tetrahedron* **1984**, *40*, 1245.

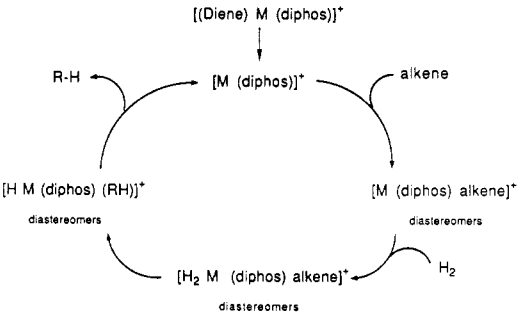


Figure 2. Catalytic cycle for hydrogenations.[34]

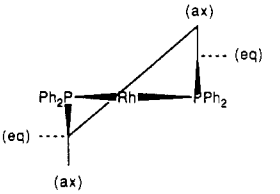


Figure 3. Conformation of complex intermediate in catalytic hydrogenation.[33]

products have been obtained in >95% optical purity.

Some recent examples of catalytic asymmetric hydrogenation of olefins are shown in Table I.

Bidentate ligands were found to impart a conformational rigidity to the intermediate catalyst–substrate complexes (Figure 2). This appears to be a major factor involved in the increased selectivity seen in these cases.[33,34] Diphosphines DIOP (1) and BPPM (5) form seven-membered chelate rings whereas DIPAMP (2), Prophos (3), Chiraphos (4), and Norphos (6) form more

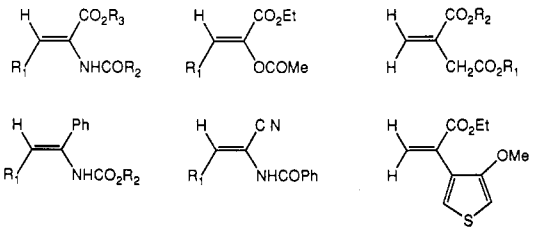


Figure 4. Substrates most successful in asymmetric catalytic hydrogenation.[34]

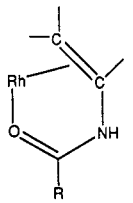


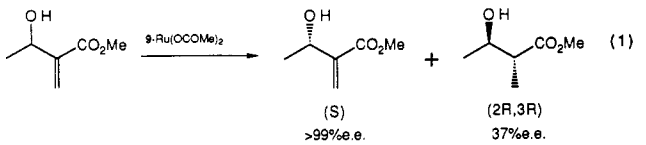
Figure 5. Second avenue of chelation in hydrogenation.[35]

rigid, puckered, five-membered-ring chelates (Figure 3).

With the smaller ring size, substituents on the phosphine tend to orient themselves in a pseudoequatorial position. It was thought that the fixed five-membered-ring conformation, by reducing the number of possible diastereomeric interactions with the enantiotopic faces of the substrate (Figure 3), would more readily allow one conformation to predominate, thereby leading to a single enantiomer of the hydrogenated product being preferentially formed.[33]

Halpern[35] has in fact shown that, while indeed a major diastereomeric catalyst–substrate complex is formed, the major product produced, and therefore the selectivity of the reaction, are derived from the *minor* diastereomer. Apparently, the minor diastereomer has a greatly enhanced reactivity over the more stable major component, and this reactivity then determines the configuration of the hydrogenated product.

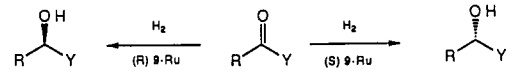
Noyori[37] has recently employed the difference in reactivity of the diastereomeric catalyst–substrate complexes to effect the kinetic resolution of racemic allylic alcohols (eq 1).



The role of the substrate in determining the stereochemical outcome is not to be discounted. In general, olefins that produce the highest degree of enantiomeric excess (ee) upon hydrogenation are those that are capable of a secondary interaction with the metal center in addition to the primary coordination of the olefin.[34-36] These general types are shown in Figure 4. It should be noted that these olefins all possess an appendant oxygen functionality that can coordinate to the "ligand-deficient" metal center and help to direct the reaction (Figure 5). This secondary interaction helps to increase the rigidity of the catalyst–substrate system, which, as discussed earlier, helps to increase the observed enantioselectivity. Olefins that are incapable of this secondary interaction generally result in lower asymmetric induction.

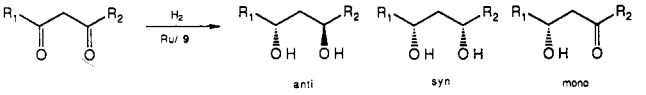
Catalytic asymmetric homogeneous hydrogenation has been extensively studied and is the subject of many reviews.[33-36,38] It is still a popular field of research today as new chiral ligands, catalyst systems, and substrates are explored for their effect on the enantioselectivity of the reaction. For example, Noyori and co-workers[39] have applied a chiral ruthenium–BINAP (**9**) catalyst for the hydrogenation of ketones with excellent results (Table 2).

TABLE 2. Asymmetric Catalytic Hydrogenation of Ketones[39]



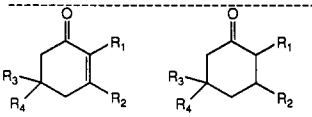
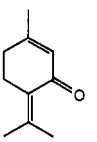
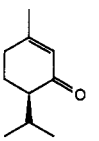
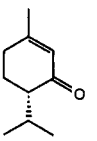
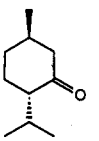
R	Y	config. of ligand	yield	%e.e. (config)
Me	CH_2NMe_2	S	72	96 (R)
^iPr	CH_2NMe_2	S	83	95 (S)
Ph	CH_2NMe_2	S	85	95 (S)
Me	CH_2OH	R	100	92 (R)
Me	CO_2Me	R	97	83 (R)
Me	CH_2CH_2OH	R	100	98 (R)
Me	CH_2CO_2Et	R	100	>99 (R)
Me	CH_2CONMe_2	S	100	96 (S)
Me	CH_2COSEt	R	42	93 (R)
Me	CH_2COMe	R	100	100 (R,R)
Me	$CH(CH_3)COMe$	S	100	99 (S,S)

TABLE 3. Asymmetric Catalytic Hydrogenation of β-Diketones[40]



R_1	R_2	anti:syn:mono	%e.e. (anti)
Me	Me	99 : 1 : -	>99
Me	Et	94 : 6 : -	94
Me	^iPr	97 : 3 : -	98
Me	^tBu	91 : 9 : -	98
Et	Et	98 : 2 : -	96
Me	Ph	89 : 9 : 2	99

TABLE 4. Asymmetric Catalytic Hydrogenation of α,β-Unsaturated Ketones

Substrate	Product	Catalyst	%yield	%e.e.	ref.
					
R_1 H, R_2 Me, R_3 Me, R_4 Me			20	62 (R)	(a)
R_1 H, R_2 Me, R_3 H, R_4 H		$HRuCl(TBPC)_2$[c]	40	22 (R)	(a)
R_1 Me, R_2 H, R_3 H, R_4 H			38	26 (S)	(a)
		$HRuCl(TBPC)_2$[c]	26	48.5	(b)
		$Ru_2Cl_4(DIOP)_3$	35	40	(b)
		$HRuCl(TBPC)_2$[c]		80 (S,R)	(b)

[a] LeMaux, P.; Simonneaux, G. *J. Organomet. Chem.* **1987**, *327*, 269. [b] LeMaux, P.; Massonneau, V.; Simonneaux, G. *Tetrahedron* **1988**, *44*, 1409. [c] (−)-*trans*-1,2-Bis[(diphenylphosphino)methyl)]-cyclobutane.

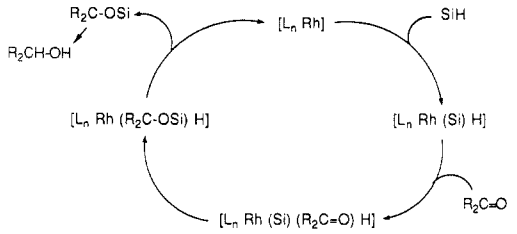
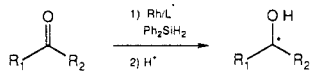
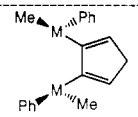
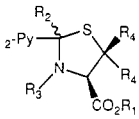


Figure 6. Catalytic cycle for hydrosilylation.[34]

TABLE 5. Asymmetric Catalytic Hydrosilylation of Ketones



R_1	R_2	L*	%e.e. (config.)	Ref.
Me	Ph	 A M = As	36 (S)	(a)
Me	Ph	B M = P	36 (S)	(a)
Me	Ph	 C R_1 = Me R_2,R_3,R_4 = H	83.2 (R)	(b)
Me	Ph	D R_1,R_2 = Me R_3,R_4 = H	84.1 (R)	(b)
Me	Ph	E R_1 = Et R_2,R_3,R_4 = H	97.6 (R)	(b)
Me	Ph	F R_1,R_2,R_3,R_4 = H	76.6 (R)	(b)
Me	Ph	G R_1,R_2,R_3 = Me R_4 = H	69.8 (R)	(b)
Me	tBu	A	4 (S)	(a)
Me	tBu	D	68.5 (R)	(b)
Me	tBu	B	41	(a)
Me	$PhCH_2$	C	52.7 (R)	(b)
Me	$PhCH_2$	D	39.5 (R)	(b)
Me	$PhCH_2CH_2$	D	26.9 (-)	(b)

[a] Mokhlesur, A. F. M.; Wild, S. B. *J. Mol. Catal.* **1987**, *39*, 155. [b] Brunner, H.; Becker, R.; Riepl, G. *Organometallics* **1984**, *3*, 1354.

Additionally, 1,3-diketones[40] (Table 3) and α,β-unsaturated ketones (Table 4) have been examined.

As with hydrogenations, asymmetric catalytic hydrosilylation of prochiral carbonyl compounds, imines, and olefins is promoted by transition-metal catalysts possessing chiral phosphine ligands. A reasonable catalytic cycle for the reaction is shown in Figure 6.[34] Generally, the asymmetric induction involved in hydrosilylation is somewhat lower than that achieved in hydrogenation. Interestingly, as opposed to hydrogenation, both uni- and bidentate phosphine ligands appear to work equally well. The nature of the silane, however, has a marked effect on the selectivity. For example, hydrosilylation of phenyl *tert*-butyl ketone with dimethylphenylsilane results in the stereoselective formation of the *S* enantiomer of the corresponding alcohol in 62% ee, whereas the use of trimethylsilane results in a 28% ee of the *R* enantiomer.[41] Asymmetric hydrosilylation of α-keto esters and amides and γ-keto esters gives somewhat better results, up to 75–85% ee.[41] As with hydrogenation, selectivity appears to be increased when a possibility for a secondary interaction

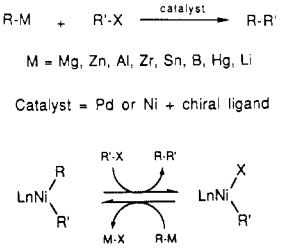
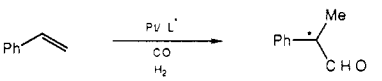


Figure 7. Asymmetric catalytic cross-coupling.[43]

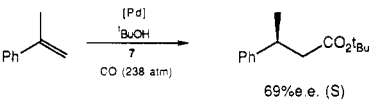
TABLE 6. Asymmetric Catalytic Hydroformylation[42]



L*	%e.e. (config.)	%yield
10	23.9 (S)	95
11	14.2 (S)	96
12	36.3 (S)	92.5
13	48.1 (S)	97
(R,R)-1	18 (S)	85.5

of an ancillary carbonyl functionality with the metal center exists. Recent examples are shown in Table 5.

In a similar reaction, transiton-metal catalysts will also promote an asymmetric one-carbon homologation of a prochiral olefin in the presence of an alcohol and carbon monoxide to give a saturated ester in low to moderate enantiomeric excess.[41] An example, using a palladium catalyst, is shown in eq 2. Catalytic asymmetric hydroformylation gives chiral aldehydes in moderate enantiomeric excess (Table 6).[42]



(2)

69%e.e. (S)

B. Asymmetric Coupling Reactions

Chiral transition-metal catalysts have also been used to mediate asymmetric cross-coupling reactions of alkenyl or aryl halides or allylic compounds with some metalated species. Generally, catalysts of nickel or palladium bearing chiral phosphine ligands are employed.[43] The actual mechanism of this coupling is not known; however, an unsymmetrical diorganometallic complex, $L_nM^{II}(R)(R')$, is most likely the key intermediate (Figure 7).

Chiral phosphine ligands such as have been previously discussed (Figure 1) are also employed in cross-coupling reactions. In addition, a large number of ferrocene and amino acid derivatives have also been studied (Figure 8).[43]

The first examples of this procedure gave disappointing results (<17% ee), but more recent experiments have yielded higher selectivities (Table 7).

It has been noted from studies involving the coupling of (1-phenylethyl)magnesium chloride with vinyl bromide (entry 2, Table 7) that higher stereoselectivities are obtained with those ligands possessing an amine functionality and that this stereoselectivity is strongly affected by changing the steric bulk of this amine in the phosphinoferrocenyl ligands **20a–g**. The optical purity is most likely determined during the transmetalation of the alkyl group from the Grignard reagent to the catalyst (Figure 7). The amine grouping is then able

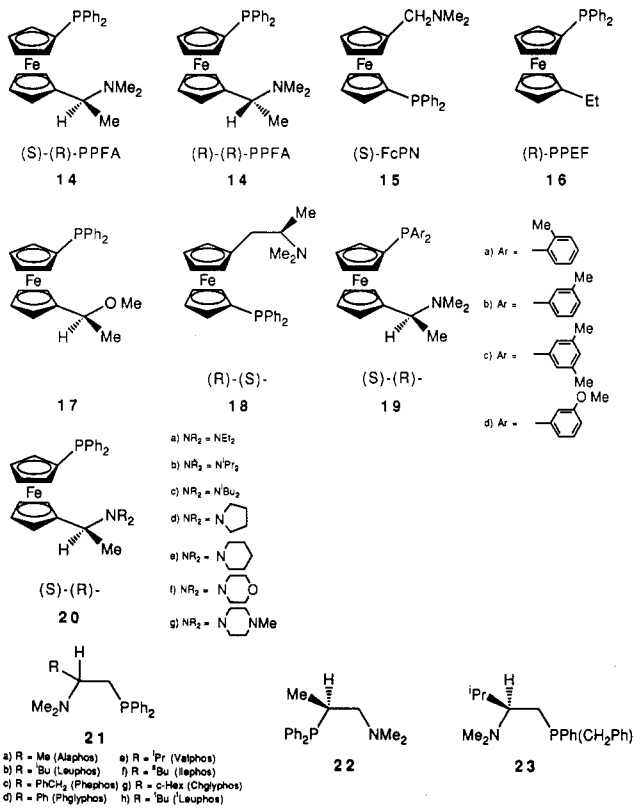
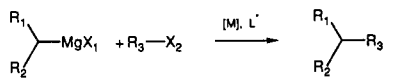
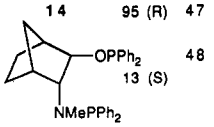


Figure 8. Chiral phosphine ligands used in cross-coupling and hydroformylation.[43]

TABLE 7. Asymmetric Catalytic Cross-Coupling



ENTRY	R_1	R_2	R_3	X_1	X_2	M	L*	%e.e.	Ref.
1	Me	Et	Ph	Br	Cl	Ni	1	17	44
2	Me	Ph	$CH=CH_2$	Cl	Br	Ni	14	68 (S)	43
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	20a	35 (R)	
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	20c	15 (S)	
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	20d	62 (R)	
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	20f	17 (R)	
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	20g	65 (R)	
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	21c	71 (S)	
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	21f	81 (S)	
	Me	Ph	$CH=CH_2$	Cl	Br	Ni	21h	94 (R)	
3	Me	p-MeC_6H_4	$CH=CH_2$	Br	Br	Ni	21e	83 (S)	45
4	Me	$^nC_6H_{13}$	$CH=CH_2$	Cl	Br	Ni	14	37 (S)	46
5	Ph	$SiMe_3$	$CH=CH_2$	Br	Br	Pd	14	95 (R)	47
6	Me	Ph	transPhCH=CH	Cl	Br	Pd	 13 (S)		48

to coordinate to the magnesium, forming an intermediate or transition state such as is shown in Figure 9.[43] This is analogous to the secondary coordination of appendant carbonyl functionalities of the substrate and their effect on the observed stereoselectivity during hydrogenations and hydrosilylations.

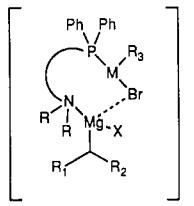


Figure 9. Intermediate in asymmetric catalytic cross-coupling.[43]

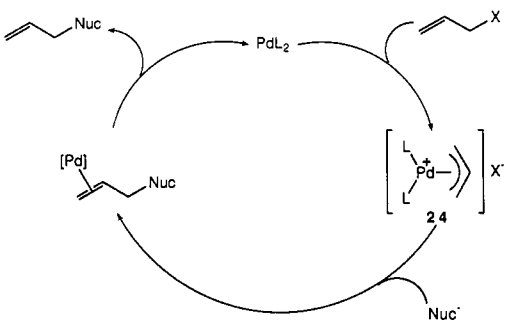


Figure 10. Palladium-catalyzed allylic alkylation.

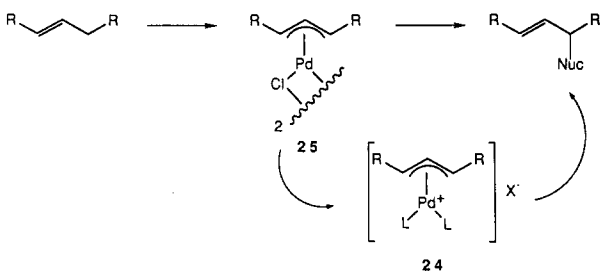
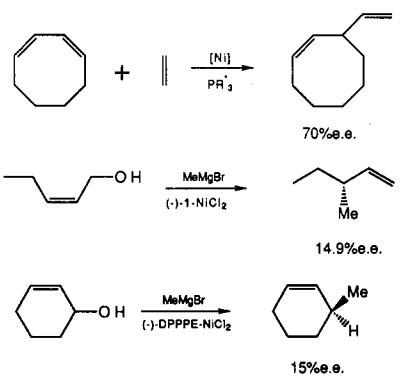


Figure 11. Alkylation of palladium chloride dimers.[51a]

Other applications of transition-metal catalysts containing a chiral ligand include asymmetric codimerization of olefins (eq 3),[34] an asymmetric version of the Felkin reaction (eq 4 and 5),[49] and asymmetric dihydroxylation of olefins (Table 8).[50]



III. Asymmetric Alkylations Involving the Use of Chiral Auxiliaries

A. Palladium

One of the most useful reactions developed in the organometallic field is the palladium(0)-catalyzed alkylation of allylic acetates, alcohols, halides, amines, etc. to give a new allylic species (Figure 10).[51]

Complementary stoichiometric reactions involving (π-allyl)palladium dimers are also known where alkylation of **25** will occur in the presence of added phos-

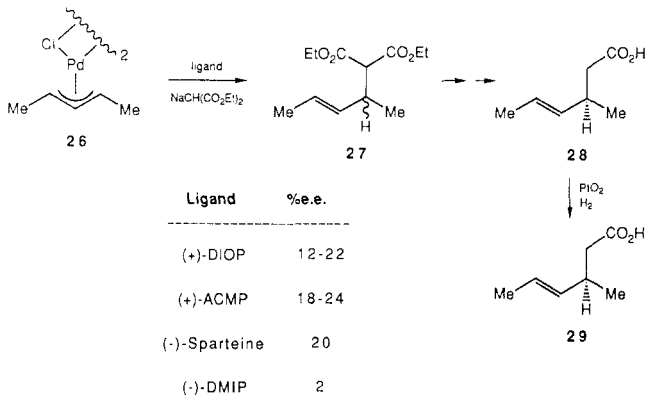
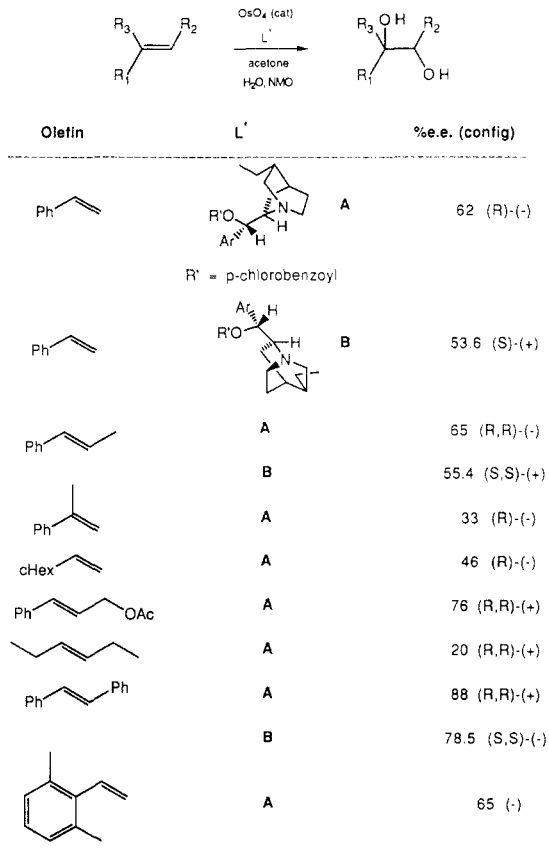


Figure 12. Asymmetric alkylation of a palladium chloride dimer.[52]

TABLE 8. Osmium-Catalyzed Asymmetric Dihydroxylation[50]



phines (Figure 11). These phosphine ligands presumably displace chlorine, generating a cationic allyl–palladium complex (**24**) which is subsequently alkylated.[51a]

In recent years, this chemistry has been extended into the field of asymmetric organic synthesis. Trost reported in 1973[52] the asymmetric addition of sodium dimethyl malonate to (*syn,syn*-1,3-dimethyl-π-allyl)-palladium chloride dimer (**26**) in the presence of a variety of chiral phosphine ligands (Figure 12). By further chemical transformation to compounds of known rotation, **28** or **29**, he was able to determine the amount of asymmetric induction in the original addition adduct **27**.

Better results have been achieved in analogous catalytic reactions. Trost[53] first reported that the use of a chiral phosphine ligand in the palladium-catalyzed alkylation of *cis*-3-acetoxy-5-carbomethoxycyclohexane (**30**) resulted in a 24% diastereomeric excess (de) of the

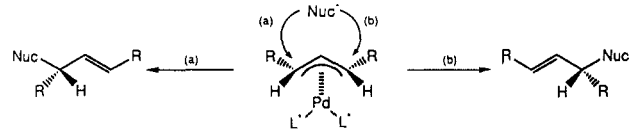


Figure 13. Paths of nucleophile addition to meso palladium complexes.[54]

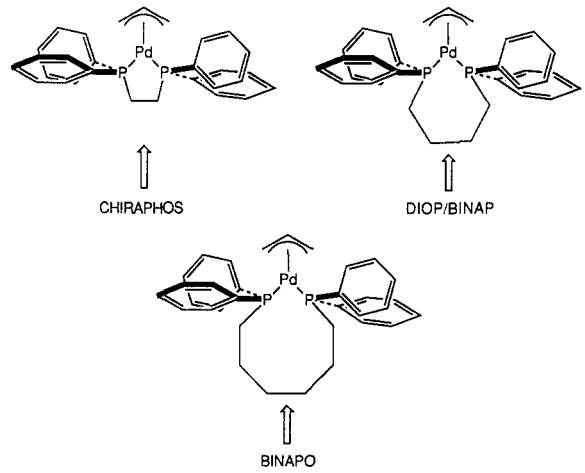
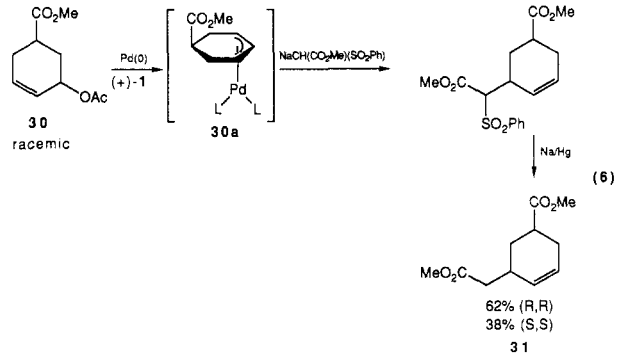


Figure 14. "Chiral pocket" concept for chelating ligands on allyl–palladium complex.[54]

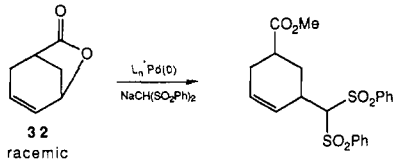
R,R diastereomer of **31** following the desulfonylation of the alkylation product (eq 6).



In this case, a symmetrical palladium complex intermediate, **30a**, is formed with achiral ligands. The use of chiral ligands, then, causes both allylic termini to become diastereotopic. Preferred attack of a nucleophile at one of these termini then results in asymmetric induction. Alternatively, this induction may be due to a preference for the formation of a more stable intermediate olefin–palladium complex (Figure 10).

Trost[54] has suggested a kinetic approach to the question in which the chiral ligands of a meso palladium complex such as **30a** form a local asymmetric environment, a "chiral pocket", which then directs the nucleophile preferentially to one end of the allyl moiety (Figure 13). The larger the ring size formed in the bidentate phosphine–palladium complex, the more the "arms" of the ligand are forced around the allyl moiety and the incoming nucleophile, and the higher the observed selectivity (Figure 14).[54] Indeed, alkylation of **32** with bis(phenylsulfonyl)methane using a variety of ligands that give different chelate ring sizes evidenced this general trend (Table 9). Of particular note, the introduction of meta substitution on the phosphine aryl

TABLE 9. Asymmetric Palladium-Catalyzed Alkylation of Lactone[54]



32
racemic

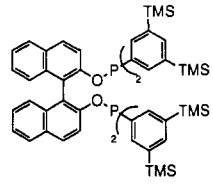
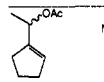
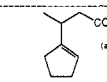
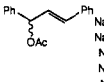
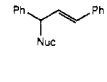
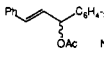
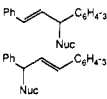
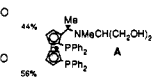
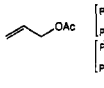
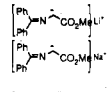
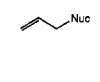
CHELATE RING SIZE	L*	%d.e.	%yield
5	(-)-4	18	72
7	(+)-1	16	82
7	(-)-9	31	92
9	(-)-BINAPO	38	66
9		69	82

TABLE 10. Asymmetric Palladium-Catalyzed Alkylation of Allylic Acetates

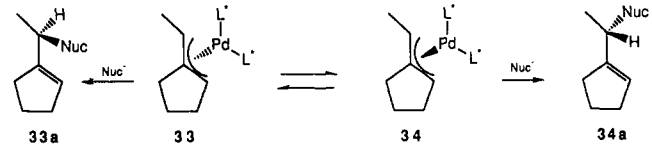
Acetate	Nucleophile	Product	L*	%e.e.	%yield	Ref.
	$NaCH(CO_2Me)_2$	 (a)	1	37		53
			2	16		53
			Camphos	37		53
	$NaCH(CO_2Me)(SO_2Ph)$		Camphos	39		53
			1	46		53
	$NaC(Me)(CO_2Me)_2$		9	50 (R)	81	54
	$NaC(Me)(CO_2Me)_2$		BINAPO	68 (S)	75	54
	$NaCH(CO_2Me)_2$		BINAPO	55 (S)	87	54
	$NaCH(SO_2Ph)_2$		BINAPO	66 (S)	85	54
	$NaCH(COMe)_2$		A	90 (S)	97	(b)
	$NaCH(COMe)_2$			95 (S)	92	(b)
				80 (S)		
			1	39		(c)
			6	45		(c)
			1	62	86	(c)

[a] After decarboxylation or desulfonylation. [b] Hayashi, T.; Yamamoto, A.; Hagihara, T.; Ito, Y. *Tetrahedron Lett.* **1986**, *27*, 191. Hayashi, T.; Yamamoto, A.; Ito, Y. *Chem. Lett.* **1987**, 177. [c] Genet, J.-P.; Juge, S.; Montez, J. R.; Gaudin, J.-M. *J. Chem. Soc., Chem. Commun.* **1988**, 718.

rings, by nature of their propeller-like arrangement, creates the most specific "chiral pocket", resulting in quite high diastereomeric excess.

Alkylation of allylic acetates has also been examined (Table 10). In cases where unsymmetrical allyl–palladium complexes are formed as intermediates (i.e., entry 1, Table 10), equal amounts of complexes **33** and **34** should be formed regardless of whether the ligands are chiral if one assumes that the oxidative addition of Pd(0) to the allylic acetate is stereospecific. It is known that exo attack of a nucleophile is stereospecific and therefore, since **33** and **34** are formed in equal amounts, one would expect that **33a** and **34a** would also be formed in equal amounts (Figure 15).

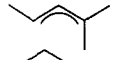
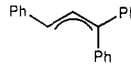
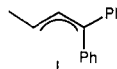
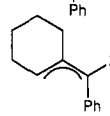
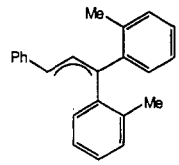
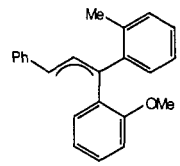
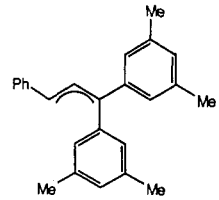
Bosnich and Mackenzie[55] have suggested that the asymmetric induction that is in fact observed in these cases depends upon an equilibrium established between the two diastereomeric π-allyl–palladium intermediates. They have measured this equilibrium by ^{31}P NMR using (*SS*)-Chiraphos (**4**) as the ligand. The magnitude of this equilibrium constant could then be a measure



33a 33 34 34a

Figure 15. Modes of nucleophile addition to diastereomeric allyl–palladium complex intermediates.[54]

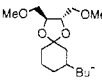
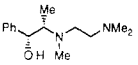
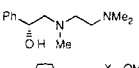
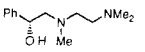
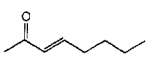
TABLE 11. Equilibrium Studies of (*S,S*)-4-Palladium Complexes of Various Allylic Fragments[55]

Allyl Ligand	Solvent	Equil. Ratio	%e.e.[a]
	$CDCl_3$	1	
	DMF	1	
	$CDCl_3$	1.7	
	DMF	1.8	
	DMF	1.7	
	$CDCl_3$	1.8	
	$CDCl_3$	1	
	DMF	1	
	$CDCl_3$	6	
	DMF	7.5	
	$CDCl_3$	5.7	
	DMF	6	86
	THF	3.7	84
	$CDCl_3$	4	
	DMF	6	
	THF	-	62
	$CDCl_3$	3.1	
	DMF	2.7	
	$CDCl_3$	5	
	DMF	7.4	
	$CDCl_3$	1.5	
	DMF	1.6	
	$CDCl_3$	1.3	
	DMF	1.2	
	$CDCl_3$	14	
	DMF	12	
	DMSO	12	
	THF	-	

[a] Of product after alkylation using dimethyl sodiomalonate.

of any asymmetric induction involved in the reaction. A study of this equilibrium with a variety of allyls is shown in Table 11. It should be noted that the observed % ee's from subsequent alkylation do not correspond directly with the measured diastereomeric ratio of the two intermediate palladium complexes, indicating that the asymmetric induction involves more than simple thermodynamic control.

TABLE 12. Cuprate Addition to α,β-Unsaturated Carbonyls in the Presence of Asymmetric Chelating Ligands

Substrate	Cuprate	L*	%e.e. (config)	%Yield	Ref.
	$Me_2CuMgBr$		26 (S)	61	(a)
	Me_2CuLi		14.3 (S)	53.5	(b)
	$^nBu_2CuLi$		15 (S)	84	(b)
	$Li_2Cu(Et)L^*$		92 (R)-(+)	90	(c)
	$Li_2Cu(^nBu)L^*$		89 (R)-(+)	90	(c)
	$Li_2Cu(^tBu)L^*$		85 (R)-(-)	73	(c)
	$Li_2Cu(Me)L^*$		90 (R)-(+)	60	(c)
	$MeCuLiL^*$	 X = OMe	82 (S)	77	(d)
		X = SPh	80 (R)	71	(d)
		X = SMe	80 (S)	68	(d)
		X = OH	69 (R)	53	(d)
	$Li_2Cu(Et)L^*$		77 (R)-(+)	68	(c)
	$Li_2Cu(^nBu)L^*$		72 (R)-(+)	60	(c)
	$Li_2Cu(^tBu)L^*$		81 (R)-(+)	52	(c)
	$MeCuLiL^*$		41 (S)	77	(d)
	$^tBuCuLiL^*$		50 (S)	50	(d)
	Me_2CuLi	 R = Me	7 (R)		(e)
		R = ^{t}BuOCO	33 (R)		(e)
		R = ^{t}BuCO	75 (R)		(e)
	$Me_2CuMgBr$		88 (S)	80	(f)
		 X = OMe	68 (R)	37	(d)
		X = SMe	64 (S)	52	(d)
	$MeCuLiL^*$	X = SMe	83 (R)	78	(d)

[a] Leyendecker, F.; Jesser, F.; Ruhland, B. *Tetrahedron Lett.* **1981**, *22*, 3601. [b] Langer, W.; Seebach, D. *Helv. Chim. Acta* **1979**, *62*, 1710. [c] Corey, E. J.; Naef, R.; Hannon, F. J. *J. Am. Chem. Soc.* **1986**, *108*, 7114. [d] Dieter, R. K.; Tokles, M. *J. Am. Chem. Soc.* **1987**, *109*, 2040. [e] Leyendecker, F.; Laucher, D. *Tetrahedron Lett.* **1983**, *24*, 3517. [f] Imamoto, T.; Mukaiyama, T. *Chem. Lett.* **1980**, 45.

Other applications of asymmetric palladium catalysts include cyclizations (eq 7),[56] allylation of 1,3-diketones (eq 8),[57] and intramolecular cyclization of dicarbonates (eq 9)[58] and dicarbamates (eq 10).[59]

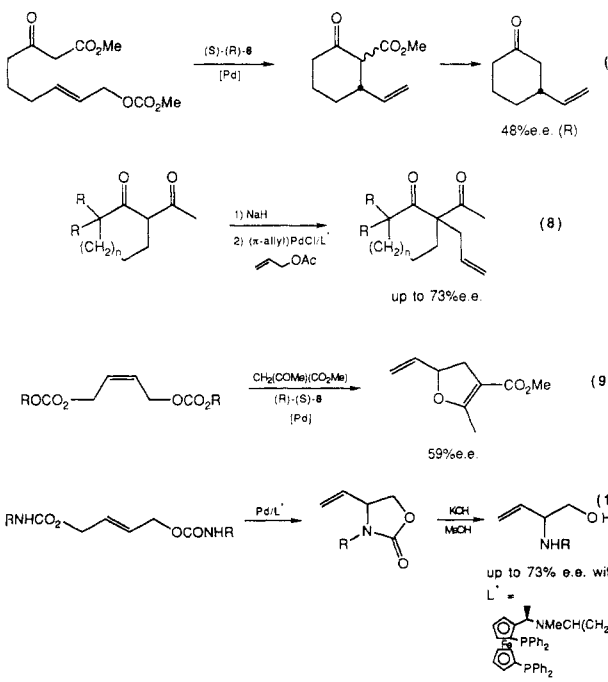
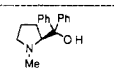
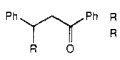
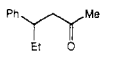
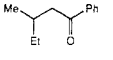
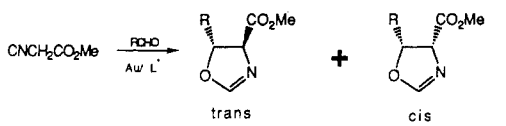


TABLE 13. Alkylation of Carbonyl Compounds with Alkylzinc Reagents in the Presence of Chiral Ligands

Substrate	Zinc Rgt.	Product	L*	%e.e.	%Yield	Ref.
PhCHO	Et_2Zn			92 (S)	98	(a)
pCl-C_6H_4CHO	Et_2Zn			91 (S)	100	(a)
pMeO-C_6H_4CHO	Et_2Zn			81 (S)	100	(a)
	Et_2Zn			65 (S)	91	(a)
PhCHO	Et_2Zn			71 (R)	100	(a)
pCl-C_6H_4CHO	Et_2Zn			70 (R)	92	(a)
pMeO-C_6H_4CHO	Et_2Zn			62 (R)	97	(a)
	Me_2Zn		R = Me, R = Et; $Ni(acac)_2$ + 	40 (R)	72	(b)
	Et_2Zn			45 (R)	75	(b)
	Et_2Zn			12 (R)	63	(b)
	Et_2Zn			44 (R)	78	(b)

[a] Soai, K.; Ookawa, A.; Ogawa, K.; Kaba, T. *J. Chem. Soc., Chem. Commun.* **1987**, 467. [b] Soai, K.; Yokoyama, S.; Hayasaka, T.; Ebihara, K. *J. Org. Chem.* **1988**, *53*, 4148.

TABLE 14. Gold-Catalyzed Asymmetric Aldol Condensations of α-Isocyano Carboxylates[60a]



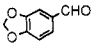
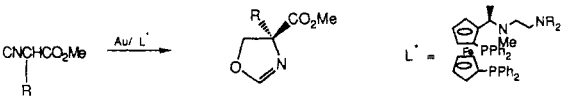
R	NR_2	% yield	trans:cis	%e.e. (trans)
Me		99	89 : 11	89 (4S, 5R)
^iPr		100	99 : 1	92 (4S, 5R)
Ph		93	95 : 5	95 (4S, 5R)
		86	95 : 5	96 (4S, 5R)

TABLE 15. Gold-Catalyzed Intramolecular Asymmetric Aldol Condensations of α-Isocyano Carboxylates[60b]



R	NR_2	%yield	%e.e. (config)
H	NMe_2	99	52 (S)
Me		100	64 (S)
Et		89	70 (S)
^iPr		99	71 (S)
Ph		75	67

B. Copper and Zinc

Chiral ligands have also been employed to effect the asymmetric Michael addition of organocuprates to α,β-unsatured carbonyl compounds (Table 12).

Similarly, alkylzinc reagents have been utilized for asymmetric alkylation in the presence of chiral ligands (Table 13).

C. Gold

Hayashi and Ito have recently employed the phosphinoferrocenyl chiral ligands used in catalytic cross-coupling reactions to effect asymmetric gold-catalyzed aldol reactions of α-isocyano carboxylates (Tables 14 and 15).[60] This methodology has been employed for the synthesis of *threo*- and *erythro*-sphingosines.[61]

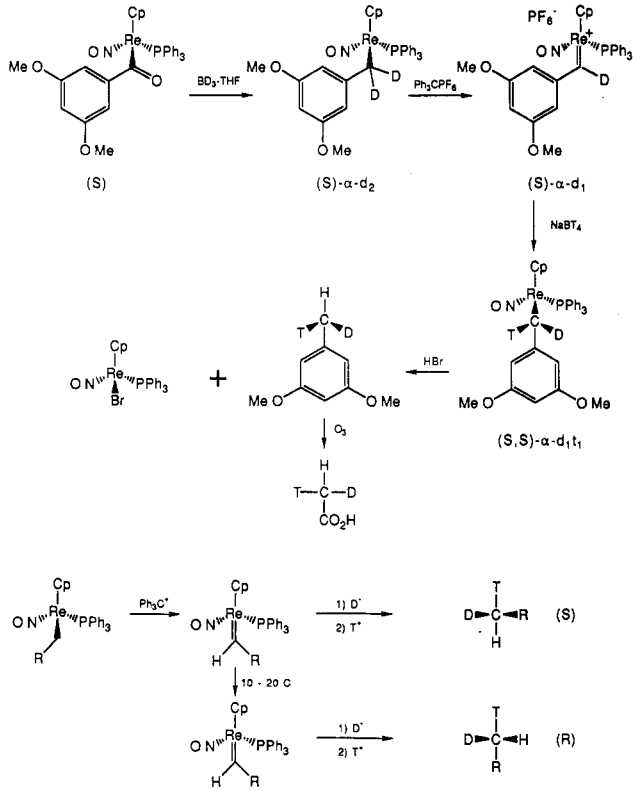
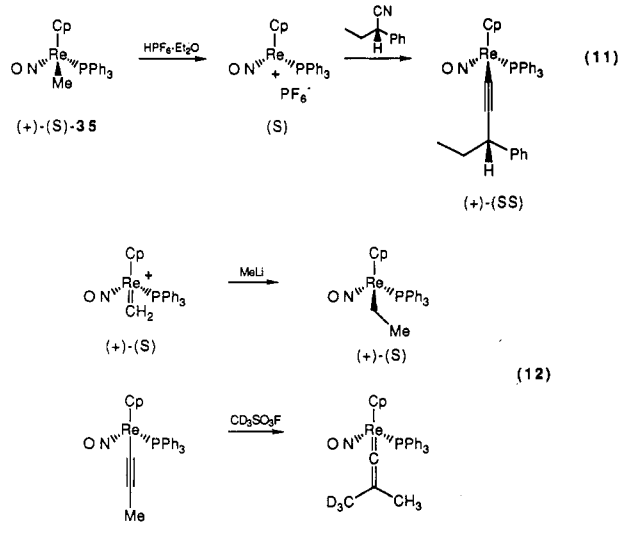


Figure 16. Chiral rhenium complexes as chiral methyl synthons.[67]

IV. Metal-Centered Asymmetry

A. Chiral Rhenium Complexes

In this section we will be dealing with stoichiometric organometallic reactions where the metal itself is a chiral center. These types of complexes can be resolved analogously to normal organic compounds into optically enriched (or pure) material. For instance, Gladysz[63] synthesized optically active $CpRe(NO)(PPh_3)(X)$ complexes to allow methodology developed on racemic compounds[62] to be utilized in an asymmetric fashion. These complexes can then be transformed into optically active $CpRe(NO)(PPh_3)(CH_3)$, $[CpRe(NO)(PPh_3)(=CH_2)]^+PF_6^-$, etc. For example, reaction of optically pure **35** with a chiral nitrile proceeds with overall retention of configuration at rhenium (eq 11).[64] Alkylation of alkylidene and acetylide complexes is also readily observed (eq 12).[65]



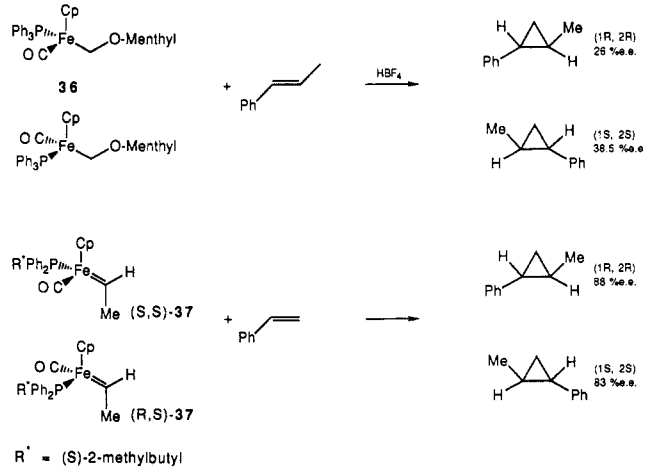
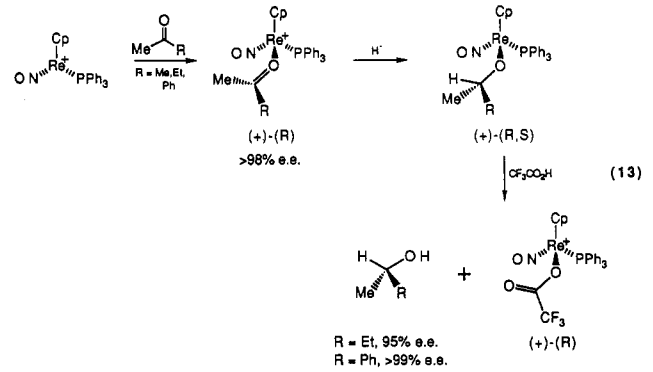


Figure 17. Asymmetric cyclopropanation using chiral iron complexes.[69]

Gladysz has been primarily interested in determining the mechanistic aspects of stereospecific hydride abstraction and various asymmetric rhenium to carbon inductions that occur in this system.[66] Some interesting synthetic applications of his mechanistic work involving deuterium include the development of a synthon for a chiral, pyramidal methyl carbenium ion (Figure 16).[67]

Additionally, chiral rhenium–ketone complexes can be used to give optically active alcohols in high enantiomeric excess (eq 13).[68]

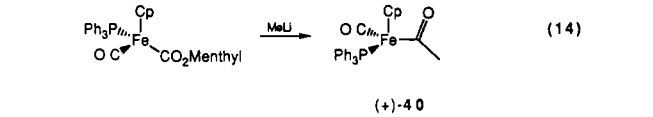


B. Chiral Iron Complexes

Chiral-at-iron complexes are one of the most active areas of study in the asymmetric organometallic field. Generally, chiral Fp* complexes are employed [Fp* = carbonyl(η^5-cyclopentadienyl)(triphenylphosphine)iron].

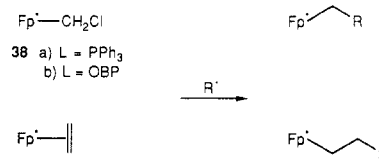
Chiral iron–alkyl complexes (**36**) and chiral iron–carbene complexes (**37**) have been used to effect asymmetric cyclopropanation of olefins (Figure 17).[69] Alkylation of halo compounds **38** and olefin derivatives **39** can proceed with a significant degree of asymmetric induction, especially when the steric bulk of the iron center is increased by using tri(*O*-biphenyl) phosphite (OBP) rather than triphenylphosphine (Table 16).[70]

Chiral iron–acyl complexes such as **40** have been synthesized by Brunner[71] from the corresponding menthyl esters by the addition of methyllithium (eq 14).



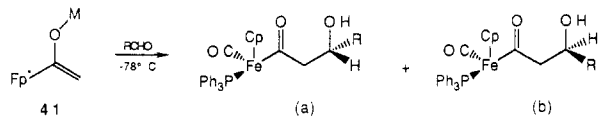
A great deal of work has been carried out with these chiral iron–acyl complexes, primarily by Liebeskind and

TABLE 16. Nucleophilic Addition to Chiral Iron Complexes[70]



Complex	R	%e.e.
38a	$CH(COMe)CO_2{}^tBu$	22
38a	$CHC(O)(CH_2)_4$	18
39a	$CH(COMe)CO_2{}^tBu$	46
39a	$CHC(O)(CH_2)_4$	10
38b	$CHC(O)(CH_2)_4$	60
39b	$CHC(O)(CH_2)_4$	64

TABLE 17. Asymmetric Aldol Condensations with Chiral Iron Enolate 41 and Various Metal Counterions



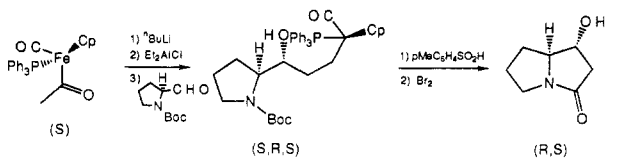
R	M	Ratio a:b	Ref.
Et	Al^iBu_2	5.2 : 1	73
Et	$AlEt_2$	>100 : 1	74[a]
Et	SnCl	1 : 5.4	73
^{n}Pr	Al^iBu_2	7.5 : 1	73
^{n}Pr	SnCl	1 : 11.4	73
^{i}Pr	Al^iBu_2	8.2 : 1	73
^{i}Pr	$AlEt_2$	>100 : 1	74[a]
^{i}Pr	SnCl	1 : 11.0	73
Ph	Al^iBu_2	3.7 : 1	73
Ph	$AlEt_2$	20 : 1	74[a]
Ph	SnCl	1 : 12	73
^{t}Bu	$AlEt_2$	>100 : 1	74[a]

[a] This disparity may be a function of the excess of aluminum reagent employed by Davies.

by Davies. These complexes can be deprotonated to form enolate 41 and reacted with a variety of electrophiles.[72] In the first cases, with a simple lithium counterion, aldol condensations with aldehydes proceeded in high yield, but with little or no selectivity. It was soon discovered by both groups, however, that changing the counterion of 41 produces significant changes in stereoselectivity (Table 17).

Liebeskind also noticed this effect of counterion during the addition of imines to 41 (Table 18).

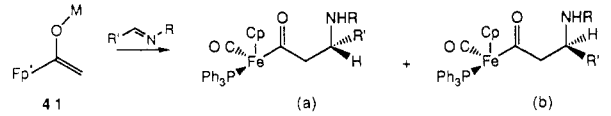
Davies[76] has employed the remarkable stereoselectivity of these reactions in the synthesis of diastereomerically pure 1-hydoxypyrrolizidin-3-ones after a single recrystallization (eq 15).



(15)

The enolate derived from Fp*-$COCH_2CH_3$ (42) has also been found to undergo highly selective aldol condensations to form, after demetalation, *threo*- or *erythro*-α-methyl-β-hydroxy carboxylic acids depending on the metal counterion employed and the steric bulk of the aldehyde (Table 19).[78]

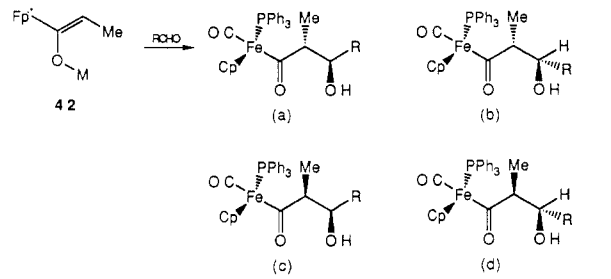
TABLE 18. Asymmetric Addition of Imines to 41



M	(E)-Imine	Temp(°C)	Ratio a:b	Ref.
Li	PhCH=NPh	-42	5.5 : 1	75
Li	PhCH=NPh	-78	12.2 : 1	75
Li	PhCH=NPh	-78	100 : 1	76[a]
$AlEt_2$	PhCH=NPh	-42	5.7 : 1	75
$AlEt_2$	PhCH=N^{n}Pr	-42	>20 : 1	75
$AlEt_2$	^{i}PrCH=N^{n}Pr	-42	>20 : 1	75
$AlEt_2$	PhCH=N-cC_6H_7	-42	>20 : 1	75
$AlEt_2$	^{i}PrCH=N-cC_6H_7	-42	>20 : 1	75

[a] This disparity may be due to differences in reaction conditions employed by Davies.

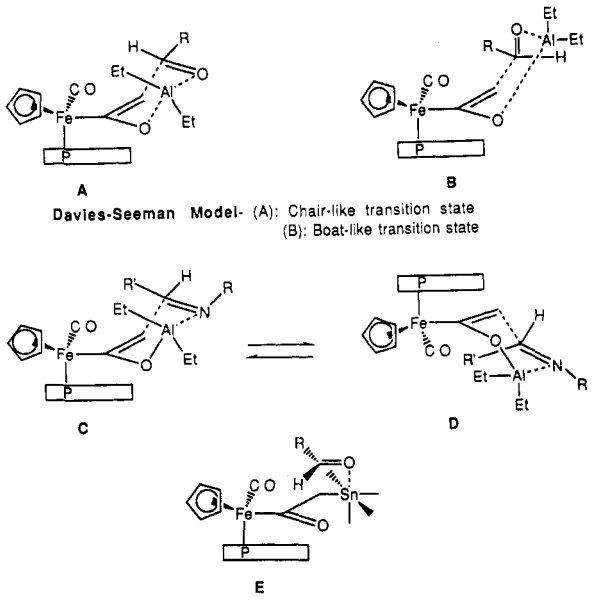
TABLE 19. Asymmetric Aldol Condensations of 42[78]



RCHO	M	Temp(°C)	a	b	c	d
MeCHO	$AlEt_2$	-100	100	-	7	3
MeCHO	CuCN	-78	14	100	<1	-
EtCHO	$AlEt_2$	-100	100	-	14	-
EtCHO	CuCN	-78	10	100	<1	-
^{i}PrCHO	$AlEt_2$	-100	100	-	10	<1
^{i}PrCHO	CuCN	-78	7	100	<1	-
^{t}BuCHO	$AlEt_2$	-100	100	-	-	-
^{t}BuCHO	CuCN	-78	4	100	-	-
PhCHO	CuCN	-78	4	100	<1	-

From these examples it can be seen that the nature of the metal counterion has a profound effect on the stereochemical outcome of the reaction. By changing from an aluminum to a copper or tin enolate, opposite stereoselectivity is obtained. Models to explain these observations have been proposed by Davies and Seeman,[79] with Liebeskind proposing some modifications.[80] Simply speaking, these models state that reactions of enolate 41 will occur on the face away from the bulky triphenylphosphine ligand. The Davies–Seeman model also assumes that reaction occurs at the α-carbon only from the anti (oxygen to carbonyl) conformation since the cyclopentadienyl ring effectively blocks the enolate oxygen. The chair conformation (Figure 18A) produces a steric interaction between the alkyl groups on aluminum and the Cp ring which is relieved in the boat conformation (Figure 18B). The aldehyde substituent R assumes an equatorial position to relive any 1,3-diaxial interactions, so conformation B becomes the preferred mode of attack.

Liebeskind, however, did not feel that this model alone could explain the results he obtained in the imine system (Table 18). The effect of the size of the substituent R′ on these (*E*)-imines suggested to him two

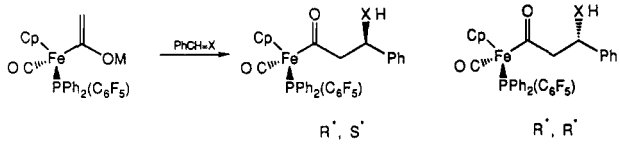


Davies-Seeman Model- (A): Chair-like transition state
(B): Boat-like transition state

Liebeskind Model- (C) and (D): Aluminum enolate equilibrium
(E): C-metallated tin enolate transition state

Figure 18. Proposed models for the reaction of enolate 41.

TABLE 20. Condensations of Chiral Iron Enolate Possessing a Pentafluorophenyl Phosphine Ligand[84]



X	M	%Yield	R'S' : R'R'
O	Li	88	60 : 1
O	SnCl	88	35 : 1
O	$AlEt_2$	63	8 : 1
O	Cu	51	7 : 1
O	$Li/SnCl_2$	47	80 : 1[a]
O	Li/BF_3OEt_2	61	80 : 1[a]
O	$Li/AlClEt_2$	58	80 : 1[a]
NPh	Li	65	25 : 1
NPh	SnCl	70	10 : 1
NPh	$AlEt_2$	62	30 : 1
NPh	Cu	73	8 : 1
NPh	$Li/SnCl_2$	78	30 : 1[a]
NPh	Li/BF_3OEt_2	72	30 : 1[a]
NPh	$Li/AlClEt_2$	92	50 : 1[a]

[a] Reaction of the lithium enolate of the iron complex with a solution of PhCH=X and the Lewis acid.

competing transition states. He proposed two chair-like transition states (Figure 18C,D) of both the syn and anti conformations of the enolate. In this case, the interaction between R′ and either CO (anti) or Cp (syn) governs which transition state is preferred, and therefore the extent of the stereoselectivity observed. Liebeskind also states that the change in stereoselectivity with tin enolates may be due to a significant concentration of the C-metalated species (Figure 18E).

This methodology has been utilized by both groups in the synthesis of β-lactams.[75,76,81] Other applications include Michael addition/alkylation sequences forming substituted acids, esters, and amides,[81] stereoselective α-alkylation of chiral dienolates,[82] and asymmetric synthesis of phenyl alkyl sulfoxides.[83] Recent work in this area has involved a study of the effect of the phosphine ligand of Fp* on the stereoselectivity of reactions (Tables 20[84] and 21[85]).

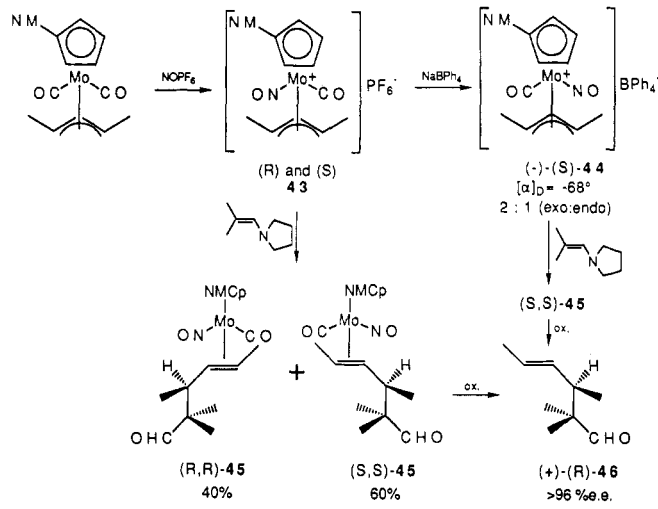


Figure 19. Resolution and reaction of an optically active π-allyl-molybdenum complex.[86]

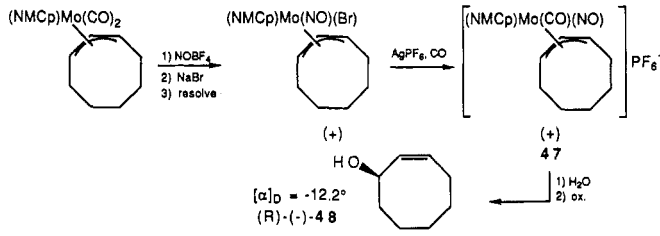
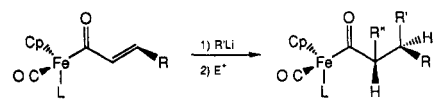


Figure 20. Synthesis, resolution, and reaction of a chiral π-allyl cyclooctenyl-molybdenum complex.[87]

TABLE 21. Protonation and Alkylation of a Chiral Iron Complex Bearing a Variety of Phosphine Ligands[85]



L	R	R'	E^+	R''	%Yield	Diastereoselectivity
PPh_3	Me	Ph	H_2O	H	87	29 : 1
$P(pCF_3C_6H_5)_3$	Me	Ph	H_2O	H	84	39 : 1
PMe_2Ph	Me	Ph	H_2O	H	76	18 : 1
PMe_2Ph	Me	Ph	MeI	Me	72	24 : 1
PMe_2Ph	Ph	Me	H_2O	H	63	32 : 1
P^nBu_3	Me	Ph	H_2O	H	71	11 : 1
P^nBu_3	Ph	Me	H_2O	H	15	22 : 1
$P(OPh)_3$	Me	Ph	H_2O	H	0	-

C. Chiral Molybdenum Complexes

Similar to the chiral iron–acyl complexes, π-allyl–molybdenum compounds become chiral with four different ligands on the metal—cyclopentadienyl, nitrosyl, carbonyl, and the allyl moiety itself. Faller[86] has developed a method whereby introduction of a neomenthyl (NM) group on the cyclopentadienyl ring yields a mixture of diastereomers from which a single enantiomer, (*S*)-44, can be isolated as its tetraphenylborate salt. Alternatively, reaction of a mixture of (*R*)- and (*S*)-43 with 1-pyrrolidinyl-2-methylpropene yields a diastereomeric mixture of products that are easily separated (Figure 19). After removal of the metal by mild air oxidation, (+)-2,2,3-trimethylhex-4-enal (46) can be obtained through either route. The high selectivity obtained even with a mixture of *exo*- and *endo*-45 is attributed to a much faster addition to the exo isomer combined with a nucleophile-catalyzed interconversion from the endo to the exo isomer.[86]

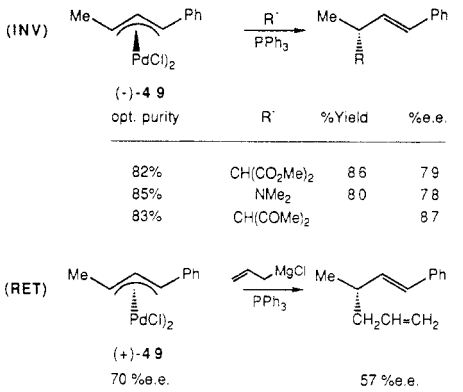
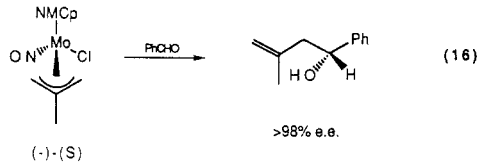


Figure 21. Alkylation of optically enriched allyl–palladium dimer.[89,90]

Similarly, addition of hydroxide to optically active (η^3-cyclooctenyl)–molybdenum complex **47** [from resolved (NMCp)Mo(NO)(CO)(Br)(C_8H_{13})] proceeds with a high degree of selectivity to give (−)-(*R*)-3-hdyroxycyclooctene (**48**) in 93% ee (Figure 20).[87]

Recently, Faller[88] has employed similar compounds in an asymmetric aldol reaction to give optically active secondary homoallylic alcohols (eq 16).

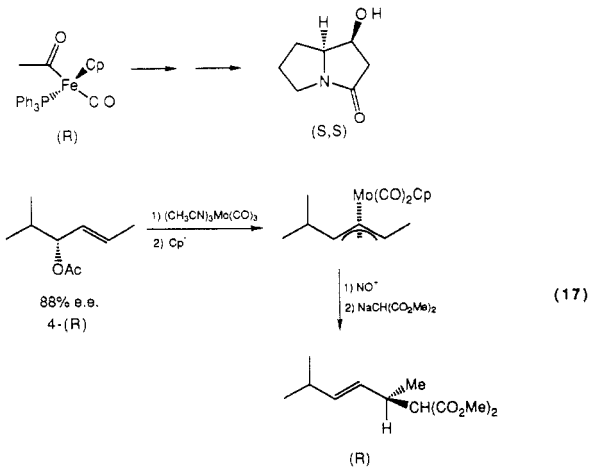


(16)

V. Chiral Olefin–Metal Templates

This section deals with the use of chiral olefin–metal π-complexes in which the asymmetry is defined by the coordination of a metal moiety to the olefin. In some cases, as with the palladium complex in Figure 21, the organic ligand is initially chiral and this optical activity is maintained through the stereoselective complexation of the metal. With compound **49**, nucleophilic attack directly on the fact of the allyl ligand opposite to palladium results in overall inversion, while retention results from attack first on the metal center followed by transfer to the allyl moiety on the same face as palladium.[89-91]

Allylic alkylation of chiral π-allyl–molybdenum complexes maintains the optical purity of the original allyl through stereoselective complexation and alkylation (eq 17).[92]



(17)

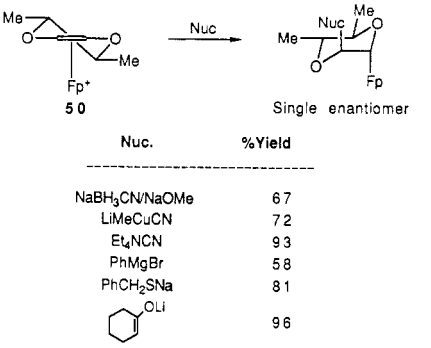


Figure 22. Stereospecific alkylation of a chiral iron–Fp complex.[93]

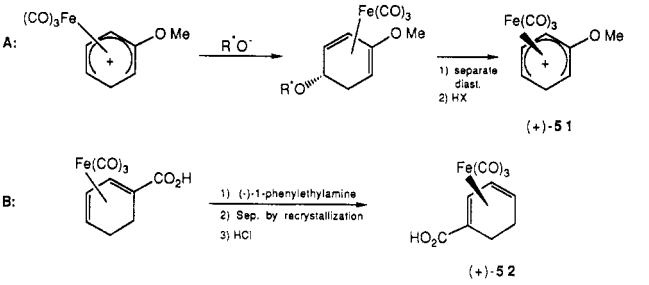


Figure 23. Methods of resolution for diene–iron complexes.

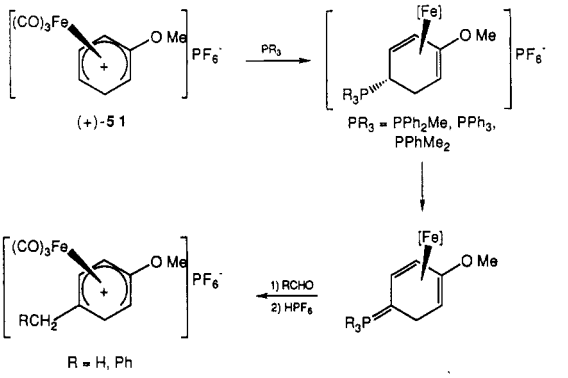


Figure 24. Synthesis of chiral 5-alkyl iron–dienyl salts.[96]

Alkylation of optically pure olefin-Fp [Fp = (η^5-cyclopentadienyl)dicarbonyliron] **50** with a variety of nucleophiles proceeds stereospecifically in good to excellent yields to give a single diastereomer (Figure 22).[93]

Tricarbonyliron complexes of unsymmetrically substituted diene or dienyl systems are chiral since the metal moiety occupies a single face of the organic ligand. Recent developments in the resolution of these types of chiral complexes[94,95] have led to several applications to asymmetric organic synthesis. Resolution can be achieved either by addition of a chiral nucleophile to a racemic dienyl salt followed by separation of the resulting diastereomers and regeneration of the starting salt (Figure 23A) or by direct classical resolution of an appropriately substituted diene complex through its phenylethylammonium salt (Figure 23B).

From the optically pure salt **51**, Howell[96] has been able to synthesize 5-alkyl-substituted derivatives through addition of a phosphine followed by Wittig reaction and protonation with overall retention of configuration (Figure 24).

Birch has applied chiral iron complexes in the synthesis of (−)- and (+)-gabaculine (Figure 25).[95] The stereospecificity of nucleophilic addition to these types of complexes and the regiospecificity of hydride ab-

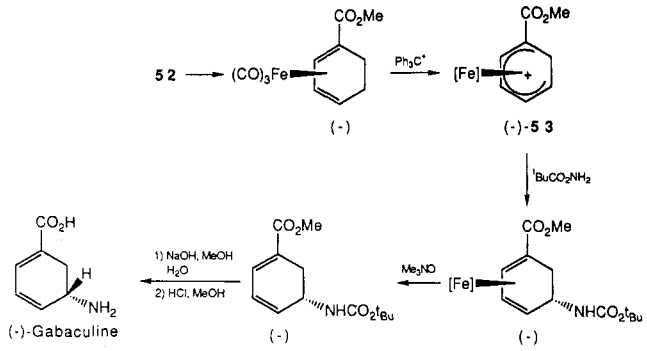


Figure 25. Synthesis of (−)-gabaculine via a chiral iron complex.[95]

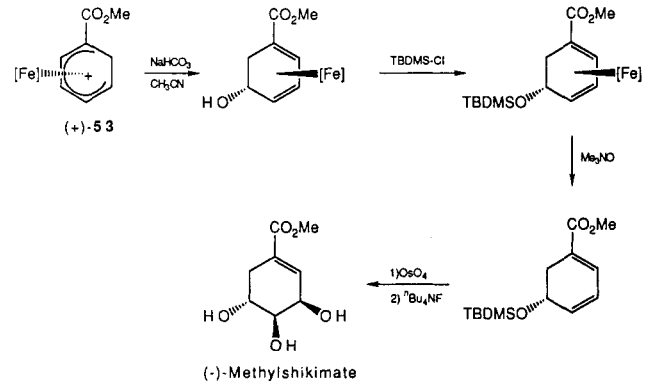
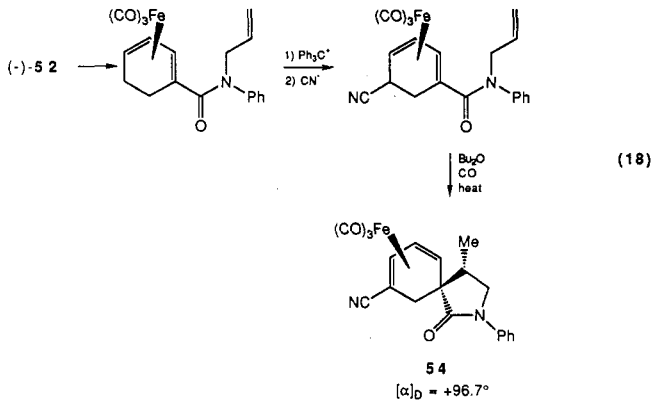


Figure 26. Synthesis of (−)-methyl shikimate via a chiral iron complex.[97]

straction maintain the stereochemical integrity of the species throughout the sequence.

Birch has also employed this methodology in the synthesis of (+)- and (−)-methylshikimate (Figure 26).[97]

Pearson and Zettler[98] have shown that **52** can be manipulated to give optically pure spirolactam **54** in a coupling reaction equivalent to an intramolecular [6 + 2] ene reaction (eq 18).



(18)

Resolution of acyclic diene–iron complex **55**[99] has led to its use in the total synthesis of (−)-verbenalol and (−)-epiverbenalol (Figure 27).[100]

Davies[101] has used a chromium tricarbonyl template to effect the stereospecific synthesis of (−)-(8*R*)- and (−)-(8*S*)-methylcanadine (Figure 28).

The demonstrated utility of these types of complexes, particularly iron,[2,102,103] in organic synthesis combined with the availability of optically pure material and the aforementioned stereospecificity of reactions potentially makes this an extremely useful and powerful methodology for asymmetric synthesis.

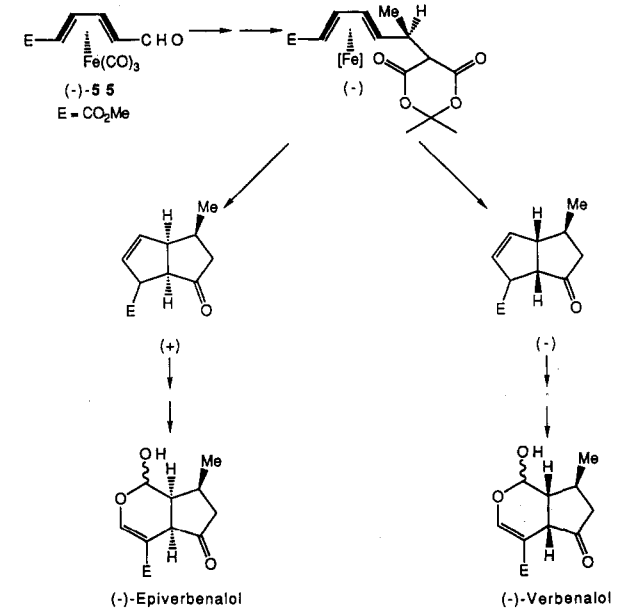


Figure 27. Synthesis of (−)-verbenalol and (−)-epiverbenalol via a common chiral iron complex.[100]

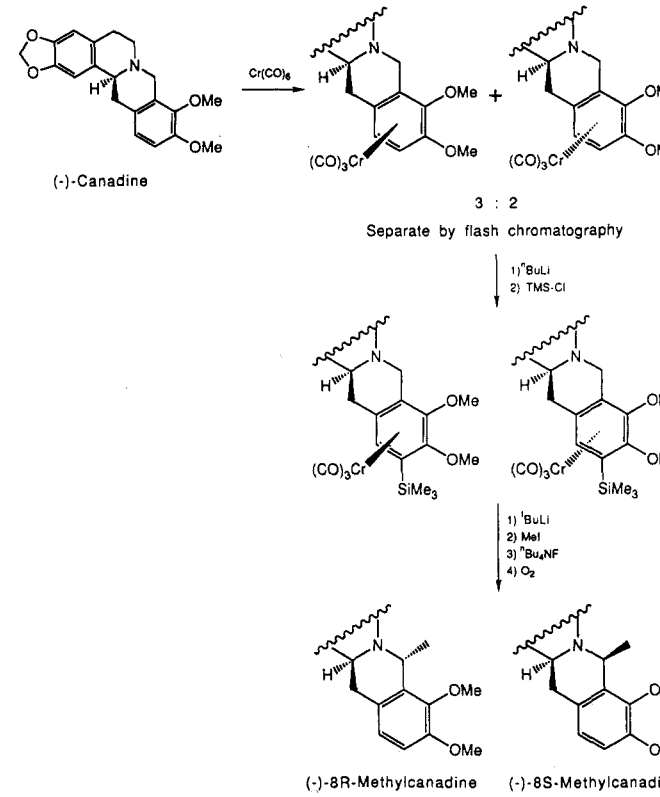


Figure 28. Synthesis of 8(*R*)- and 8(*S*)-methylcanadine via an organochromium complex template.[101]

VI. Use of Chiral Nucleophiles

It can be seen from the discussion thus far that an organometallic chemist's first reaction in adapting or developing an organometallic procedure for asymmetric applications is to add a chiral phosphine ligand. While this has been highly successful, especially for hydrogenations, it is somewhat limited. Most other work in this area that does not involve the use of chiral phosphine ligands has concentrated on the synthesis and resolution of chiral organometallic complexes. An entire area that has received little attention, except for reso-

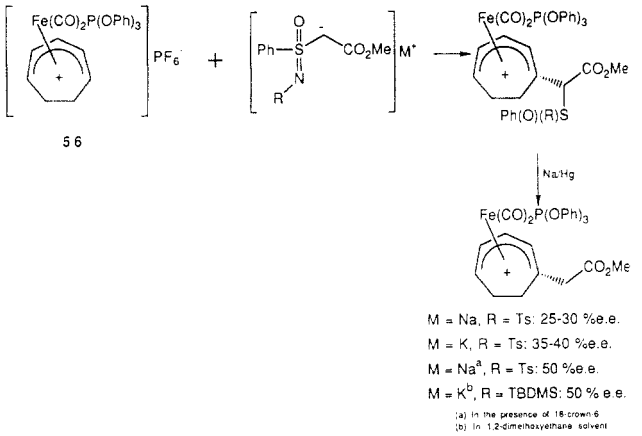
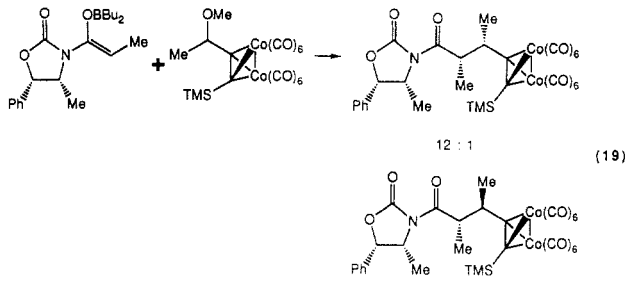


Figure 29. Asymmetric addition of a chiral sulfoximinyl enolate nucleophile to a prochiral iron complex.[105,106]

lution purposes, is the addition of a chiral *nucleophile* to an organometallic species. In his study of dicobalt hexacarbonyl–propargyl cations, Schreiber reacted a racemic propargyl complex with Evan's chiral boron enolate, observing a high degree of diastereoselectivity (eq 19).[104] In this case, both the chiral nucleophile and

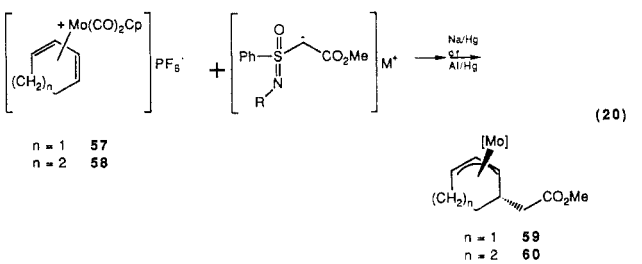


(19)

the metal complex have a preferred mode of attack. Regarding the cation, Schreiber indicates that the stereochemistry of the resulting products is consistent with a rapid (relative to alkylation) alkylidene ligand migration from one $Co(CO)_3$ center to the other. Each cation then reacts at a different rate, effecting a kinetic resolution, the least sterically demanding reacting faster to give the observed syn-alkylated product.

Pearson and Yoon[105,106] have reported the addition of a chiral enolate nucleophile to symmetrical iron–dienyl complex **56**, generating, after removal of the sulfoximine moiety, an ester-substituted diene complex in up to 50% ee, depending upon reaction conditions (Figure 29).

As with the iron–dienyl cases, addition of chiral sulfoximine ester enolates to achiral organomolybdenum complexes proceeds in asymmetric fashion to yield an optically active monosubstituted π-allyl complex (eq 20).[106,107] These organomolybdenum complexes, however, with *N*-trialkylsilyl-substituted sulfoximines proceed with high enantiomeric excess (up to 89% ee) (Table 22).



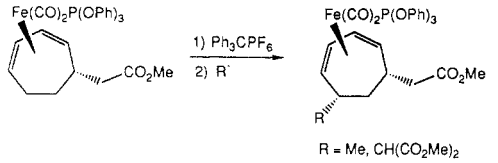
(20)

TABLE 22. Asymmetric Addition of Sulfoximinyl Ester Enolates to Organomolybdenum Complexes 56 and 57[106,107]

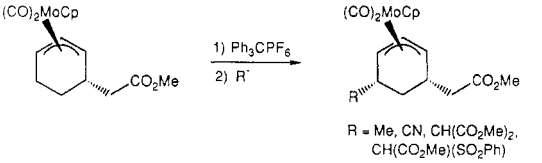
Starting Complex	R(enant.)	M	Monoester product (yield)	%e.e.
57	Ts (+)	Na	59 (77)	12-14
57	Me (+)	Na	59 (45)	35
57	TBDMS (+)	Na	59 (75)	75
57	DMTS (-)	Na	59 (83)	75
58	Ts (+)	K	60 (70)	49
58	TBDMS (+)	Na	60 (77)	86
58	DMTS (-)	Na	60 (83)	89

Some general features of this reaction can be noted from Figure 28 and Table 22. The iron–dienyl complexes seem to be most dependent on the method in which the suloximine enolate is generated (i.e., solvent, couterion), while the diene–molbydenum complexes appear to be most affected by the N-substituent of the sulfoximine (i.e., tosyl, alkyl, silyl). The reasons for these dependencies and for the difference in them from the iron to molybdenum systems are unclear at this point.[106]

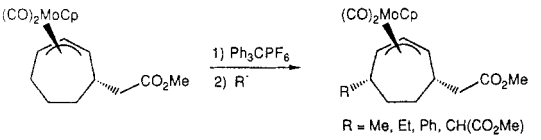
The value of these types of complexes to traditional organic synthesis, as mentioned previously, has already been demonstrated.[2,10] As with racemic compounds, optically enriched complexes from the above procedure can undergo hydride abstraction and addition of a second nucleophile without destruction of the stereocenter already established (eq 21–23). This method, then, generates two centers of 1,3- or 1,4-relationship with defined relative and absolute stereochemistry. Although complete stereospecificity (absolute) has not yet been achieved and the chiral auxiliary is destroyed when removing it from the complex, the success achieved thus far in this new area bodes well for further study.



(21)



(22)



(23)

VII. Concluding Remarks

As is evident from the preceding, the use of organometallics for enantioselective synthesis has great potential for being a very powerful tool. As the trend in chemistry, as in other disciplines, is going more and more for specificity, whether in the alkylation of an organic molecule or the development of a specific substrate for a specific protein, the uses of this exciting field will become ever more apparent. New ligands for catalytic reactions, the development of new catalytic processes, and increased use of stoichiometric organo-

metallic procedures are active areas of research where new and exciting results are being achieved at an ever increasing rate.

List of Abbreviations Used in This Review

ACMP	*o*-anisylcyclohexylmethylphosphine
Alaphos	2-(dimethylamino)-1-(diphenylphosphino)propane
Binap	2,2′-bis(diphenylphosphino)-1,1′-binaphthyl
BinapO	2,2′-bis(diphenylphosphino)-1,1′-binaphthyl
BPPFA	*N*,*N*-dimethyl-1-[1′,2-bis(diphenylphosphino)ferrocenyl]ethylamine
BPPM	*N*-(*tert*-butoxycarbonyl)-4-(diphenylphosphino)-2-[(diphenylphosphino)methyl]pyrrolidine
Camphos	1,2,2-trimethyl-1,3-bis[(diphenylphosphino)methyl]cyclopentane
Chglyphos	1-(dimethylamino)-1-cyclohexyl-2-(diphenylphosphino)ethane
Chiraphos	2,3-bis(diphenylphosphino)butane
Cp	η^5-cyclopentadienyl
DIOP	2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphino)butane
DIPAMP	1,2-bis[(*o*-methoxyphenyl)phenylphosphino]ethane
DIPHOL	isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphino)butane
DIPHOS	1,2-bis(diphenylphosphino)ethane
DMIP	dimenthylisopropylphosphine
DPPPE	1,2-bis(diphenylphosphino)-1-phenylethane
FcPN	1-[(dimethylamino)methyl]-2-(diphenylphosphino)ferrocene
Fp	(η^5-cyclopentadienyl)dicarbonyliron
Fp*	carbonyl(η^5-cyclopentadienyl)(triphenylphosphine)iron
Ilephos	2-(dimethylamino)-3-methyl-1-(diphenylphosphino)pentane
Leuphos	2-(dimethylamino)-4-methyl-1-(diphenylphosphino)pentane
^{t}Leuphos	2-(dimethylamino)-3,3-dimethyl-1-(diphenylphosphino)butane
NM	neomenthyl
Norphos	2,3-bis(diphenylphosphino)bicyclo[2.2.1]hept-5-ene
OBP	tris(*O*-biphenyl) phosphite
Phephos	2-(dimethylamino)-3-phenyl-1-(diphenylphosphino)propane
Phglyphos	1-(dimethylamino)-1-phenyl-2-(diphenylphosphino)ethane
PPEF	1-(diphenylphosphino)-2-ethylferrocene
PPFA	*N*,*N*-dimethyl-1-[2-(diphenylphosphino)-ferrocenyl]ethylamine
Prophos	2,3-bis(diphenylphosphino)propane
Tf	trifluoromethanesulfonate
Valphos	2-(dimethylamino)-3-methyl-1-(diphenylphosphino)butane

References

(1) (a) Pearson, A. J. *Metallo-Organic Chemistry*; Wiley: New York, 1985. (b) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987. (c) Davies, S. G. *Organotransition Metal Chemistry: Applications to Organic Synthesis*; Pergamon Press: Oxford, England, 1982.

(2) (a) Pearson, A. J.; Ray, T. *Tetrahedron* **1984**, *41*, 5765. (b) Birch, A. J.; Cross, P. E.; Lewis, J.; White, D. A.; Wild, S. B. *J. Chem. Soc. C* **1968**, 332. (c) Birch, A. J.; Parson, A. J. *Tetrahedron Lett.* **1975**, 2379. (d) Bandara, B. M. R.; Birch, A. J.; Khor, T.-C. *Tetrahedron Lett.* **1980**, *21*, 3625. (e) Pearson, A. J.; Kole, S. L.; Ray, T. *J. Am. Chem. Soc.* **1984**, *106*, 6060. (f) Pearson, A. J.; Ong, C. W. *J. Org. Chem.* **1982**, *47*, 3780.

(3) Clebuski, J.; Rosenblum, M. *Tetrahedron* **1985**, *41*, 5741.

(4) Noyori, R.; Hayakawa, Y. *Tetrahedron* **1985**, *41*, 5879.

(5) Glass, R. S.; McConnell, W. W.; Andruski, S. W. *J. Org. Chem.* **1986**, *51*, 5123.

(6) Takacs, J. M.; Anderson, L. G. *J. Am. Chem. Soc.* **1987**, *109*, 2200.

(7) Barrett, A. G. M.; Sturgess, M. A. *J. Org. Chem.* **1987**, *52*, 3940.

(8) Sutherland, R. G.; Chowdhury, R. L.; Piorko, A.; Lee, C. C. *J. Org. Chem.* **1987**, *52*, 4618.

(9) (a) VanArsdale, W. E.; Winter, R. E. K.; Kochi, J. K. *Organometallics* **1983**, *5*, 645. (b) Faller, J. W.; Rosan, A. M. *Ann. N.Y. Acad. Sci.* **1977**, *295*, 186. (c) VanArsdale, W. E.; Winter, R. E. K.; Kochi, J. K. *J. Organomet. Chem.* **1985**, *296*, 31.

(10) (a) Faller, J. W.; Murray, H. H.; White, D. L.; Chao, K. H. *Organometallics* **1983**, *2*, 400. (b) Green, M.; Greenfield, S.; Kersting, M. *J. Chem. Soc., Chem. Commun.* **1985**, *18*. (c) Pearson, A. J.; Khan, M. N. I.; Clardy, J. C.; Cun-heng, H. *J. Am. Chem. Soc.* **1985**, *107*, 2748. (d) Pearson, A. J.; Khan, M. N. I. *J. Org. Chem.* **1985**, *50*, 5276.

(11) Burkhardt, E. R.; Doney, J. J.; Bergman, R. G.; Heathcock, C. H. *J. Am. Chem. Soc.* **1987**, *109*, 2022.

(12) Trost, B. M.; Lautens, M. *J. Am. Chem. Soc.* **1987**, *109*, 1469.

(13) Mawby, A.; Walker, P. J. C.; Mawby, R. J. *J. Organomet. Chem.* **1973**, *55*, C39.

(14) Pearson, A. J.; Richards, I. C. *J. Organomet. Chem.* **1983**, *258*, C41.

(15) Pearson, A. J.; Bruhn, P. R.; Richards, I. C. *Tetrahedron Lett.* **1984**, *25*, 387.

(16) (a) Semmelhack, M. F.; Bozell, J. J.; Keller, L.; Sato, T.; Spiess, E. J.; Wulff, W.; Zask, A. *Tetrahedron* **1985**, *41*, 5803. (b) Yamashita, A. *Tetrahedron Lett.* **1986**, *27*, 5915. (c) Xu, Y.-C.; Wulff, W. D. *J. Org. Chem.* **1987**, *52*, 3263. (d) Wulff, W. D.; Xu, Y.-C. *Tetrahedron Lett.* **1988**, *29*, 415. (e) Peterson, G. A.; Kunng, F. A. McCallum, J. S.; Wulff, W. D. *Tetrahedron Lett.* **1987**, *28*, 1381.

(17) (a) Hegedus, L. S.; Schultze, L. M.; Toro, J.; Yijun, C. *Tetrahedron* **1985**, *41*, 5833. (b) Borel, C.; Hegedus, L. S.; Krebs, J.; Satoh, Y. *J. Am. Chem. Soc.* **1987**, *109*, 1101.

(18) Bragg, J.; Davies, S. G.; Goodfellow, C. L.; Sutton, K. H. *J. Chem. Soc., Perkin Trans. 1* **1987**, 1805.

(19) (a) Pauson, P. L. *Tetrahedron* **1985**, *41*, 5855. (b) Magnus, P.; Exon, C.; Albaugh-Robertson, P. *Tetrahedron* **1985**, *41*, 5861. (c) Magnus, P.; Principe, L. M.; Slater, M. J. *J. Org. Chem.* **1987**, *52*, 1483. (d) Sampath, V.; Lund, E. C.; Knudsen, M. J.; Olmstead, M. M.; Schore, N. E. *J. Org. Chem.* **1987**, *52*, 3595. (e) Krafft, M. E. *J. Am. Chem. Soc.* **1988**, *110*, 968.

(20) Liebeskind, L. S.; Chidambaram, R. *J. Am. Chem. Soc.* **1987**, *109*, 5025.

(21) Chiba, K.; Mori, M.; Ban, Y. *Synthesis* **1985**, 387.

(22) Backvall, J. E.; Bystrom, S. E.; Nystrom, J. E. *Tetrahedron* **1985**, *41*, 5761.

(23) (a) Trost, B. M.; Genet, J. P. *J. Am. Chem. Soc.* **1976**, *98*, 8516. (b) Trost, B. M.; Godleski, S. A.; Genet, J. P. *J. Am. Chem. Soc.* **1975**, *100*, 3930.

(24) (a) Carruthers, W.; Cummings, S. A. *J. Chem. Soc., Chem. Commun.* **1983**, 3930. (b) Godleski, S. A.; Heacock, D. J.; Meinhardt, J. D.; Wallendael, S. V. *J. Org. Chem.* **1983**, *48*, 2101.

(25) Clough, J. M.; Mann, I. S.; Widdowson, D. A. *Tetrahedron Lett.* **1987**, *28*, 2645.

(26) Stille, J. K.; Simpson, J. H. *J. Am. Chem. Soc.* **1987**, *109*, 2138.

(27) Trost, B. M.; Jebaratram, D. J. *Tetrahedron Lett.* **1987**, *28*, 1611.

(28) Hegedus, L. S.; Toro, J. L.; Miles, W. H.; Harrington, P. J. *J. Org. Chem.* **1987**, *52*, 3319.

(29) (a) Tani, K.; Yamagat, T.; Akutagawa, S.; Kumobayashi, H.; Taketomi, T.; Takaya, H.; Miyashita, A.; Noyori, R.; Otsuka, S. *J. Am. Chem. Soc.* **1984**, *106*, 5208. (b) Tani, K.; Yamagata, T.; Tatsuno, Y.; Yamagata, Y.; Tomita, K.-I.; Akutagawa, S.; Kumobayashi, H.; Otsuka, S. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 217.

(30) (a) Kagan, H. B.; Frian, J. C. *Top. Stereochem.* **1977**, *10*. (b) Morrison, J. D.; Masler, W. F.; Neuberg, M. K. *Adv. Catal.* **1976**, *25*, 81. (c) Kagan, H. B. *Pure Appl. Chem.* **1975**, *43*, 401. (d) Morrison, J. D.; Masler, W. F.; Hathaway, S. *Cata-*

lysis in Organic Synthesis; Academic Press: Orlando, FL, 1976. (e) Marko, L.; Heil, B. *Catal. Rev.* **1974**, *8*, 269. (f) Valentine, D.; Scott, J. W. *Synthesis* **1978**, 329. (g) Bodanovic, B. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 954. (h) Brunner, H. *J. Organomet. Chem.* **1986**, *300*, 39. (i) Bosnich, B.; Fryzuk, M. D. *Top. Stereochem.* **1981**, *12*, 119. (j) Pino, P.; Consiglio, G. *Pure Appl. Chem.* **1983**, *55*, 1781. (k) Morrison, J. D., Ed. *Asymmetric Synth.* **1985**, *5*. (l) Brunner, H. *Synthesis* **1988**, 645.

(31) (a) Horner, L.; Seigel, H.; Buthe, H. *Angew. Chem., Int. Ed. Engl.* **1968**, *7*, 942. (b) Knowles, W. S.; Sabacky, M. J. *J. Chem. Soc., Chem. Commun.* **1968**, 1445.

(32) Knowles, W. S.; Sabacky, M. J.; Vineyard, B. D.; Weinkauff, D. J. *J. Am. Chem. Soc.* **1975**, *97*, 2567.

(33) Brunner, H. *J. Organomet. Chem.* **1986**, *300*, 39.

(34) Bosnich, B.; Fryzuk, M. D. *Top. Stereochem.* **1981**, *12*, 119.

(35) Halpern, J. *Asymmetric Synth.* **1985**, *5*, 41.

(36) Koenig, K. E. *Asymmetric Synth.* **1985**, *5*, 71.

(37) Kiyamura, M.; Kasahara, I.; Manabe, K.; Noyori, R.; Takaya, H. *J. Org. Chem.* **1988**, *53*, 708.

(38) (a) Kagan, H. B.; Frian, J. C. *Top. Stereochem.* **1977**, 10. (b) Morrison, J. D.; Masler, W. F.; Neuberg, M. K. *Adv. Catal.* **1976**, *25*, 81. (c) Kagan, H. B. *Pure Appl. Chem.* **1975**, *43*, 401. (d) Morrison, J. D.; Masler, W. F.; Hathaway, S. *Catalysis in Organic Synthesis*; Academic Press: Orlando, FL, 1976. (e) Marko, L.; Heil, B. *Catal. Rev.* **1974**, *8*, 269. (f) Valentine, D.; Scott, J. W. *Synthesis* **1978**, 329. (g) Bogdanovic, B. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 954. (h) Pimo, P.; Consiglio, G. *Pure Appl. Chem.* **1983**, *55*, 1781.

(39) Kitamura, M.; Ohkuma, T.; Inoue, S.; Sayo, N.; Kumobayashi, H.; Akutagawa, S.; Ohta, T.; Takaya, H.; Noyori, R. *J. Am. Chem. Soc.* **1988**, *110*, 629.

(40) Kawano, H.; Ishii, Y.; Saburi, M.; Uchida, Y. *J. Chem. Soc., Chem. Commun.* **1988**, 87.

(41) Ojima, I.; Hirai, K. *Asymmetric Synth.* **1985**, *3*, 103.

(42) Mutez, S.; Mortreux, A.; Petit, F. *Tetrahedron Lett.* **1988**, *29*, 1911.

(43) Hayashi, T.; Kumada, M. *Asymmetric Synth.* **1985**, *5*, 147.

(44) (a) Consiglio, G.; Botteghi, C. *Helv. Chim. Acta* **1973**, *56*, 460. (b) Kiso, Y.; Tamao, K.; Miyake, N.; Yamamoto, K.; Kumada, M. *Tetrahedron Lett.* **1974**, *15*, 3.

(45) Hayashi, T.; Konishi, M.; Fukushima, M.; Kanehira, K.; Hioki, T.; Kumada, M. *J. Org. Chem.* **1983**, *48*, 2195.

(46) Hayashi, T.; Konishi, M.; Fukushima, M.; Mise, T.; Kagotani, M.; Tajika, M.; Kumada, M. *J. Am. Chem. Soc.* **1982**, *104*, 180.

(47) Hayashi, T.; Konishi, M.; Ito, H.; Kumada, M. *J. Am. Chem. Soc.* **1982**, *104*, 4692.

(48) Dobler, C.; Kreuzfeld, H.-J. *J. Organomet. Chem.* **1988**, *344*, 249.

(49) (a) Cherest, M.; Umpley, J. D.; Felkin, H. *J. Chem. Soc., Chem. Commun.* **1981**, 681. (b) Consiglio, G.; Morardini, F.; Piccolo, O. *Helv. Chim. Acta* **1980**, *63*, 987.

(50) Jacobsen, E. N.; Marko, I.; Mungall, W. S.; Schroder, G.; Sharpless, K. B. *J. Am. Chem. Soc.* **1988**, *110*, 1968.

(51) For leading references on palladium in organic synthesis see: (a) Trost, B. M. *Tetrahedron* **1977**, *33*, 2615. (b) Trost, B. M.; Verhoeven, T. R. *Compr. Organomet. Chem.* **1982**, *8*, 799. (c) Heck, R. F. *Palladium Reagents in Organic Synthesis*; Academic Press: New York, 1985.

(52) Trost, B. M.; Dietsche, T. S. *J. Am. Chem. Soc.* **1973**, *95*, 8200.

(53) Trost, B. M.; Strege, P. E. *J. Am. Chem. Soc.* **1977**, *99*, 1649.

(54) Trost, B. M.; Murphy, D. J. *Organometallics* **1985**, *4*, 1143.

(55) Bosnich, B.; Mackenzie, P. B. *Pure Appl. Chem.* **1982**, *54*, 189.

(56) Yamamoto, K.; Tsuji, J. *Tetrahedron Lett.* **1982**, *23*, 3089.

(57) Hayashi, T.; Kanehira, K.; Hagihara, T.; Kumada, M. *J. Org. Chem.* **1988**, *53*, 113.

(58) Hayashi, T.; Yamamoto, A.; Ito, Y. *Tetrahedron Lett.* **1988**, *29*, 669.

(59) Hayashi, T.; Yamamoto, A.; Ito, Y. *Tetrahedron Lett.* **1988**, *29*, 99.

(60) (a) Ito, Y.; Sawamura, M.; Hayashi, T. *Tetrahedron Lett.* **1987**, *28*, 6125. (b) Ito, Y.; Sawamura, M.; Shirakawa, E.; Hayashizaki, K.; Hayashi, T. *Tetrahedron Lett.* **1988**, *29*, 235.

(61) Ito, Y.; Sawamura, M.; Hayashi, T. *Tetrahedron Lett.* **1988**, *29*, 239.

(62) (a) Kiel, W. A.; Lin, G.-Y.; Constable, A. G.; McCormick, F. B.; Strouse, C. E.; Eisenstein, O.; Gladysz, J. A. *J. Am. Chem. Soc.* **1982**, *104*, 4865. (b) Constable, A. G.; Gladysz, J. A. *J. Organomet. Chem.* **1980**, *202*, C21.

(63) Merrifield, J. H.; Strouse, C. E.; Gladysz, J. A. *Organometallics* **1982**, *1*, 1204.

(64) Fernandez, J. M.; Gladysz, J. A. *Inorg. Chem.* **1986**, *25*, 2674.

(65) (a) Merrifield, J. H.; Lin, G.-Y.; Kiel, W. A.; Gladysz, J. A. *J. Am. Chem. Soc.* **1983**, *105*, 5811. (b) Wong, A.; Gladysz, J. A. *J. Am. Chem. Soc.* **1982**, *104*, 4948.

(66) (a) Bodner, G. S.; Smith, D. E.; Hatton, W. G.; Heah, P. C.; Georgiou, S.; Rheingold, A. L.; Geib, S. J.; Hutchinson, J. P.; Gladysz, J. A. *J. Am. Chem. Soc.* **1987**, *109*, 7688. (b) Kiel, W. A., Lin, G.-Y.; Bodner, G. S.; Gladysz, J. A. *J. Am. Chem. Soc.* **1983**, *105*, 4958. (c) Georgiou, S.; Gladysz, J. A. *Tetrahedron* **1986**, *42*, 1109. (d) Kiel, W. A.; Buhro, W. E.; Gladysz, J. A. *Organometallics* **1984**, *3*, 879.

(67) O'Conner, E. J.; Kobayashi, M.; Floss, H. G.; Gladysz, J. A. *J. Am. Chem. Soc.* **1987**, *109*, 4837.

(68) (a) Fernandez, J. M.; Emerson, K.; Larsen, R. D.; Gladysz, J. A. *J. Chem. Soc., Chem. Commun.* **1988**, 37. (b) Fernandez, J. M.; Emerson, K.; Larsen, R. H.; Gladysz, J. A. *J. Am. Chem. Soc.* **1986**, *108*, 8268.

(69) (a) Davidson, A.; Krusell, W. C.; Michaelson, R. C. *J. Organomet. Chem.* **1974**, *72*, C7. (b) Brookhart, M.; Timmers, D.; Tucker, J. R.; Williams, G. D.; Husk, G. R.; Brunner, H.; Hammer, B. *J. Am. Chem. Soc.* **1983**, *105*, 6721.

(70) Jensen, J. E.; Campbell, L. L.; Nakanishi, S.; Flood, T. C. *J. Organomet. Chem.* **1983**, *224*, 61.

(71) (a) Brunner, H.; Schmidt, E. *J. Organomet. Chem.* **1970**, *21*, P53. (b) Brunner, H.; Schmidt, E. *J. Organomet. Chem.* **1972**, *36*, C18. (c) Brunner, H.; Schmidt, E. *J. Organomet. Chem.* **1973**, *50*, 219.

(72) Liebeskind, L. S.; Welker, M. E. *Organometallics* **1983**, *2*, 194.

(73) Liebeskind, L. S.; Welker, M. E. *Tetrahedron Lett.* **1984**, *25*, 4341.

(74) (a) Davies, S. G.; Dordor, I. M.; Warner, P. *J. Chem. Soc., Chem. Commun.* **1984**, 957. (b) Davies, S. G.; Dordor-Hedgecock, I. M.; Warner, P. *J. Organomet. Chem.* **1985**, *285*, 213.

(75) Liebeskind, L. S.; Welker, M. E.; Goedken, V. *J. Am. Chem. Soc.* **1984**, *106*, 441.

(76) Broadley, K.; Davies, S. G. *Tetrahedron Lett.* **1984**, *25*, 1743.

(77) Beckett, R. P.; Davies, S. G. *J. Chem. Soc., Chem. Commun.* **1988**, 160.

(78) Davies, S. G.; Dordor-Hedgecock, I. M.; Warner, P. *Tetrahedron Lett.* **1985**, *26*, 2125.

(79) (a) Davies, S. G.; Seeman, J. I. *Tetrahedron Lett.* **1984**, *25*, 1845. (b) Davies, S. G.; Seeman, J. I. *J. Am. Chem. Soc.* **1985**, *107*, 6522. (c) Davies, S. G.; Seeman, J. I.; Williams, I. H. *Tetrahedron Lett.* **1986**, *27*, 619.

(80) Liebeskind, L. S.; Welker, M. E.; Fengl, R. W. *J. Am. Chem. Soc.* **1986**, *108*, 6328.

(81) (a) Liebeskind, L. S.; Welker, M. E. *Tetrahedron Lett.* **1985**, *26*, 3079. (b) Davies, S. G.; Walker, J. C. *J. Chem. Soc., Chem. Commun.* **1985**, 209. (c) Davies, S. G.; Dordor-Hedgecock, I. M.; Sutton, K. H.; Walker, J. C. *Tetrahedron* **1986**, *42*, 5123.

(82) Davies, S. G.; Easton, R. J. C.; Sutton, K. H.; Walker, J. C.; Jones, R. H. *J. Chem. Soc., Perkin Trans. 1* **1987**, 489.

(83) Davies, S. G.; Gravatt, G. L. *J. Chem. Soc., Chem. Commun.* **1988**, 780.

(84) Ojima, I.; Kwan, H. B. *J. Am. Chem. Soc.* **1988**, *110*, 5617.

(85) Herndon, J. W.; Wu, C.; Ammon, H. L. *J. Org. Chem.* **1988**, *53*, 2873.

(86) Faller, J. W.; Chao, K.-H. *J. Am. Chem. Soc.* **1983**, *105*, 3893.

(87) Faller, J. W.; Chao, K.-H. *Organometallics* **1984**, *3*, 927.

(88) Faller, J. W.; Linebarrier, D. L. *J. Am. Chem. Soc.* **1989**, *111*, 1937.

(89) (a) Faller, J. W.; Tully, M. T. *J. Am. Chem. Soc.* **1972**, *94*, 2676. (b) Becker, Y.; Stille, J. K. *J. Am. Chem. Soc.* **1978**, *100*, 845. (c) Hayashi, T.; Konishi, M.; Kumada, M. *J. Chem. Soc., Chem. Commun.* **1983**, 736.

(90) Hayashi, T.; Konishi, M.; Kumada, M. *J. Chem. Soc., Chem. Commun.* **1984**, 107.

(91) Hayashi, T.; Yamamoto, A.; Ito, Y. *J. Organomet. Chem.* **1988**, *338*, 261.

(92) Faller, J. W.; Linebarrier, D. *Organometallics* **1988**, *7*, 1670.

(93) Turnbull, M. M.; Foxman, B. M.; Rosenblum, M. *Organometallics* **1988**, *78*, 200.

(94) (a) Howell, J. A. S.; Thomas, M. J. *J. Chem. Soc., Dalton Trans.* **1983**, 1401. (b) Bandara, B. M. R.; Birch, A. J.; Kelly, L. F.; Khor, T. C. *Tetrahedron Lett.* **1983**, *24*, 2491. (c) Birch, A. J.; Bandara, B. M. R. *Tetrahedron Lett.* **1980**, *21*, 2981. (d) Atton, J. G.; Evans, D. J.; Kane-Maguire, L. A. P.; Stephenson, G. R. *J. Chem. Soc., Chem. Commun.* **1984**, 1246.

(95) Bandara, B. M. R.; Birch, A. J.; Kelly, L. F. *J. Org. Chem.* **1984**, *49*, 2496.

(96) Howell, J. A. S.; Thomas, M. J. *Organometallics* **1985**, *4*, 1054.

(97) Birch, A. J.; Kelly, L. F.; Weerasuria, D. V. *J. Org. Chem.* **1988**, *53*, 278.

(98) Pearson, A. J.; Zettler, M. W. *J. Chem. Soc., Chem. Commun.* **1987**, 1243.

(99) Monpert, A.; Martelli, J.; Gree, R.; Carrier, R. *Tetrahedron Lett.* **1981**, *21*, 1961.

(100) Loabassi, M.; Gree, R. *Tetrahedron Lett.* **1988**, *29*, 611.

(101) Baird, P. D.; Blagg, J.; Davies, S. G.; Sutton, K. H. *Tetrahedron Lett.* **1988**, *44*, 171.

(102) (a) Bandara, B. M. R.; Birch, A. J.; Khor, T.-C. *Tetrahedron Lett.* **1980**, *21*, 3625. (b) Birch, A. J.; Pearson, A. J. *J. Chem. Soc., Perkin Trans. 1* **1976**, 954.
(103) Stephenson, G. R. *J. Organomet. Chem.* **1985**, *286*, C41.
(104) Schreiber, S. L.; Klimas, M. T.; Sammaka, T. *J. Am. Chem. Soc.* **1987**, *109*, 5749.
(105) Pearson, A. J.; Yoon, J. *J. Chem. Soc., Chem. Commun.* **1987**, 1467.
(106) Pearson, A. J.; Blystone, S. L.; Nar, H.; Pinkerton, A.; Roden, B. A.; Yoon, J. *J. Am. Chem. Soc.* **1989**, *111*, 134.
(107) Pearson, A. J.; Blystone, S. L.; Roden, B. A. *Tetrahedron Lett.* **1987**, *28*, 2459.