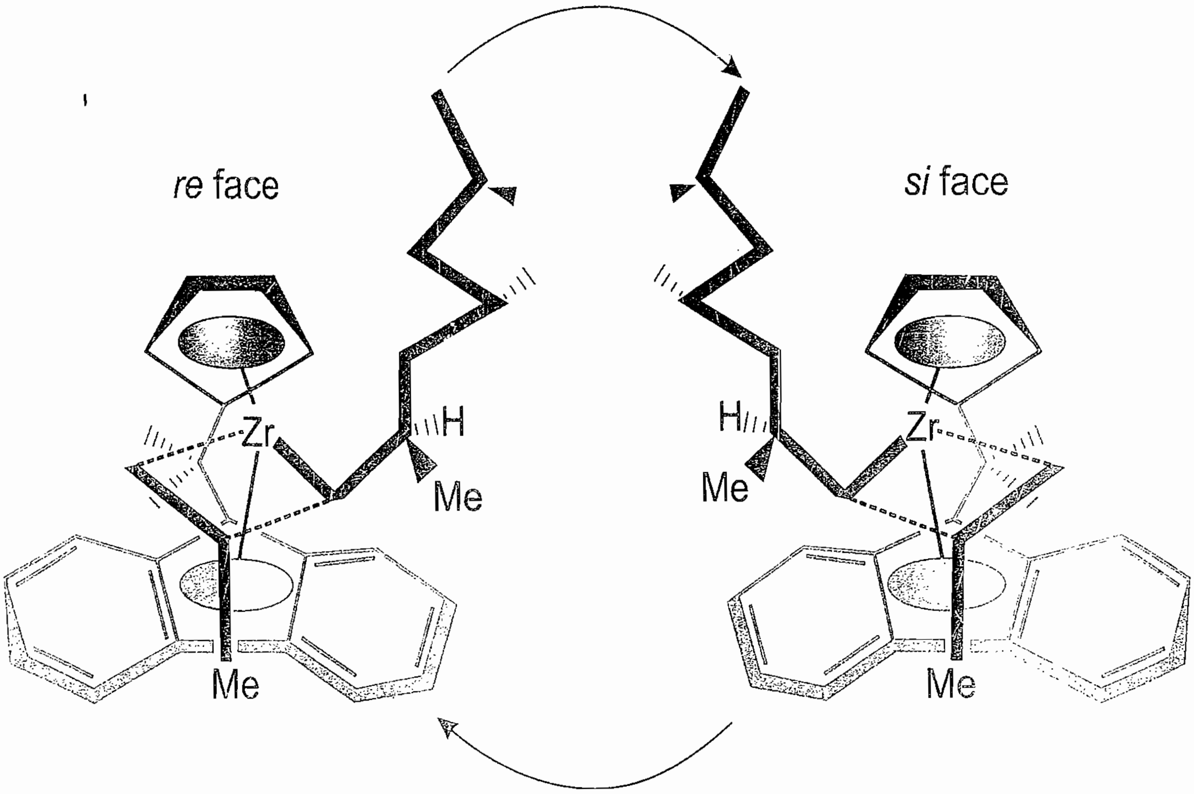
Basic Organometallic Chemistry

Concepts, Syntheses and Applications

SECOND EDITION



B D Gupta | A J Elias

Universities Press

Gupta | Elias Basic Organometallic Chemistry

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FOREWORD

Organometallic chemistry has blossomed in the last five decades into an important branch of chemical sciences. Although the first organometallic compound is nearly 200 years old, the discovery of ferrocene in the 1950s has arguably put this topic on the fast track. The nature of the M–C bond and bonds of this type has evoked considerable theoretical and synthetic interest. As the old bonding paradigms were found to be insufficient to explain many new features of organometallic compounds, new bonding models were needed and are being constantly developed to enrich our understanding of what constitutes a chemical bond. The industrial importance of organometallic compounds first hinted at by the ubiquitous Grignard reagents and then by the use of transition metal salts and complexes in organic synthesis is fully emphasised by the use of Ziegler–Natta catalysts in the olefin polymerisation industry worldwide. The applications of organometallic compounds in the real world are on the rise and are constantly driving this subject forward. The award of the 2005 Nobel Prize in Chemistry to Chauvin, Grubbs and Schrock for their role in the development of olefin metathesis catalysis is another pointer to the importance this subject has gained.

Given the above background, it becomes an important pedagogic exercise to bring this complex subject to the doorstep of students. It is heartening to see that Gupta and Elias have been able to bring out a highly readable and up to date text book fulfilling an important need. They have drawn from their vast experience as teachers at the Indian Institutes of Technology, and put together a comprehensive and yet readable text book. Each topic has been painstakingly researched and the state-of-the art reactions have been distilled for ready use. A highly commendable feature of this book is the value it emphasises on the history of the development of the subject along with its current status. This treatment enables the reader to get a picture of the involvement of humankind with the development of science. While the book is comprehensive, each chapter is provided with a large number of practice problems which are very useful to the teacher and the student. I am confident that this book of Gupta and Elias will be warmly received by all the readers.

Prof. V Chandrasekhar FNA
Department of Chemistry, IIT Kanpur

PREFACE TO THE SECOND EDITION

It is not usual that within three years of publishing a book, the next edition is released. We decided to do so considering the warm welcome this book received from the chemistry community across India and abroad. Meanwhile, a few reviews of the book appeared. The reviewers had made some suggestions vital to the improvement of the quality of the book. Since the first edition of the book was almost entirely sold out, we decided to carry out a few revisions to take care of the errors which usually come up in the first editions of all books, and to incorporate the suggestions made by the reviewers.

The changes that we have incorporated in this edition are:

- full text references to reactions and schemes from all chapters with a modified and enlarged supplementary reading section,
- rectification of all errors pointed out by users and reviewers,
- addition of a few topics in 6–7 chapters some of which the reviewers suggested and we felt would be apt,
- deletion of a few paragraphs which we felt were unnecessary, and
- overall improvement of the layout of the book, especially the figures and margins.

While we, the authors, were working at this, I had a very unexpected shock—the sudden and untimely demise of Prof. B D Gupta, the first author and the pillar behind the creation of this book. Prof. Gupta, a very good friend, was a great teacher and researcher who had dedicated his life to the development of organometallic chemistry in India. With great pain in my heart at this loss, the revision, which we began together has been completed by me. I dedicate this edition of our book to fond memories of him and the exciting time we spent together in learning, discussing and creating this book.

I must thank my colleagues, students and friends in India who were very supportive in this venture especially Dr N D Reddy, Pondicherry University, and Dr S Nagendran, IIT Delhi who used the book and pointed out errors in the first edition. I thank all the M Sc students of IIT Delhi who read through the book and gave suggestions for improvement. I also thank our reviewers Prof. Amitabha Sarkar, IACS, Kolkata, India and Prof. David A Vicic, University of Hawaii, Honolulu with the assurance that most of their suggestions for improvement have been incorporated in this edition.

Users of this book may kindly note that additional challenging problems for this book are provided by this author on his IIT Delhi website http://web.iitd.ac.in/~elias/.

Anil J Elias
IIT Delhi, 2013

PREFACE TO THE FIRST EDITION

Organometallic chemistry is an integral part of every chemistry curriculum all over the world primarily because it bridges two main subdisciplines of chemistry, namely, inorganic and organic chemistry. The subject is of great interest to chemists, both in academia and industry because of its rich chemistry and extensive applications in industry and in catalysis. Although our understanding of this topic has increased exponentially in the last three to four decades, the few existing books, exclusively on transition metal organometallic chemistry, are relatively outdated and most of them, in our view, have failed to cover many important topics and recent developments in this area. Also, most of these books do not contain problems, exercises and their solutions, which are essential for proper comprehension of the subject. Some books have been written more like terse comprehensive reviews and are unfriendly to teachers and students who wish to use them as textbooks.

We (the authors), have been teaching basic and advanced level organometallic chemistry courses at IIT Kanpur and IIT Delhi for several years. The core of this book is based on our lecture notes. We have always received very positive student feedback on the contents of our courses and the usefulness of our lecture notes. A major part of the 250+ problems presented in the book have been class tested and fine-tuned in the IIT classrooms. We decided to compile our lecture material in the form of a book so that a wider audience could benefit from the same. We hope that the hallmark of the IIT system can be noticed in the final outcome of this book with respect to clarity of the subject, creativity in presentation and novelty in problems and exercises.

The objective of this book is to inculcate interest in understanding transition metal organometallic chemistry in beginners of organometallic, inorganic and organic chemistry as well as experienced research scholars in academia and industry. The twenty chapters in this book cover a broad range of topics. The first ten chapters cover the basics of organometallic chemistry and the rest deal with their applications. We hope that the content and layout of the book will aid an educator in planning the course material required for a basic level one semester course that can also be extended to another semester, if required. The large number of problems and exercises at the end of each chapter with detailed solutions, will give the students some experience in problem solving and will also be helpful in preparing for competitive examinations. We have also included a number of quick revision questions at the end of the book, to help in testing one's understanding of the topic.

It will be grossly unfair, if we do not acknowledge the help we have received from our graduate and post doctoral students, past and present, who supplied us with the electronic copies of many references, whenever required. We are extremely thankful to our families who supported and encouraged us in this venture at every stage of this book and missed their husband/father on many important occasions when we were not available. We are very happy that Prof. V Chandrasekhar, a renowned organometallic chemist and member, editorial board of *Organometallics*, found time to read the whole manuscript and for writing the foreword for this book. Our sincere thanks are also to Dr Gita S Dattatri and her editorial team of Universities Press, Hyderabad, for their excellent cooperation.

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December 2009

LIST OF ABBREVIATIONS

A	associative
ADMET	acyclic diene metathesis
AdoCbl	adenosine cobalamine
BAE	N, N′-bis(acetylacetato) ethylene diimine
BBN	borabicyclononane
BINAP	2, 2′-bis(diphenylphosphino)-1,1-binaphthyl
BISBI	2, 2′-bis(diphenylphosphinomethyl)-1,1′-biphenyl
Bn	benzyl
Bza	5,6-dimethylbenzimidazole
CM	cross metathesis
CNCbl	cyanocobalamine
CoA	coenzyme A
COD	cyclooctadiene
COT	cyclooctatetraene
Cp	cyclopentadienyl
CQ	chloroquine
D	dissociative
dba	dibenzylideneacetone
DCPD	dicyclopentadiene
DEHP	diethylhexyl phthalate
DINP	diisononyl phthalate
DIOP	2,2-dimethyl-4,5-[(diphenylphosphino)dimethyl]dioxolane
DIPAM	bis[(2-methoxyphenyl)phenylphosphino]ethane
DPPF	1,1′-bis(diphenylphosphino)ferrocene
dppp	diphenylphosphinopropane
DuPHOS	1,2-bis-(2,5-dimethylphospholano)benzene
EAN	effective atomic number
ee	enantiomeric excess
EM	enyne metathesis
EPA	environmental protection agency
ER	estrogen receptor
Fc	ferrocenyl
FDA	food and drug administration
FE	fenokishi eteru (phenoxy ether)
FI	fenokishi imin (phenoxy imine)
FQ	ferroquine
G	Gibbs free energy of activation
GSH	reduced form of glutathione
HDPE	high density polyethylene
HMD	hexamethylene diamine
HNCC	high nuclearity carbonyl clusters
HOMO	highest occupied molecular orbital
I_a	associative interchange
I_d	dissociative interchange
II	indorido imin (indolide imine)
iPP	isotactic polypropylene
LBD	ligand binding domain
L-DOPA	L-dopamine
LDPE	low density polyethylene
LED	light emitting diode
LLDPE	low density linear polyethylene
LNCC	low nuclearity carbonyl clusters
LUMO	lowest unoccupied molecular orbital

MAO	methylalumoxane
MDPE	medium density polyethylene
MMT	methylcyclopentadienyl manganese tricarbonyl
M_n	number average molecular weight
MO	molecular orbital
MTBE	methyl tertiarybutylether
MUFA	monounsaturated fatty acid
M_w	weight average molecular weight
NHC	N-heterocyclic carbene
NMR	nuclear magnetic resonance
OCT	olefin conversion technology
PEC	polyhedral electron count
PEPPSI	pyridine enhanced precatalyst preparation stabilisation and initiation
PI	pirorido imin (pyrrolide imine)
Ppfa	[2-(1-dimethylamino ethyl)- 1-diphenylphosphino ferrocene]
PSA	pressure swing absorption
PUFA	polyunsaturated fatty acid
PVC	polyvinylchloride
RCEYM	ring closing enyne metathesis
RCM	ring closing metathesis
ROM	ring opening metathesis
ROMP	ring opening metathesis polymerisation
SALEN	salicylic aldehyde-ethylenediimine
SERM	selective estrogen receptor module
SHOP	Shell's higher olefin process
SIMES	1,3-dimesitylimidazolin-2-ylidene
SPECET	single photon emission computed tomography
sPP	syndiotactic polypropylene
Spy	square pyramid
TBP	trigonal bipyramid
TBT	bis tributyltin oxide
TEC	total electron count
TEL	tetraethyllead
Tg	glass transition temperature
TMEDA	tetramethyl ethylenediamine
TO	turnover
TOF	turnover frequency
TON	turnover number
TPPTS	3,3′,3″-phosphinidyne tris(benzenesulphonic acid)trisodium salt
UHMWPE	ultra high molecular weight polyethylene
ULDPE	ultra low density polyethylene
Z	zusammen (together)

CONTENTS

CHAPTER 10 METAL CLUSTERS 178

Interestingly, the way chemists look at organometallic compounds differs according to their basic background. Both inorganic and organic chemists, who are the key players in this field, agree that the industrial importance of homogeneous catalysts has played a very important role in the development and application of organometallic compounds.

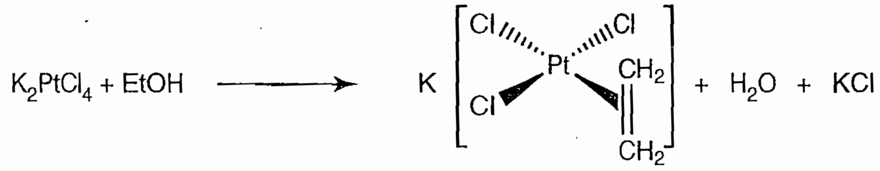
1.2 A BRIEF HISTORY OF ORGANOMETALLIC CHEMISTRY

Important developments and events in the history of organometallic chemistry are given below.

1760 Discovery of 'Cadets fuming liquid', the first main group organometallic compound. In a Paris military pharmacy, Cadet, while working on inks based on cobalt salts prepared from cobalt minerals containing arsenic, discovered a fuming liquid, also called cacodyl (malodorous) oxide.[1]

$$As_2O_3 + 4CH_3COOK \longrightarrow [(CH_3)_2As]_2O$$

1827 Discovery of Zeise's salt, $K[PtCl_3C_2H_4].H_2O$, the first transition metal organometallic compound. W C Zeise, a Danish pharmacist, refluxed K_2PtCl_4 in ethanol and obtained an unusual compound which was called Zeise's salt; it was characterised later as the first organometallic olefin (π) complex. The choice of platinum was fortunate as many noble metal alkene complexes are air and moisture stable.[2]



1849 Edward Frankland made diethylzinc. Frankland, who was a student of Robert Bunsen (Marburg, Germany), while attempting to make ethyl radicals hit upon Et_2Zn (a pyrophoric liquid) and ethylzinc iodide (solid). Frankland also coined the term 'organometallic'.[3]

$$3C_2H_5I + 3Zn \longrightarrow (C_2H_5)_2Zn + C_2H_5ZnI + ZnI_2$$

1852 Frankland used methyl halides and sodium amalgam to make dimethyl mercury. Later on, alkyl transfer reactions using R_2Zn and R_2Hg were used by many to make more main group organometallic compounds. In the same year Löwig and Schweizer in Zurich prepared tetraethyllead using Na/Pb alloy and in 1863 Friedel and Craft used alkylzinc reagents for making organochlorosilanes.

$$2CH_3X + 2Na/Hg \longrightarrow (CH_3)_2Hg + 2NaX$$

$$SiCl_4 + m/2\ ZnR_2 \longrightarrow R_mSiCl_{4-m} + m/2\ ZnCl_2$$

1868 Schützenberger made the first metal carbonyl compound, $[PtCl_2(CO)]_2$.[4]

$$PtCl_2 + CO \longrightarrow [PtCl_2(CO)]_2 + cis\ PtCl_2(CO)_2$$

INTRODUCTION

CHAPTER 1

1.1 WHAT IS ORGANOMETALLIC CHEMISTRY?

Organometallic chemistry deals with molecules that contain a metal–carbon bond. While many chemists prefer to say that for a compound to be classified as an organometallic compound, the type of metal–carbon bonding in a molecule should be covalent or partially covalent in nature, the scientific community as well as journals publishing articles in organometallic chemistry take a more liberal view. The leading journals of the field define an 'organometallic' compound as one in which there is a bonding interaction (ionic or covalent, localised or delocalised) between one or more carbon atoms of an organic group or molecule and a main group, transition, lanthanide or actinide metal atom (or atoms). Following longstanding tradition, organic derivatives of the metalloids such as boron, silicon, germanium, arsenic and tellurium are also included in this definition. It is also understood that the element to which carbon is bound is more electropositive than carbon in organometallic compounds.

Based on the periodic table, one can broadly classify organometallic chemistry further into transition metal, main group metal and lanthanide/actinide based organometallics. Among these the most well developed, mechanistically understood and widely utilised in catalysis is transition metal organometallic chemistry. Therefore, the focus of this book will be mostly on transition metal organometallic chemistry.

Traditional chemists do not agree to classifying metal cyanide complexes as organometallic while many refer to molecules such as the well known Wilkinson's catalyst as organometallic even though such molecules lack the required metal–carbon bond. While the latter is formally incorrect, it is convenient to use when the molecule in question has reaction chemistry that is derived from or will lead to an organometallic intermediate/s or product/s.

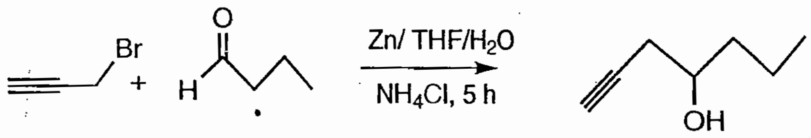
The importance of organometallic chemistry lies in its diversity and versatility as an area which bridges conventional organic and inorganic chemistry and provides a common platform for organic and inorganic chemists to come together and derive the benefits of both fields. This branch of chemistry plays a vital role in the economy of developed nations as about a third of all chemicals produced nowadays use organometallic catalysis. The applications of organometallic compounds in organic synthesis, industrial catalysis and materials chemistry have increased the importance of this branch of chemistry.

1890 Ludwig Mond, the founder of the British chemical company ICI made $Ni(CO)_4$, the first binary metal carbonyl; it is used in the refining of nickel.[5]

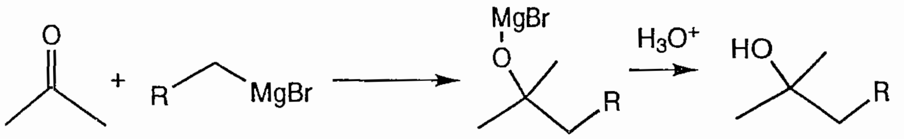
$$\mathrm{Ni} \quad + \quad 4\,\mathrm{CO} \xrightarrow[\text{1 bar, 25°C}]{} \mathrm{Ni(CO)_4}$$

colourless gas: bp 42°C

1899 The Barbier reaction was introduced by Philippe Barbier, a teacher of Victor Grignard. Although less verstile than the Grignard reaction, it allows the reaction to be carried out in one pot and even in the presence of water.



1900 Grignard replaces Zn with Mg in the Barbier reaction. The Grignard reagents are much more versatile and have more applications than organozinc reagents.[6]



1912 V Grignard and P Sabatier received the Nobel Prize for the Grignard reagent and Sabatier's method of hydrogenation using metal powders.

1917 Wilhelm Schlenk prepared the first alkyllithium derivatives by transalkylation of organomercury compounds. The synthetic capabilities of lithium derivatives eventually replaced Grignard reagents as the primary anionic reactive intermediates.[7]

$$2\,\mathrm{Li} + \mathrm{R_2Hg} \longrightarrow 2\,\mathrm{RLi} + \mathrm{Hg}$$

$$2\,\mathrm{EtLi} + \mathrm{Me_2Hg} \longrightarrow 2\,\mathrm{MeLi} + \mathrm{Et_2Hg}$$

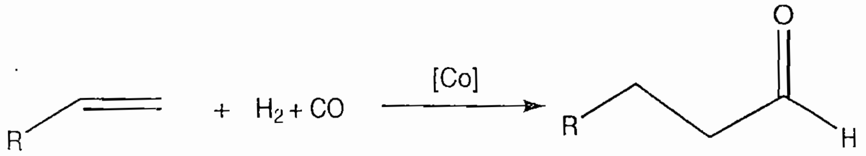
1921 Thomas Midgley working for GE motors introduced tetraethyllead as an antiknock additive in gasoline.[8]

1930 K Ziegler introduced the preparation of organolithium compounds by a simpler route which was further finetuned by Gilman. This encouraged wider use of organolithium compounds.

$$2\,\mathrm{Li} + \mathrm{PhCH_2OMe} \longrightarrow \mathrm{PhCH_2Li} + \mathrm{MeOLi}$$

$$\mathrm{RX} + 2\,\mathrm{Li} \longrightarrow \mathrm{R\,Li} + \mathrm{LiX} \quad \textit{(most common procedure)}$$

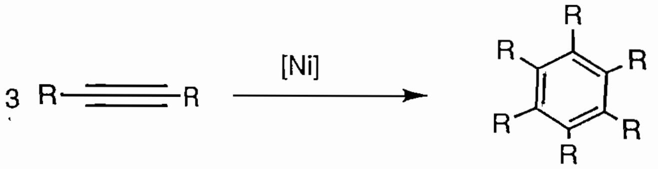
1938 Otto Roelen discovered hydroformylation (the Oxo process), the first use of an organometallic compound in homogeneous catalysis.[9]



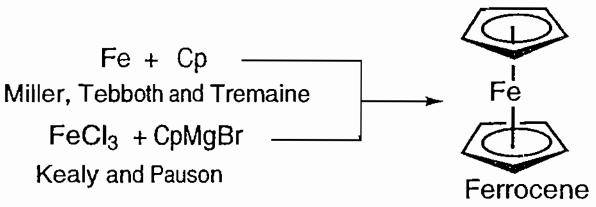
1943 E G Rochow discovered the direct synthesis of organochlorosilanes which initiated the large scale production of silicones.[10]

$$2\,CH_3Cl + Si\,(Cu) \xrightarrow[300°C]{} (CH_3)_2SiCl_2 \quad (\sim 80\%)$$

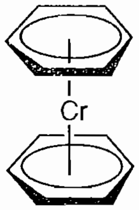
1948 W Reppe discovered nickel catalysed acetylene trimerisation.[11]



1951 Two groups independently prepared ferrocene and suggested a sigma bonded structure. The sandwich structure was proposed by Wilkinson, Fischer and Woodward.[12]



1955 E O Fischer and W Hafner prepared bis(benzene)chromium by a rational synthesis although F Hein had possibly made the same by a reaction of $CrCl_3$ and PhMgBr in 1919.[13]



1955 K Ziegler and G Natta developed olefin polymerisation at low pressure using mixed metal catalysts (transition metal halide /AlR_3).[14]

1959 First stabilisation of cyclobutadiene by complexation to a metal.[15]

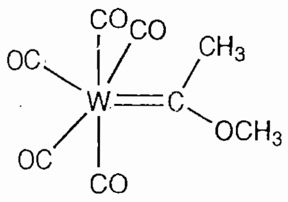
$$[(C_4Me_4)NiCl_2]_2$$

1961 Discovery of Vaska's complex which reversibly binds oxygen.[16]

trans $IrCl(CO)(PPh_3)_2$

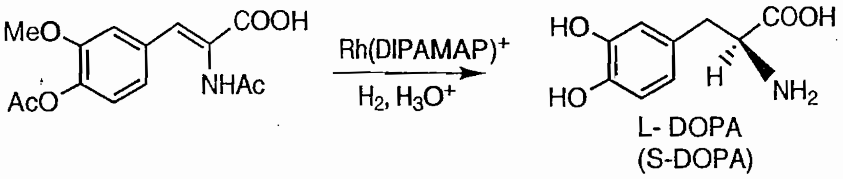
1963 Nobel prize for Ziegler and Natta.

1964 E O Fischer prepared the first metal carbene complex.[17]



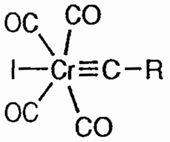
1965 Wilkinson and Coffey, in separate studies, used $(PPh_3)_3RhCl$ as a homogeneous catalyst in the hydrogenation of alkenes.[18]

1968 William S Knowles discovered asymmetric catalysis, whereby complexes containing chiral ligands catalyse the conversion of achiral substrates to chiral products with high enantiomeric excess. The first such system involves the asymmetric hydrogenation of α-acetamidocinnamic acid derivatives using a rhodium catalyst.[19]



1972 R F Heck and T Mizorki discovered the palladium catalysed substitution of vinylic hydrogen atoms with aryl halides which opens up diverse palladium based catalysis reactions in organic chemistry.[20]

1973 E O Fischer prepared the first metal carbyne complex.[21]



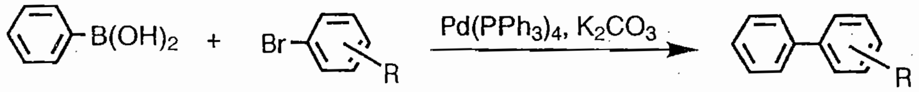
$$\mathrm{I{-}Cr(CO)_4{\equiv}C{-}R}$$

1973 Nobel Prize for E O Fischer and G Wilkinson for their work on metal sandwich compounds.

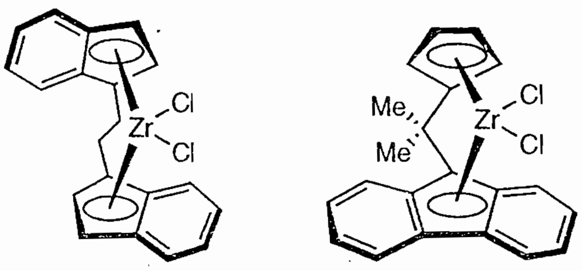
1976 M F Lappert prepared the first main group element dimetallenes by making the first tin–tin double bonded compound.[22]

$$[(Me_3Si)_2CH]_2Sn = Sn[CH(SiMe_3)_2]_2$$

1979 Suzuki and Miyaura published their first paper on Suzuki coupling of aryl boronic acids using palladium catalysts.[23]



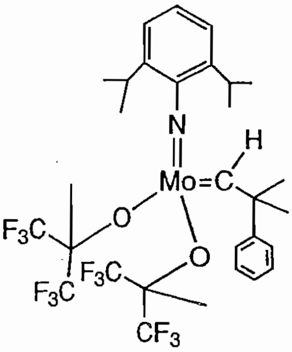
1980 Walter Kaminsky made zirconocene based catalysts exclusively for iso and syndiotactic polypropylene.[24]



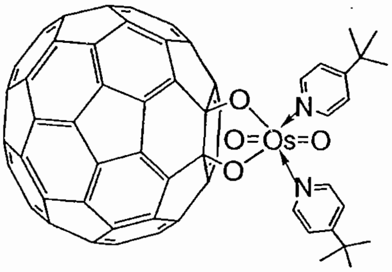
1981 Robert West made the first stable compound having a silicon–silicon double bond.[25]

$$(1,3,5\text{-}Me_3C_6H_2)_4Si_2$$

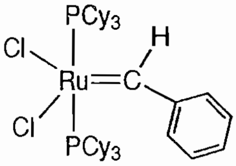
1990 Richard Schrock discovered a molybdenum based catalyst for olefin metathesis.[26]



1991 J M Hawkins made the first fullerene based organometallic compound which was also the first structurally characterised fullerene derivative $C_{60}(OsO_4)(4\text{-}t\text{-BuPy})_2$. Later on, a host of organometallic compounds with direct metal–carbon bonds with η^2-bonding were discovered.[27]



1995 Robert Grubbs prepared his ruthenium based olefin metathesis catalyst (first generation Grubbs catalyst).[28]



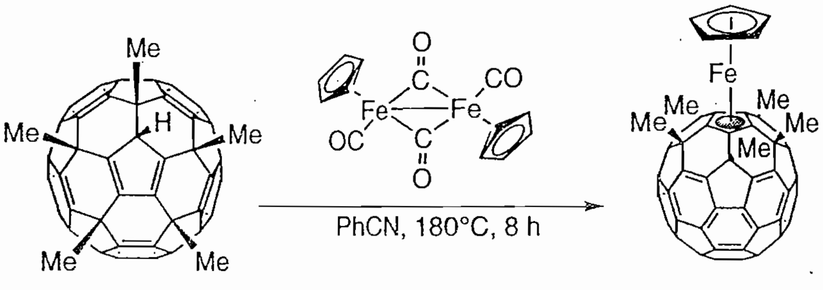
1997 C C Cummins showed the C atom as a ligand in an organometallic compound.[29]

$[(R_2N)_3MoC]^-$

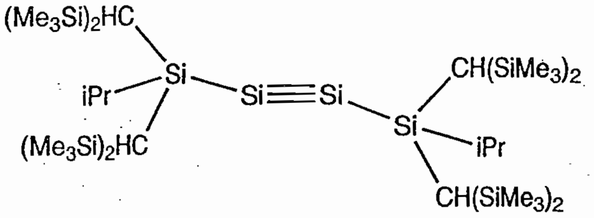
1997 G M Robinson synthesised the salt $Na_2[ArGaGaAr]$ and postulated a gallium–gallium triple bond.[30]

2001 W S Knowles received the Nobel prize for asymmetric hydrogenation along with K B Sharpless and R Noyori.

2002 E Nakamura prepared 'bucky ferrocenes' – molecular hybrids of ferrocene and fullerene – by treatment of $C_{60}HMe_5$ or $C_{70}HMe_3$ with $[FeCp(CO)_2]_2$.[31]



2004 A Sekiguchi prepared the first Si–Si triple bonded molecule and carried out its structural characterisation.[32]



2004 E Carmona prepared the first Zn (I) organometallic compound.[33]

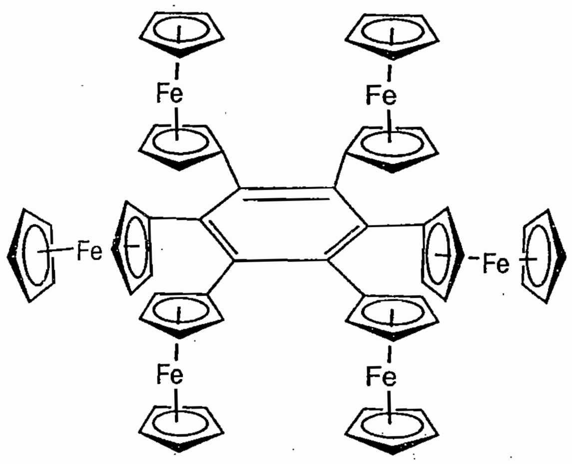
$Zn_2(Cp^*)_2$

2005 Yves Chauvin (France), Robert H Grubbs (Caltech) and Richard R Schrock (MIT), USA received the Nobel prize for olefin metathesis.

2005 Philip Power prepared the first stable organometallic compound with a possible quintuple bond (five fold metal-metal bond).[34]

Ar-Cr ≣ Cr-Ar

2006 Peter C Vollhardt prepared hexaferrocenyl benzene (thought of as an impossible molecule).[35]



1.3 IMPORTANCE OF ORGANOMETALLIC COMPOUNDS

1.3.1 Organometallic Compounds as Reagents

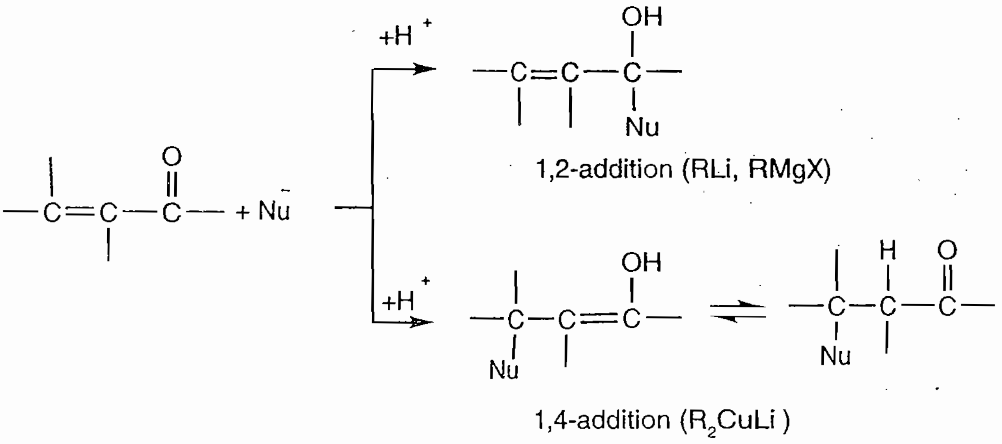
Organic chemists use organometallic compounds as reagents as well as catalysts. The usefulness of organometallic compounds, especially the alkali and alkaline earth compounds such as butyllithium and organomagnesium (Grignard) reagents, is the most visible face of organometallics to organic chemists. A variety of carbon–carbon coupling reactions such as Suzuki, Sonogashira, Heck and Negishi which use palladium complexes and involve organometallic intermediates, are well known for their functional group tolerance. Organosilicon protecting groups such as trimethylsilyl or tertiarybutyl dimethylsilyl (TBDMS) and triisopropylsilyl (TIPS) also form an integral part of the organic chemists' repertory. Organic chemists use many organometallic reagents and catalysts for very specific applications. Some of these are highlighted below.

Organozinc reagents

The Barbier reaction (1899) is the zinc equivalent of the Grignard reaction and actually the older and the more tolerant of the two. In the presence of traces of water, the formation of the organomagnesium halide will fail whereas the Barbier reaction can even take place in water. On the downside, organozinc compounds are much less nucleophilic than Grignard reagents. The Reformatsky reaction which converts α-haloesters and aldehydes to β-hydroxyesters also goes through an intermediate organozinc halide. In the Simmons–Smith reaction, the carbenoid (iodomethyl)zinc iodide reacts with alkenes to form cyclopropanes. The Negishi coupling involves palladium catalysed cross coupling of organozinc reagents.[36]

Organocopper reagents

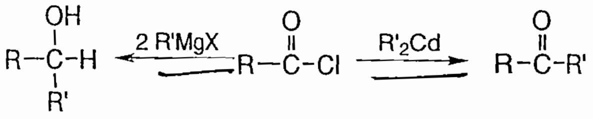
The most useful organocopper reagents are lithium dialkylcuprates, R_2CuLi. These are formed by the reaction of two equivalents of an organolithium compound with a copper (I) halide. These reagents are soluble in ethers and are useful in the displacement of halogens especially in the coupling of two different alkyl halides (also known as the Corey–Posner–House–Whitesides synthesis). Addition to α,β-unsaturated aldehydes and ketones brings out the difference in the reactivity between organocopper reagents on the one hand and, organomagnesium and lithium reagents on the other. While organolithium and magnesium reagents react by simple addition, that is, when the nucleophile adds across the double bond of the carbonyl groups (called 1,2 addition, it resembles addition to conjugated dienes), the dialkylcuprates preferentially react by conjugate addition (called 1,4 addition):[37]



(1.1)

Organocadmium reagents

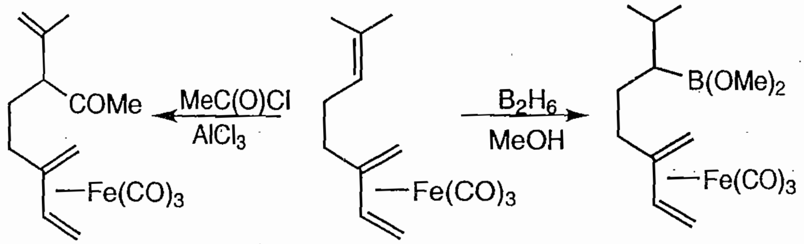
The alkyl groups present in the organocadmium compounds are less nucleophilic than those in the organozinc compounds due to the general increase in electronegativity going down group 12. This reduced reactivity is demonstrated in the conversion of acid chlorides to ketones using these reagents. With Grignard reagents, such a reaction would continue to form the tertiary alcohol.[38]



$$\mathrm{R{-}\overset{OH}{\underset{R'}{C}}{-}H} \xleftarrow{2\,\mathrm{R'MgX}} \mathrm{R{-}\overset{O}{\overset{\|}{C}}{-}Cl} \xrightarrow{\mathrm{R'_2Cd}} \mathrm{R{-}\overset{O}{\overset{\|}{C}}{-}R'} \qquad (1.2)$$

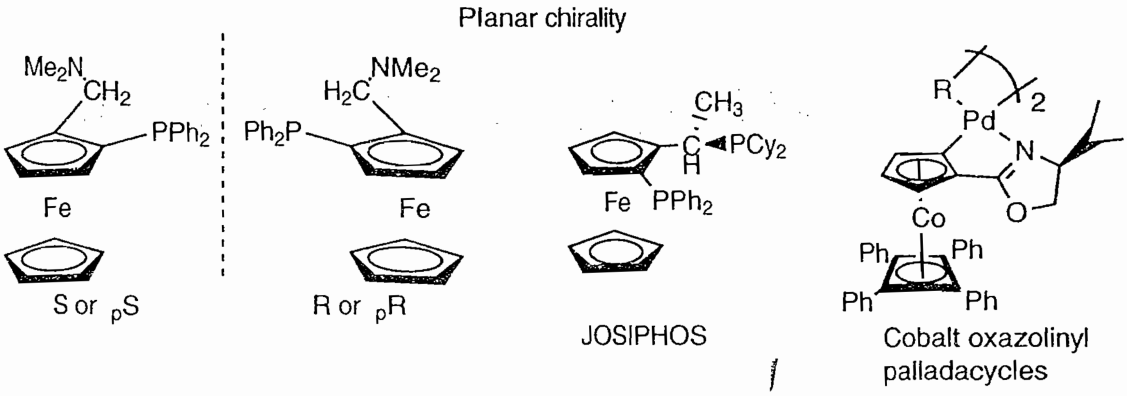
Organoiron reagents

The efficiency of the $Fe(CO)_3$ moiety in protecting 1,3-dienes, and its use as a stereodirecting group in various types of reactions is well documented. Acyclic diene-tricarbonyliron complexes are valuable intermediates particularly for the asymmetric synthesis of polyenic natural products and structural analogues. The diene system is temporarily protected and this allows reactions to occur at remote centres of the molecule without interference from the diene. Another interesting fact is that the chemical reactivity of the molecule can be altered or completely modified as against the uncomplexed compounds.[39, 40]

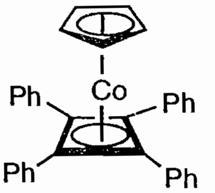


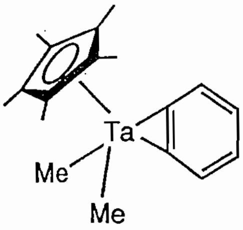
(1.3)

Planar chirality shown by organometallic compounds such as ferrocene and other sandwich compounds is unique and makes a very significant contribution in the area of asymmetric catalysis. Unlike other forms of chirality, there is no racemisation possible without bond breaking in such molecules. Derivatives of ferrocene and a few other stable metallocenes and half-sandwich complexes are well known for their planar chirality.[41]



Many organic species which are highly unstable and often invoked as intermediates can be stabilised once they are bound to a metal. This provides valuable evidence for their mechanism, especially the formation of intermediates. The examples given below show how the highly unstable cyclobutadiene and benzyne molecules are stabilised by metal complexation.[42]





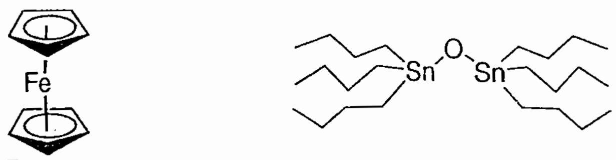
The interest of inorganic chemists in organometallic chemistry is dominated by the usefulness and diversity shown by organometallics as homogeneous catalysts. Inorganic chemists also explore the synthesis of new organometallic compounds, their stability and structural studies, and then determine their potential applications especially as catalysts. To a minor extent, they are also interested in using organometallic compounds in the production of devices and as carriers for depositing a fine coating of a specific metal (chemical vapour deposition); and as polymer and material precursors. More of these will be discussed in the forthcoming chapters.

1.3.2 Organometallic Compounds as Additives

Organometallic compounds find application either as bulk additives for modifying the existing property of a specific compound or as catalysts in the synthesis of industrially important organic compounds especially in reactions where stereospecificity is required (Fig. 1.1). Due to strict environmental safety rules and regulations, the use of organometallic compounds has been dwindling in the former category while their use has increased over the years as homogeneous catalysts. For many applications, it is not easy to find alternatives for organometallic compounds and hence they are used even today although in much lesser amounts and in situations where they do not cause much environmental harm. Some of the well known examples are given below.

Tetraethyllead (TEL)

Methylcyclopentadienylmanganesetricarbonyl (MMT)



Ferrocene (Fc)

Tributyltin [Bis(tribuyltin)oxide] (TBT)

Fig. 1.1 Examples of well known organometallic additives

Tetraethyllead (TEL)

Thomas Midgley working at General Motors Research, USA, discovered in 1921 that tetraethyllead, a viscous colourless liquid can act as an effective antiknocking agent. Particles of lead and lead oxide, PbO are formed on combustion of TEL added gasoline. This helps the gasoline to burn more slowly and smoothly, preventing knocking and with higher octane ratings. After experimenting with chemicals such as iodine and aniline and trying out a variety of organic and organometallic additives, Midgley discovered the very high relative antiknock effectiveness of TEL. Table 1.1 gives a comparison of TEL with some of the other early additives. In 1970, the annual consumption of lead in antiknock additives peaked at 279,000 metric tons per year in the USA and 326,000 metric tons worldwide.[8, 43]

Tetraethyllead is prepared using the following reaction

$$Pb + 4\,Na + 4\,CH_3CH_2Cl \longrightarrow (CH_3CH_2)_4Pb + 4\,NaCl \tag{1.4}$$

Table 1.1 Relative antiknock effectiveness of selected early organometallic and organic gasoline additives

Additive	Relative effectiveness	Additive	Relative effectiveness
Aniline	1	Diethyltelluride	27
Ethanol	0.1	Nickel carbonyl	35
Dimethylcadmium	1.2	Iron pentacarbonyl	50
Tetraethyltin	4	Tetraphenyllead	73
Diethylselenide	7	Tetraethyllead	118

More powerful high-compression engines were built to use the higher octane leaded gasoline. One of the initial drawbacks was that the solid Pb and PbO formed were found to quickly accumulate and affect the efficiency of the engine. To solve this problem, lead scavengers such as ethylene dibromide and 1,2-dichloroethane were tried out and were used in conjunction with TEL. These compounds form volatile but poisonous lead bromide and lead chloride respectively, and are released as exhaust from the engine. An additional problem associated with leaded gasoline is that the lead in the exhaust pipe would poison the catalytic converter (a standard component for modern cars). Catalytic converters which serve to oxidise unburned hydrocarbons, carbon monoxide and nitrogen oxides contain platinum group metals that get inactivated by lead.

Leaded gasoline in cars was phased out in the USA from 1973, in the European Union from 2000, in China in 2001 and was banned in Canada from 1990. In India, the phasing out began in 1994 and was completed by 2000. TEL remains an ingredient of aviation gasoline and is also still available from a limited number of outlets as a fuel additive, mostly for owners of classic and vintage cars and motorcycles. In addition, TEL is still in use as an ingredient in the fuels used by NASCAR in the racing series and in many underdeveloped and developing countries.

Methyl cyclopentadienyl manganese tricarbonyl (MMT)

This is an organometallic manganese carbonyl compound manufactured by the Ethyl Corporation and sold under names such as HiTec 3000 and AK-33X. Unlike the non-methylated analogue cymantrene [$CpMn(CO)_3$] which has a melting point of 75°C, MMT is a liquid (m.p. of −1°C) and has antiknock properties quite similar to TEL. Ethyl corporation also indicates that the amount of MMT required as additive is much less compared to TEL per litre of petrol. Marketed initially in 1958 as a supplement to tetraethyllead, MMT was later used to increase the octane number in unleaded gasoline. Though banned as a gasoline additive in the United States from 1977 to 1995, MMT has been used in Canadian gasoline since 1976 and was recently introduced in Australia. The Clean Air Act of 1977 banned the use of MMT until the Ethyl Corporation could prove that the additive would not lead to failure of new car emissions-control systems. As a result of this ruling, the Ethyl Corporation began a legal battle with the EPA, claiming that MMT was harmless to automobiles. In 1995, the US Court of Appeals ruled that the EPA had exceeded its authority and, as a result, MMT became a legal fuel additive in the United States. Global car makers in the US and Canada, state categorically in their respective warranties for cars, that they do not recommend the use of petrol that contains MMT, as it adversely affects the spark plug and emissions systems. Although initially used in some refineries in India, the use of MMT was discontinued completely in India from 2006. Studies have demonstrated that gaseous emissions can increase by as much as 118% to 143% due to damaged emission-control systems caused by manganese deposits. It also lowers fuel economy.[44]

The health hazards associated with MMT use have been hotly debated for decades. A 2003 study by the national industrial chemicals notification and assessment services (NICNAS) of Australia suggested that MMT was highly toxic to humans, but ruled that the airborne concentrations of manganese as a result of car emissions from vehicles using fuel containing MMT were not high enough to cause a major health problem. Due in part to fears remaining from the environmental disaster that was leaded gasoline and questionable effects of MMT on automobile engines, MMT use in the United States as a gasoline additive has been virtually nonexistent. Chronic exposure to manganese has been known to cause *manganism*. The symptoms of manganism are similar to those of Parkinson's disease.

Ferrocene

Carbonaceous particulate matter emitted by diesel engines constitutes a significant health hazard. In addition to antiknock properties, another objective of using fuel additives is to reduce soot emission. The soot supressing properties of ferrocene are well known from different combustion systems. Ferrocene is readily soluble in liquid fuels, is air stable, nontoxic and unusually heat stable. Various studies prove that ferrocene reduces the formation of carbonaceous matter during combustion by a more efficient burnout of the fuel. Iron oxide particles that are formed may act as catalysts to promote soot burn out in oxygen-rich regions of the combustion system.[45]

Ferrocene is also the safest additive used so far, as it does not cause any environmental pollution or health related hazards. It is claimed that if used as fuel catalyst for rocket propellant, it can improve the combustion speed by 1–4 times, lower the temperature of exhaust pipes, and avoid infrared chase. When used in fuel oils such as diesel oil, heavy oil and light oil, it can eliminate smoke, save energy and reduce air pollution. Adding 0.1% ferrocene to diesel oil can cut down the consumption of oil by 10% to 14%, eliminate smoke by 30% to 70%, and improve power by more than 10%. Unfortunately, the iron oxide based deposits formed from ferrocene can form a conductive coating on the sparkplug surfaces leading to sparkplug failure in vehicles. Figure 1.2 shows how adding ferrocene to diesel oil can reduce the level of soot in the smoke produced.

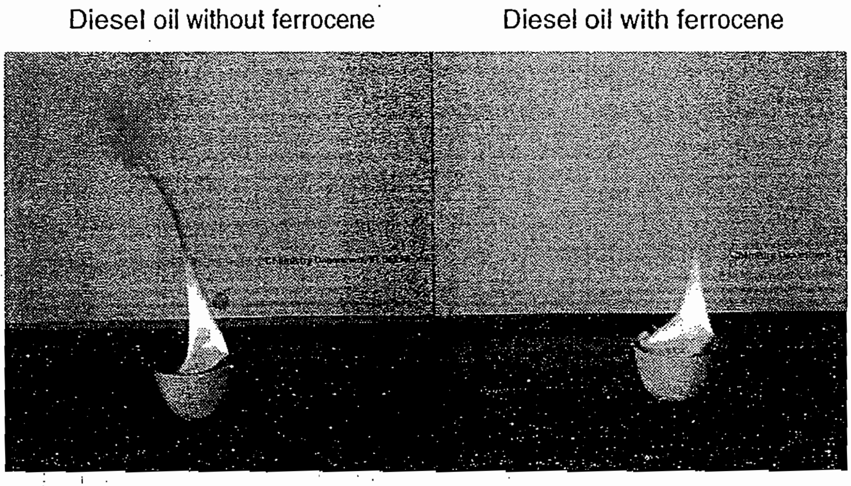


Fig. 1.2 Burning of diesel oil with and without ferrocene as an additive

Alternatives to organometallic fuel additives

Oxygenate blending adds oxygen to the fuel by using oxygen bearing compounds such as methyltertiarybutyl ether (MTBE), ethanol and ethyltertiarybutyl ether (ETBE), and reduces the amount of carbon monoxide and unburned fuel in the exhaust gas. In many areas throughout the United States of America, oxygenate blending is mandatory. Although MTBE was projected as a viable alternative to organometallic additives, it also has come under severe criticism and a possible ban as it gets into groundwater. Although it is not very toxic, it is not very biodegradable either, and has a strong taste and smell, noticeable at the 15 parts per million (ppm) level. There has been a strong movement to ban it from petrol, in California in particular. Probably another oxygen containing compound such as ethanol which will be more environmentally friendly may become a major player. Such compounds may not be toxic, though they will probably increase the cost of gasoline. Also, storage systems have to be modified since alcohols such as ethanol absorb water and can lead to rusting and growth of bioorganisms in the fuel tank.

Bistributyltin oxide (TBT)

Marine fouling, the attachment of crustaceans and other slow moving sea creatures to the submerged part of a ship at sea is a common problem faced by ship owners and naval fleets. Tributyltin antifoulants provide ship owners with effective protection against marine fouling growth for a period up to or exceeding five years. To the modern ship owner, the impact of fouling is notably felt in fuel speed and economy. As little as 5% fouling of the hull of a tanker can increase fuel costs by 17% and one study has shown that a 1 mm thick layer of slime can cause a 15% reduction in ship speed. Once fouling has been established, the only lasting solution is a costly docking of the ship to remove such growth and restore the smoothness of the hull with an effective antifouling paint system. The most effective and economic method so far to prevent fouling growth of ships has been to use a continuously releasing antifouling biocide; the most effective among such compounds has been bistributyltin oxide (TBT). Before the entry of TBT, ship builders used a formulation of natural wood rosin and copper oxide which was effective for a smaller period of time. In the 1970s, organotin copolymer paints were recognised as effective biocides and as soluble paint binders which would physically smooth the surface once applied and release the biocide at a constant rate for over a period of around five years. A US navy estimate in 1986 indicates that fleet-wide use of organotin paints can save \$110 million in fuel costs.[46]

In the late 1970s a link was established between TBT and deformities in oysters and other shellfish, especially in harbours. It was later noted that malformations could be induced by very low concentrations of TBT. The marine environment protection committee has put in place a ban on TBT based paints from 2003 so that no TBT paint will remain on ships after 2008. However a viable alternative is still not fully established. Silicone polymers are being tried currently as antifoulants but with restrictions.

1.3.3 Organometallic Compounds as Catalysts

Traditionally, industrial processes use heterogeneous catalysts, where reactants pass through a bed or gauze of solid catalyst. However, most laboratory reactions use homogeneous catalysts (reactants and products in the same phase, often as liquids). This means that the valuable catalyst either remains in the product or has to be separated from the mixture by tedious and expensive methods. Especially for pharmaceuticals and food industries, it is not good to have catalysts contaminating the product. There are also many chemical transformations which are unique to homogeneous catalysts with no satisfactory heterogeneous analogues known (Table 1.2). These include the oxidation of ethylene to acetaldehyde by the Hoechst–Wacker process (Pd/Cu chlorides) and the hydrocyanation of buta-1,3-diene to adiponitrile by Dupont (Ni/phosphate). The advantages of using organometallic homogeneous catalysts are many and selectivity in product formation is a major attraction especially in the synthesis of chiral molecules.[47]

Table 1.2 Well known organometallic homogeneous catalysts used in industry

Catalyst	Reaction	Industry
$Co_2(CO)_8$	Hydroformylation	Ruhrchemie, BASF
$[Rh(CO)_2I_2]^-$	Methanol carbonylation	Monsanto
$HRh(CO)(PPh_3)_3$	Hydroformylation	Union Carbide/ Johnson Matthey
$Ni(COD)(Ph_2PCH_2COO)$	Ethylene oligomerisation	Shell (SHOP process)
$[Cp_2Zr]$ MAO	Ethylene polymerisation	Dow and Exxon
$Rh\text{-}(BINAP)(COD)ClO_4$	L-menthol synthesis	Takasago International Corporation
$[Ir(CO)_2I_2]^-$	Methanol carbonylation	BP (Cativa process)

Supplementary reading

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THE 18 VALENCE ELECTRON RULE

CHAPTER

2

2.1 INTRODUCTION

The elementary basis for discussing structure and bonding in organometallic compounds is based on the 18 valence electron rule. This rule, in combination with the concept of backbonding or extent of π-acceptor capabilities of ligands, helps one to arrive at the relative stability of organometallic compounds.

Hapticity and sandwich compounds

A number of unsaturated organic anions and molecules such as allyl, cyclopentadienyl and benzene can bind to a metal in more than one way. The different modes are distinguished by the number of carbon atoms participating in linkage with the metal (to be more precise, one has to see how many carbon atoms are present within bonding distance from the metal atom). The hapto symbol, η, with a numerical superscript, provides a topological description by indicating the connectivity between the ligand and the central atom. For example, if all the five carbon atoms of a cyclopentadienyl moiety are equidistant from a metal atom, we term it as η^5-cyclopentadienyl.

2.2 THE 18 ELECTRON RULE

This rule was first formulated by Irwing Langmuir in 1921 with a view to extend the octet theory of G N Lewis – based on the static-atom model – beyond argon in the periodic table.[1] He derived the following equation

$$v_c = s - e$$

where v_c = the number of shared electrons of a given atom in a compound or metal complex, s = the number of electrons required for the completion of its valence shell and e = the number of valence electrons in the isolated atom. For example,

NH_3	$3 = 8 - 5$
$Ni(CO)_4$	$8 = 18 - 10$
$Cr(CO)_6$	$12 = 18 - 6$

For common organic compounds where the octet rule was followed, the value of s was 8 and for organometallic complexes – such as metal carbonyls, on which this rule was first effectively employed – the value of s was 18. An alternative electron counting procedure, now well known as the effective atomic number rule (EAN), based on Bohr's atom model and electronic configuration, was proposed by Nevil Sidgwick in 1923.[2] The focus of this rule was not just on the valence shell electrons but also on the total atom electron count of a compound and the stability of the compound was equated to the electronic configuration of the nearest noble gas. The EAN rule was popular till the 1960s and was applied to all types of metal complexes. However, by the late 1960s, the chemical community reverted to the 18 electron rule basically due to the ease of usage. It is evident that the EAN rule invokes the use of the chemically inactive core electrons that results in separate numerical stability standards for each row of the transition metals [36 (Kr, first row), 54 (Xe, second row) or 86 (Rn, third row)] while for the 18 electron rule, a single numerical standard is applicable to the entire block of transition metals. The rule has since then been very popular among organometallic chemists.[3]

To apply this rule, the assumptions made were that the ligands were Lewis bases and the metal ions were Lewis acids. The rule states that *thermodynamically stable transition metal organometallic compounds are formed when the sum of the metal d electrons and the electrons conventionally considered as being supplied by the surrounding ligands equals 18*. An alternate and general statement is that when the metal in question achieves an outer shell configuration of ns^2 $(n-1)d^{10}$ np^6, there will be 18 electrons in the valence orbitals and a closed, stable configuration is attained. This rule of thumb is obeyed with a rather high frequency by organometallic compounds. In general, the conditions favouring adherence to the 18 electron rule are, an electron rich central metal (one that is in a low oxidation state) and ligands that are good π-acceptors.[4–6]

By counting the number of outer shell electrons surrounding each metal atom in a complex, it is possible to predict whether the complex will be stable and in some cases, whether there will be metal–metal bonds present or not. There are two methods of electron counting—the neutral atom counting method and the oxidation state counting method. The neutral atom method is more foolproof as it does not require the correct assignment of metal oxidation states (which is sometimes difficult in organometallic compounds). However, the oxidation count method is more realistic as it reflects the precise number of electrons available for donation on a ligand. Table 2.1 gives the electron contributions for a variety of ligands according to the neutral atom and oxidation state counting methods.[7,8]

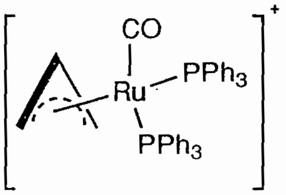
2.3 COUNTING OF ELECTRONS AND FINDING METAL–METAL BONDS

Since metal carbonyl compounds contain the metal in the low oxidation state, there are many compounds that possess M–M bonds and fall into the category of metal carbonyl clusters. Indeed, the largest and structurally most complex cluster compounds belong to this class.

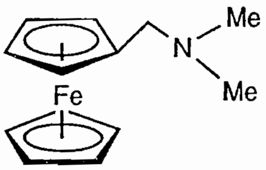
To determine the total number of M–M bonds and to find out the number of bonds each metal makes with the other metal atoms in a cluster, the following procedure is followed. This procedure applies only to those complexes having a nuclearity ≤ 4. The electronic structures are easily understandable in terms of an electron pair bond between each adjacent pair of metal atoms, with each metal atom attaining the 18 electron configuration.

Table 2.1 Common ligands and their electron contributions

Ligand	Neutral atom method	Oxidation state method		Ligand	Neutral atom method	Oxidation state method	
		Electron contribution	Formal charge			Electron contribution	Formal charge
Carbonyl (M–CO)	2	2	0	Halogen (M–X)	1	2	–1
Phosphine (M–PR_3)	2	2	0	Alkyl (M–R)	1	2	–1
Amine (M–NR_3)	2	2	0	Aryl (M–Ar)	1	2	–1
Amide (M–NR_2)	1	2	–1	Acyl [M–C(O)–R]	1	2	–1
Hydrogen (M–H)	1	2	–1	η^1-Cyclopentadienyl	1	2	–1
Alkene (sidewise) η^2-	2	2	0	η^1-Allyl	1	2	–1
Alkyne (sidewise) η^2-	2	2	0	η^3-Allyl	3	4	–1
η^2-C_{60}	2	2	0	η^5-Cyclopentadienyl	5	6	–1
Nitrosyl bent	1	2	–1	η^6-Benzene	6	6	0
Nitrosyl linear	3	2	+1	η^7-Cycloheptatrienyl	7	6	+1
Carbene (M=CR_2)	2	4	–2	Carbyne (M≡CR)	3	6	–3
Alkoxide (M–OR)	1	2	–1	Thiolate (M–SR)	1	2	–1
μ-CO [M–(CO)–M]	2	2	0	μ-H	1	2	–1
μ-Alkyne	4	4	0	μ-X (M–X–M) X = Halogen	3	4	–1
μ-Alkyl	1	2	–1	μ-Amido [M–(NR_2)–M]	3	4	–1
μ-Phosphido [M–(PR_2)–M]	3	4	–1	μ-Alkoxide [M–(OR)–M]	3	4	–1



	neutral atom method	oxidation state method
Ru	8	6 (Ru +2)
η^3-allyl	3	4
2 PPh_3	4	4
CO	2	2
charge	−1	not required
	16	16



	neutral atom method	oxidation state method
Fe	8	6 (Fe +2)
2 η^5-Cp	10	12
	18	18

Calculating the M—M bond

(i) Determine the total valence electrons (TVE) in the entire molecule (that is, the number of valence electrons of the metal plus the number of electrons from each ligand and the charge); say, it is *A*.

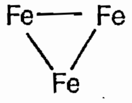
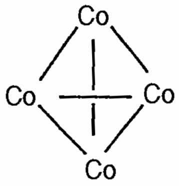
(ii) Subtract this number from $n \times 18$ where n is the number of metals in the complex, that is, $(n \times 18) - A$; say, it is *B*.

(iii) (a) *B* divided by 2 gives the total number of M–M bonds in the complex.
(b) *A* divided by n gives the number of electrons per metal. If the number of electrons is 18, it indicates that there is no M–M bond; if it is 17 electrons, it indicates that there is 1 M–M bond; if it is 16 electrons, it indicates that there are 2 M–M bonds and so on.

Table 2.2 TVE calculation of some mononuclear complexes using the oxidation state electron counting method

Compound	Formal oxidation state of metal	TVE
$Cr(CO)_6$	0	$6 + (2 \times 6) = 18$
$Fe(CO)_5$	0	$8 + (2 \times 5) = 18$
η^5-$CpFe(CO)_2Cl$	+2	$6 + 6 + 4 + 2 = 18$
$CH_3Mn(CO)_5$	+1	$2 + 6 + (2 \times 5) = 18$
$[Fe(CO)_4]^{2-}$	−2	$8 + (2 \times 4) + 2 = 18$
$[\eta^5$-$Cp_2Co]^+$	+3	$(6 \times 2) + 7 - 1 = 18$
$[Mn(CO)_6]^+$	+1	$7 + (2 \times 6) - 1 = 18$
η^3-Cp η^5-Cp Fe(CO)	+2	$4 + 6 + 6 + 2 = 18$

Table 2.3 M–M bond calculations for some multinuclear complexes

Molecule	TVE (*A*)	(18 × *n*) – *A* (*B*)	Total M–M bonds (*B*/2)	Bonds per metal	Basic geometry of metal atoms
$Fe_3(CO)_{12}$	48	54 – 48 = 6	6/2 = 3	48/3 = 16; 2	
$Co_4(CO)_{12}$	60	72 – 60 = 12	12/2 = 6	60/4 = 15; 3	
$[\eta^5\text{-CpMo(CO)}_2]_2$	30	36 – 30 = 6	6/2 = 3	30/2 = 15; 3	Mo≡Mo
$(\eta^4\text{-C}_4\text{H}_4)_2\text{Fe}_2(\text{CO})_3$	30	36 – 30 = 6	6/2 = 3	30/2 = 15; 3	Fe≡Fe
$Fe_2(CO)_9$	34	36 – 34 = 2	2/2 = 1	34/2 = 17; 1	Fe–Fe

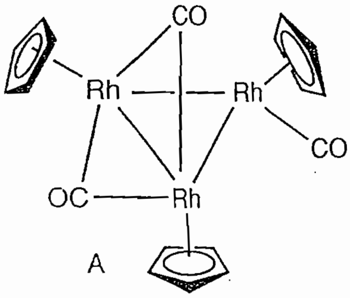
In drawing the most probable structure of the given compound, the metal core is written first. The carbonyl groups and the other ligands are arranged on the metal in such a way that each metal atom follows the 18e rule. The CO group can occupy either a terminal or a bridged position. To illustrate this concept, consider the example of $(\mu\text{-CO})_2\text{-}[\eta^5\text{-Cp Rh}]_3\ (\text{CO})$.

TVE = 4 + [(6 + 8) × 3] + 2 = 48 or 4 + [(5 + 9) × 3] + 2 = 48

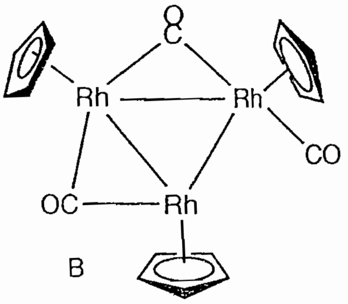
Total number of M–M bonds = (3 × 18) – 48 = 6/2 = 3

Number of bonds per metal atom = 2 (since 48/3 = 16; each metal makes two M–M bonds)

The two plausible structures are given below. Among them, structure A is the right one. The way structure B is drawn (it satisfies the given formula with 2 bridged CO and one terminal CO), the electron count on the three Rh atoms is 17e, 18e and 19e. Hence the structure is not cceptable.[9]



A



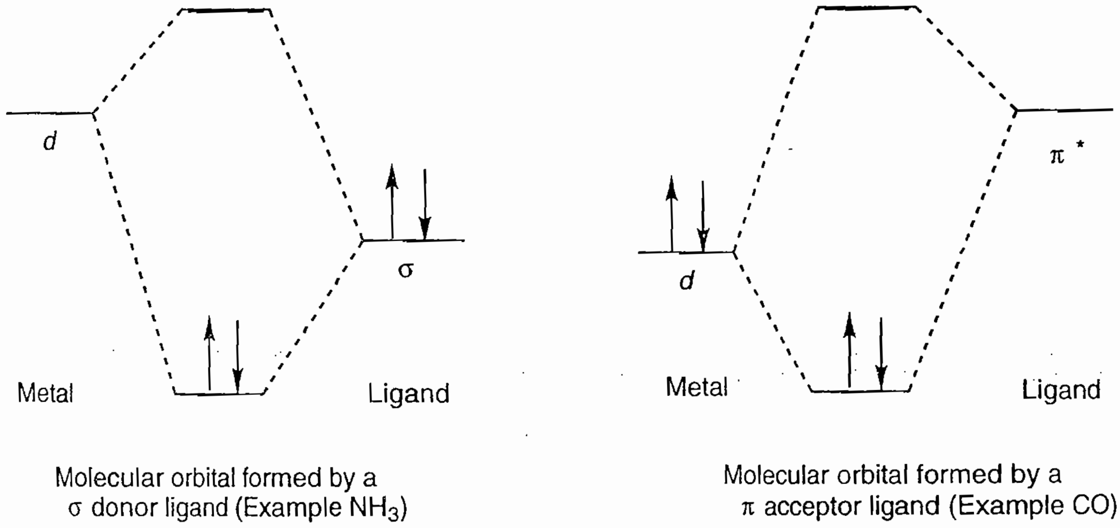
B

e 18 electron rule forms the fundamental basis on which many physical and chemical operties of organo-transition metal compounds can be explained. It can be used predict the number of ligands a particular metal can coordinate with as well as the bility/reactivity of the complex thus formed. The rule works best for low-valent metals with small ligands that are strong σ-donors and/or π-acceptors. Such small ligands allow the metal to be coordinatively saturated and give a large value of ligand field splitting. It may be noted that as in the case of the octet rule, there are many exceptions to the 18 electron rule.

[illegible] / [illegible]

2.4 COMPLIANCE AND VIOLATION OF THE 18 ELECTRON RULE

While a large number of organometallic complexes, especially those possessing strong field ligands such as CO obey the 18 electron rule, there are many complexes like those of early transition metals (such as Ti, Zr, V) and square planar late transition metals (such as Rh, Pd, Pt) which do not obey the rule. To find an explanation, the basics of the molecular orbital interactions in a typical organometallic complex have to be understood first. Based on the nature of the metal–ligand orbital interactions, organometallic ligands are observed to behave as σ-donors, π-donors or π-acceptors. While the type of interaction in the first two cases is similar – where an electron pair is donated from the ligand to an empty or partly empty orbital of the metal – in the case of the π-acceptor type interaction, the donation of electrons takes place from the metal to the antibonding orbital of the ligand which has a comparable symmetry and energy to the metal orbital involved. Figure 2.1 shows the difference between these two types of interactions (see Fig. 3.3 for a pictorial representation).



Molecular orbital formed by a σ donor ligand (Example NH_3)

Molecular orbital formed by a π acceptor ligand (Example CO)

Fig. 2.1 MO diagrams of σ-donor and π-acceptor ligands

Information on the compliance of the 18 electron rule can be obtained by considering the molecular orbital picture of the complexes. The σ only MO diagram of an octahedral complex (Fig. 2.2) indicates that there are six bonding orbitals, which are closer in energy to the original ligand group orbitals. These can accommodate a total of 12 bonding electrons from the ligands. Now most of the organometallic octahedral complexes which obey the 18 electron rule have π-acceptor ligands. The electrons from the metal can be accomodated in the t_{2g} orbitals, which in a purely σ only consideration are nonbonding, but become bonding when π back bonding is considered. For example, in the case of Mo(CO)$_6$ the strong σ-donor ability of carbon monoxide raises the energy of the $e_g{}^*$ orbitals making them more antibonding while its strong π-acceptor ability helps to stabilise the t_{2g} orbitals further as bonding orbitals. These t_{2g} bonding orbitals can now accommodate another 6 electrons, thereby giving a total of 18 electrons.

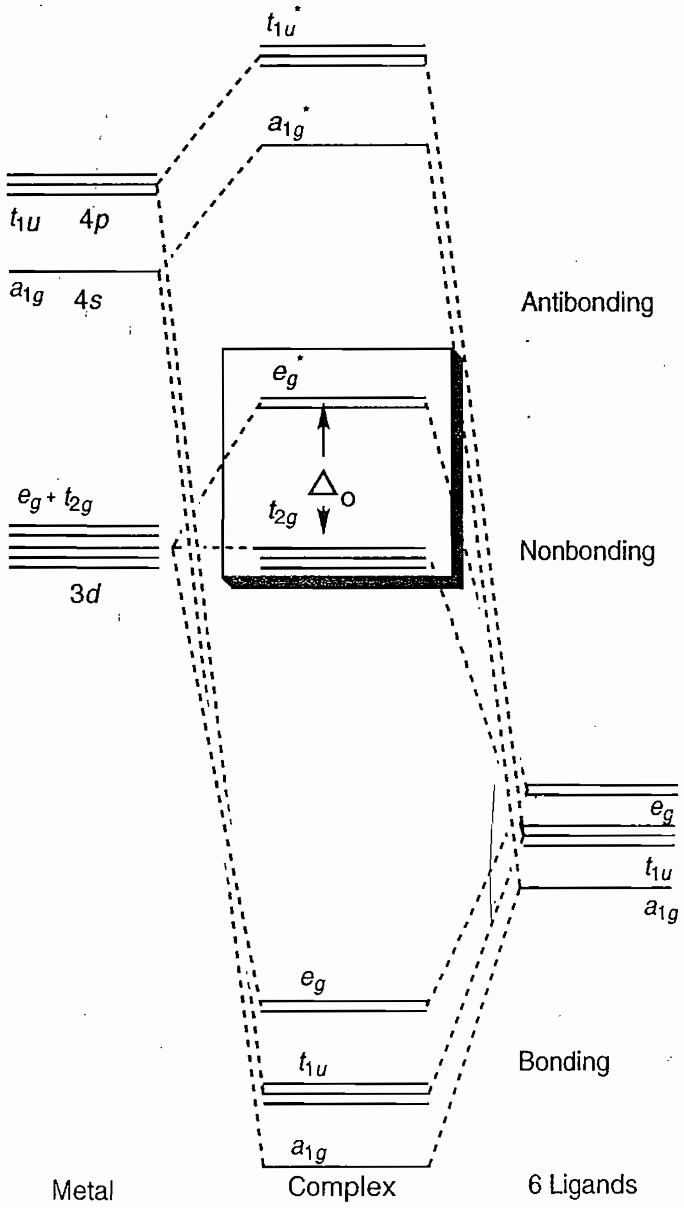


Fig. 2.2 σ only MO diagram of an octahedral complex

A similar situation can be seen in the MO diagram of sandwich compounds such as ferrocene (Fig. 18.3) where electrons are filled in the bonding and nonbonding orbitals, and the HOMO is a nonbonding a_1 $(d_z{}^2)$ orbital. The energy level diagram of bis(benzene) chromium, another 18e sandwich complex is quite similar to that of ferrocene. For complexes having only σ- or π-donor ligands, the possibility of violation of the 18 electron rule is therefore more frequent.

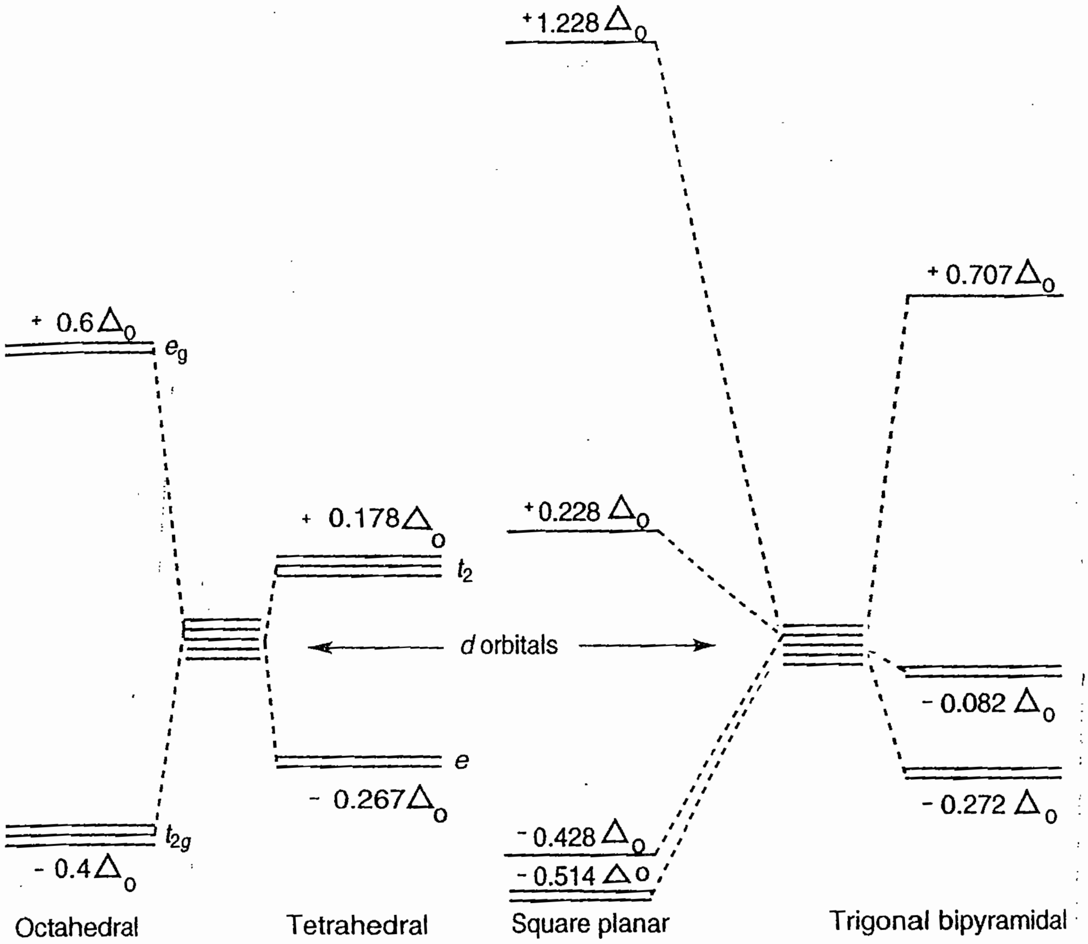


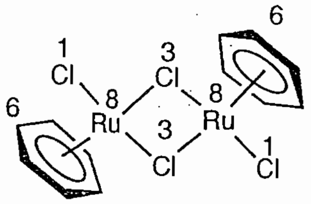
Fig. 2.3 Crystal field splitting diagrams of various geometries showing approximate energy levels

For a five-coordinate trigonal bipyramidal complex such as Fe(CO)$_5$ which obeys the 18 electron rule, the crystal field splitting diagram (Fig. 2.3) indicates that four of the metal based orbitals have negative crystal field splittings and are low in energy and only one orbital is antibonding. These four bonding/nonbonding metal based orbitals can accommodate 8 electrons and the 10 electrons donated by the five ligand group orbitals are accommodated in the ligand based bonding molecular orbitals of lower energy—the total of 18 electrons is accounted for.

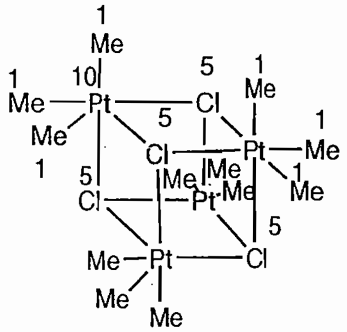
For a tetrahedral complex such as Ni(CO)$_4$ which obeys the 18 electron rule, the practice adopted so far in explaining compliance with the 18 electron rule does not appear to work since four ligands will supply 8 electrons and only two orbitals have negative crystal field splittings. However, in tetrahedral complexes the magnitude of splitting between the t_2 and e orbitals is very small and therefore both the t_2 and the e sets of d orbitals donate electrons to the π acceptor orbitals of the CO ligands leading to a bonding interaction. MO calculations have shown that these π bonding interactions dominate over the σ bonding interactions in tetrahedral complexes, which account for the splitting of the d orbitals. Thus contributions from all the five metal d orbitals are to be taken together to account for the required 10 electrons along with the 8 electrons supplied by the four ligands.[10]

Pitfalls encountered while counting electrons

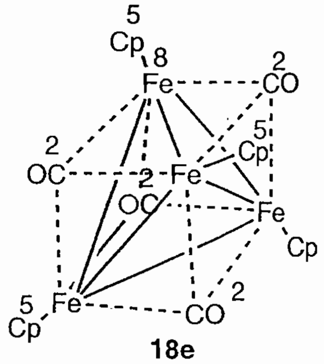
While counting of the valence electrons of organometallic complexes having only terminal ligands is rather straightforward, there are many pitfalls that one should be concerned about while undertaking the counting of electrons of multimetallic complexes possessing bridging ligands with or without metal–metal bonds. Bridging ligands are often of the μ_2 type and rarely μ_3. Selected examples of organometallic complexes having bridging ligands and their electron counting based on the neutral atom counting method are shown below.



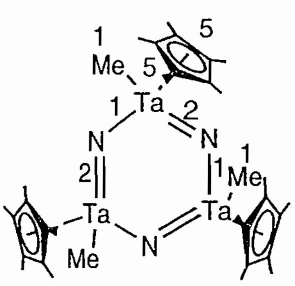
18e



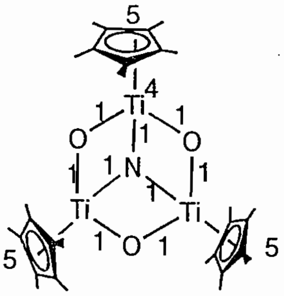
18e



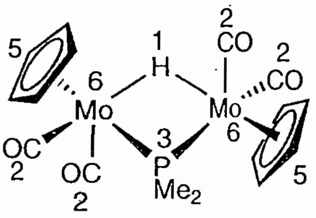
18e



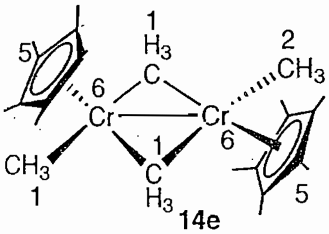
14e



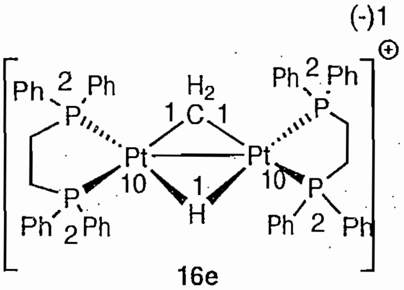
12e



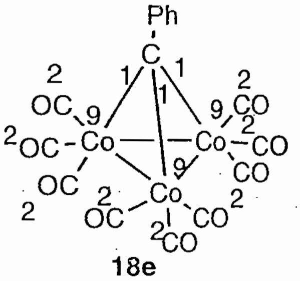
17e



14e



16e



18e

For neutral ligands such as carbonyls, irrespective of whether they are terminal, μ_2 or μ_3, or whether following the neutral atom/oxidation state counting method, the electron count remains the same (2e). For bridging mono-anionic ligands such as Cl^-, using the neutral atom counting method, it is a 3e donor when it is μ_2 and a 5e donor when it is μ_3. This can be envisaged from the assumption that the ligand binds to one metal through the anionic charge and to others using the available lone pair(s). In the case of bridging H^- and CH_3^-, since no lone pairs are available, they remain one-electron donors. For multi-anionic ligands, bridging of the metal sites takes place using the anionic charges and therefore CH_2^{2-} and O^{2-} remain 2e donors, while RC^{3-} and N^{3-} are 3e donors as per the neutral atom counting method. Note that these will be 4e and 6e donors respectively in the oxidation state counting method. Similar to bridging halides, μ_2 bridging amido ligands are 3e donors as are phosphides and alkoxides. Each metal–metal single bond involves 2 electrons and the contribution to electron counting per metal will be one electron which is essentially an electron shared from the other metal. Understanding such a metal–metal bond becomes easier if it is compared to the covalent bond between the two chlorine atoms in Cl_2.

A clear violation of the 18 electron rule is the case of square planar organometallic complexes of the late transition metals. As shown in the crystal field splitting diagram, four of the *d* orbitals either have a negative or a small positive crystal field splitting (Fig. 2.3). One of the orbitals, the $d_{x^2-y^2}$, has a large positive crystal field splitting of $+1.228\Delta_o$. In MO terms, this orbital is clearly antibonding and normally remains unoccupied. The total valance electron count in this case therefore includes 8 electrons donated by the four ligands and 8 electrons from the four low energy *d* orbitals totalling only 16.

In addition, many organometallic complexes of the early transition metals violate the 18 electron rule (for example Cp_2TiCl_2, WMe_6, Me_2NbCl_3, $CpWOCl_3$). A possible reason is that some of the orbitals of these complexes are too high in energy for effective utilisation in bonding, or the ligands are mostly σ-donors.

Many high valent d^0 complexes have a lower electron count than 18. Also, sterically demanding bulky ligands force complexes to have less than 18 electrons. The 18 electron rule fails when bonding in moderate to big organometallic clusters are considered. The bonding of clusters and their stabilities are therefore considered under other electron counting rules (see Chapter 10, Metal Clusters). Also, the rule is not applicable to organometallic compounds of main group metals and to those of lanthanide and actinide metals.

Problems and Exercises

2.1. Suggest and draw possible 18 electron structures which can be formed from the following combinations of metals and ligands. Use at least one unit of each ligand listed for the particular metal. Propose only neutral complexes. Do not use more than two metal centres and show your electron counting. If there is more than one possibility, indicate which complex will be the most stable (note that ligands are indicated without charges).

(a) Ru, CO, CH_3, PMe_3
(b) Mo, allyl, Cp, NO
(c) Rh, dppe (chelating), μ-CO, HC≡CH
(d) Ir, Cp, H, PMe_3

2.2. Consider the 18 electron rule as a guide and determine the value of *n* in the following complexes.

(a) $Na_2Fe(CO)_n$ n = 4
(b) $MnBr(CO)_n$ n = 5
(c) $W(\eta^6\text{-}C_6H_6)(CO)_n$ n = 3
(d) $Rh(\eta^5\text{-}C_5H_5)(CO)_n$ $\boxed{n = 2}$
(e) $Cr(\eta^3\text{-}C_5H_5)(CO)_n(CH_3)$ n = 4
(f) $IrBr_2(CO)_n(PPh_3)_2(CH_3)$ n = 1

2.3. For the following molecules, give the formal oxidation state of the metal, *d* electron count, total valence electrons (TVE) and the number of M–M bonds if any.

Complex	Oxidation State	*d* electron count	TVE	M–M bonds
$[CpCo(CO)]_2$ (μ-CO)	+1	8	34	1
(cyclo C_4H_4) $PdCl_2$	+2	8	16	0
(η^3-allyl)$_2$Ni	+2	8	16	0
$CpMo(CO)_3^-$	0	6	18	0
$Ru(PPh_3)_2Cl(NO)$ (linear NO)	0	8	16	0
Cp(η^6-C_6H_6)Mn	+1	6	18	0
$Cp_2ZrH(CH_2CH_2CH_3)$	+4	0	16	0
$CpMn(CO)_3$	+1	6	18	0
Cp_2ZrCl_2	+4	0	16	0

2.4. Predict M if it is a first row transition element and [M(η^3-C_5H_5)$(CO)_5$] is a stable compound. ✓

2.5. The complex [M(η^6-C_6H_6)$(CO)_2$]$_2$ obeys the 18 electron rule and has one metal–metal double bond. Predict M and sketch the probable structure of the complex.

2.6. A metal complex having the empirical formula $FeC_9H_7O_3Cl$, has one ligand as a substituted cyclopentadienyl group. It is an ionic compound and has poor solubility in hydrocarbon solvents. The compound gives a white precipitate on treatment with $AgNO_3$ solution. Assuming that it obeys the 18 electron rule, suggest its structure.

2.7. Determine the number of metal–metal bonds in the following complexes which obey the 18 electron rule.

(a) $(CO)_2Rh(\mu\text{-}Cl)_2Rh(CO)_2$ (b) (η^5-C_5H_5)(CO)Fe(μ-CO)$_2$Fe(CO)(η^5-C_5H_5)

2.8. Determine the unknown quantity M – M

(a) $[CpW(CO)_x]_2$ (has a W–W single bond) x= 3

(b) $[(CO)_3Ni\text{-}Co(CO)_3]^z$

(c) $[CpMn(CO)_x]_2$ (has Mn=Mn double bond)

(d) $[(Cp)_3Ni_3(\mu_3\text{-}CO)_2]^z$ (has 3 Ni–Ni bonds)

(e) $[CpM(CO)_3]_2$ (has a single M–M bond; M = Ist row transition metal)

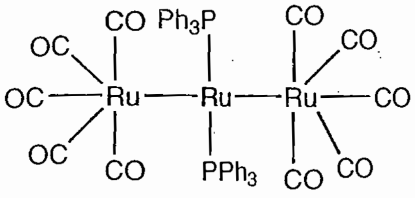
2.9. The given complexes are thermodynamically stable. Comment on the nature of NO in these complexes. Which among them is expected to have a shorter metal–nitrogen bond? Give reasons.

(a) (η^3-allyl)Ru$(CO)_2$(NO) (b) (η^5-Cp)Ru$(CO)_2$(NO)

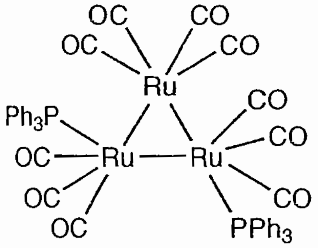
2.10. The given dimeric rhodium complexes have two symmetrically bridging groups (H and Cl). The geometry around the rhodium in both cases is square planar. Draw the possible structures and determine the expected bond order of the rhodium–rhodium bond in both cases.

(a) [(η^2-ethylene)$_2$Rh(μ-H)]$_2$ (b) [(η^2-ethylene)$_2$Rh(μ-Cl)]$_2$

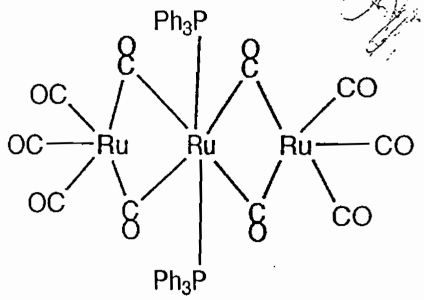
2.11. The metal cluster $[Ru_3(CO)_{10}(PPh_3)_2]$ is very stable. Which among the following will be the actual structure of the molecule? Justify your answer.



A

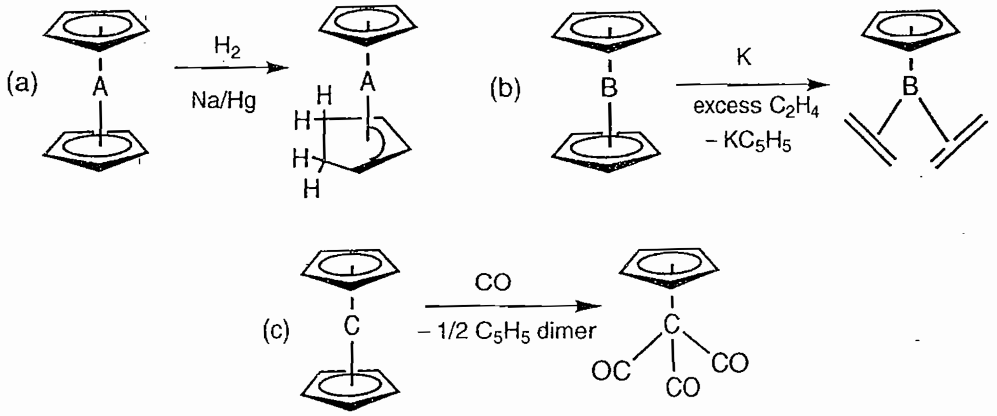


B



C

2.12. The following reactions of first row transition metal containing metallocenes having η^5-Cp ligands lead to stable products. Identify the transition metals A, B and C present in these compounds.



2.13. Chromium is known to form complexes with carbonyl and nitrosyl ligands. For complexes of the type $Cr(CO)_n(NO)_m$, determine the values of *m* and *n*, so that one can realise compounds which obey the 18 electron rule and which have only linear nitrosyl ligands. Note that there can be more than one answer. The value of *m* and *n* can be zero or higher.

2.14. Following the 18e rule as a guide, determine *x* in the following complexes.

(a) $[\eta^5\text{-CpOs(CO)}_x]_2$ (has an Os–Os single bond)   (b) $[Co(CO)_3]^x$

(c) $[(Ni(CO)_3(NO)]^x$ (consider NO as linear)   (d) $[\eta^5\text{-Cp Fe(CO)}_3]^x$

(e) $[\eta^6\text{-}(C_6H_6)Mn(CO)_2(CH_3)]^x$ (f) $[\eta^5\text{-Cp(CO)}_2Fe(PhC\equiv CH)]^x$

2.15. For the given compounds, calculate (a) the total number of M–M bonds in each molecule and (b) the number of M–M bonds each metal makes with the other metal. Also draw the most appropriate structure in each case.

(a) $(\mu\text{-H})_2[\eta^5\text{-Cp(NO)WH}]_2$ (NO is linear)   (b) $(\mu\text{-Br})_2[Mn(CO)_4]_2$

(c) $\mu\text{-CO-}\mu\text{-CH}_2\text{-}[\eta^5\text{-CpRh}]_2$ (d) $[\mu\text{-X-}\mu\text{-CH}_2Os_3(CO)_{10}]^-$

(e) $(CO)_4V(\mu\text{-}PR_2)_2V(CO)_4$ (f) $[\eta^5\text{-}CpMn(CO)_3]_2$

(g) $[\eta^5\text{-}CpCr(CO)_3]_2$ (h) $[\eta^5\text{-}CpFe(CO)_2]_2$

(i) $[\eta^5\text{-}CpMo(CO)_2]_2^{2-}$ (j) $Ir_4(CO)_{12}$

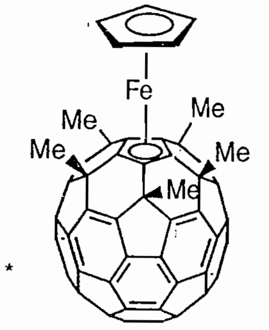
(k) $(\mu\text{-}CO)\text{-}[\eta^5\text{-}CpRe(CO)_2]_2$ (l) $(\mu\text{-}CO)\text{-}[\eta^4\text{-}(C_4H_4)Fe(CO)]_2$

(m) $(\mu_3\text{-}CO)\text{-}[Fe_4(CO)_{12}]^{2-}$

2.16. Draw the structure of $[HRu(PPh_3)_3]^+$ which obeys the 18 electron rule.

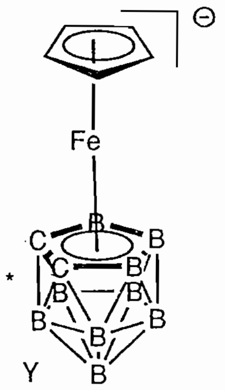
2.17. Trimetallic complexes of phosphido bridges are well known. Assuming that the 18e rule is followed, postulate the structure of $[Mn(\mu\text{-}PH_2)(CO)_4]_3$. (*Organometallics*, **1989**, Vol. 8, 857)

2.18. Predict the formal charge and the oxidation state electron count of the starred ligand in the given complexes, all of which obey the 18 electron rule. The oxidation state of Fe = +2 and Co = + 1 in these compounds.



X

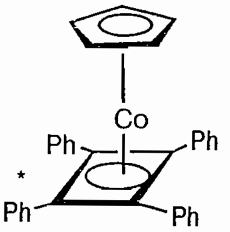
$(C_{60}Me_5)FeCp$



Y

(all C and B with one H)

$[(7,8\text{-}C_2B_9H_{11})FeCp]^-$



Z

$[(C_6H_5)_4C_4]CoCp$

Supplementary reading

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CHAPTER 3

METAL CARBONYLS

Carbon monoxide is one of the most important ligands in organometallic chemistry. Homoleptic carbonyls (complexes containing only carbonyls as ligands) can be prepared for many of the *d*-block metals and these are useful as precursors for other organometallic complexes. The bonding of the carbonyl to the metal is highly sensitive to electronic effects on the metal centre. This is usually monitored by infrared (IR) spectroscopy. Figure 3.1 shows representative examples of some well known metal carbonyls. Most of the metal carbonyls have the metal in very low oxidation states, sometimes even zero and negative oxidation states.[1-6]

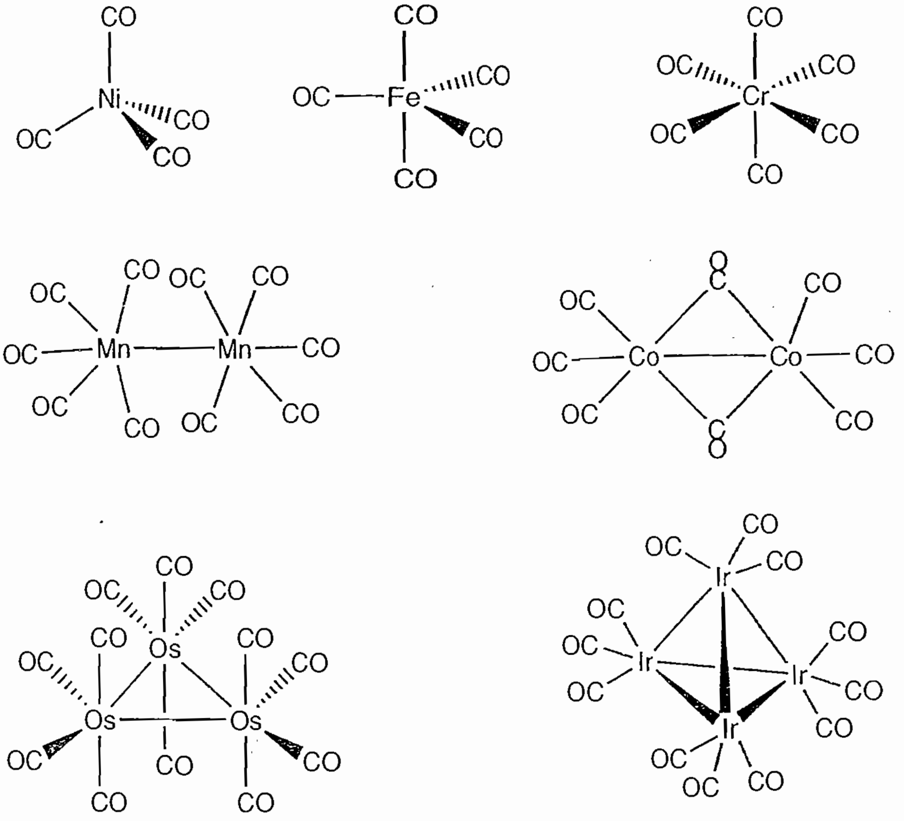


Fig. 3.1 Some examples of homoleptic metal carbonyls

3.1 STRUCTURE, π-BONDING AND INFRARED SPECTROSCOPY

The properties of CO as a π acid ligand are well explained by the molecular orbital (MO) diagram of CO (Fig. 3.2). The HOMO of CO is a σ orbital having a higher amplitude on the carbon atom than the oxygen atom and is therefore considered as a carbon based orbital which is also slightly antibonding in nature with respect to the oxygen atomic orbitals. The π* antibonding orbitals which are the LUMOs are closer in energy to the carbon atomic orbitals than the oxygen atomic orbitals and thus have a greater amplitude on carbon. This explains why CO binds through the carbon atom and also why it is good σ-donor and a good π-acceptor. There exists a strong back bonding or π overlap of metal electrons to the π* antibonding orbitals of CO.[7–9]

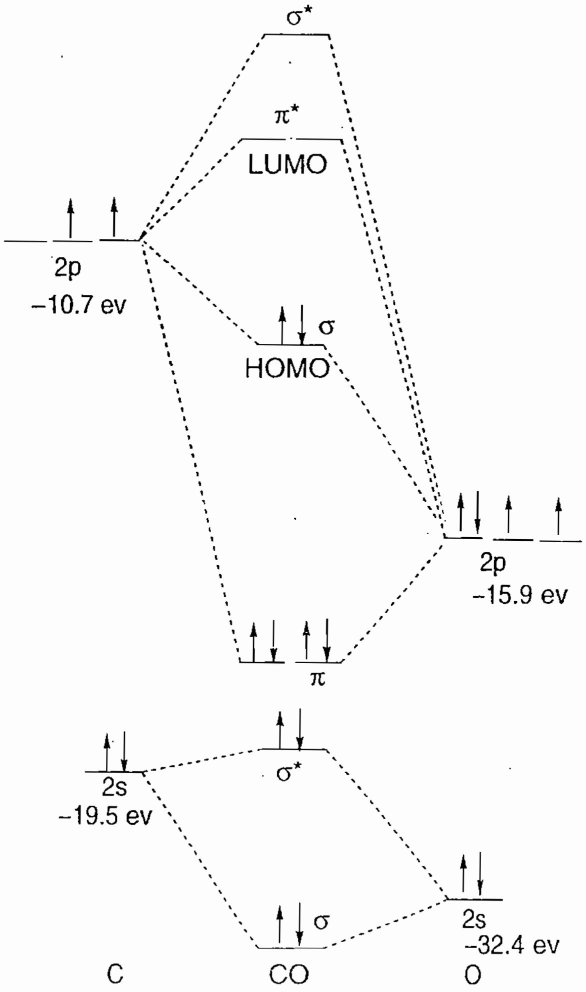


Fig. 3.2 Molecular orbital picture of carbon monoxide (not to scale)

Most of the metal carbonyls obey the 18 electron rule and in cases where it is not obeyed, the carbonyl will be comparatively more reactive and will undergo reactions such as dimerisation or electron abstraction to gain eighteen electrons. Dimerisation is also dependent upon the size of the metal and the number of ligands it can accommodate without steric repulsion. This is a reason why the 17 electron species, $V(CO)_6$ does not undergo dimerisation while another 17 electron species $Mn(CO)_5$ dimerises readily to gain 18 electrons by the formation of a metal–metal bond [$V_2(CO)_{12}$, prepared by direct condensation of V and CO is stable only in a CO matrix at extremely low temperatures].

It has been found that CO mainly shows two types of bonding—terminal and bridging. As the C–O stretching frequency is quite sensitive to small changes in the electronic environment, one can identify these by IR spectral studies. (In electron counting methods to find out if the complex obeys the 18 electron rule, both bridging and terminal CO are considered as 2 electron neutral donors.) It is rather difficult to arrive at the number of bridging and terminal ligands by using just the electron counting method. For example, $Co_2(CO)_8$ has two isomers – one with no bridging carbonyls and another with two bridging carbonyl groups – both of which are 18 electron species. The C–O stretching frequencies of terminal carbonyls are observed in the range of 2120–1850 cm^{-1} similar to the free carbon monoxide molecule (2143 cm^{-1}) while bridging carbonyl stretching frequencies are observed in the range of 1850–1750 cm^{-1} (saturated ketones ~ 1715 cm^{-1}).

The bonding of CO to a metal can be described as consisting of two components. The first component is a two electron donation of the lone pair on carbon (coordination exclusively through the oxygen is extremely rare) into a vacant metal *d* orbital. This electron donation makes the metal more electron rich, and in order to compensate for this increased electron density, a *filled* metal *d* orbital can interact with the *empty* π^* orbital on the carbonyl ligand to relieve itself of the added electron density. This second component is called π-backbonding or π-backdonation.[10-12]

The two components of this bonding are synergistic. More the σ donation by the carbonyl (or other σ donors on the metal centre), stronger is the π-backbonding interaction. Notice that although this involves the occupation of a π^* orbital on the CO, it is still a bonding

Carbon monoxide in medicine

Carbon monoxide (CO) is known as a toxic gas. Paradoxically, the human body itself produces 3–6 cm^3 of CO every day. Certain diseases cause this quantity to increase, which can be detected on the patient's breath. British researchers Mann and Motterlini have developed a family of CO-releasing complexes that could turn out to be a new class of medicines. CO has been demonstrated to play a crucial role as a signal carrier in certain physiological processes, particularly in the cardiovascular system, and is important in various areas of medicine. It thus helps to suppress rejections after organ transplants, and reduces the damage caused by disruption of the blood supply to an organ or tissue (ischemia). The use of CO as a drug thus seems obvious. Mann and Motterlini did not want to use CO as a gas; however they were searching for a 'solid' form, a compound that would release CO inside the body. They chose to use metal carbonyl complexes. A number of ruthenium and iron complexes proved to be particularly promising. The ruthenium complexes very quickly release CO in the presence of myoglobin, a protein involved in oxygen transport in muscles. In trials, they demonstrated a vasodilatory effect and a significant increase in life expectancy in animals after heart transplants. Also noteworthy are some iron complexes that do not transfer CO to myoglobin, yet still acts as vasodilators. In this case, the CO seems to be released directly into cells, which may make it possible to bring CO directly into tissues. CO-releasing molecules such as carbonyl complexes could lead to the development of new drugs for the treatment of cardiovascular diseases as well as neurodegenerative and inflammatory diseases. (Mann B et al, *Angew Chem. Int. Ed. Engl.*, 2003, Vol. 42, 3722; Otterebin L E et al, *Nature Medicine*, 2003, Vol. 9, 183) interaction as far as the metal centre is concerned. There is a fundamental similarity between the nature of carbonyl–metal bonding and that of alkenes, acetylenes, phosphines and dihydrogen. This occupation of the π* on CO does lead to a decreased bond order in the carbon monoxide molecule itself. The consequences that we might expect if the CO bond order was reduced would be a lengthening of the C–O bond, shortening of the M–C bond and a decrease in the carbonyl stretching frequency in the IR spectra. As the electron density on a metal centre increases, more π-backbonding to the CO ligand(s) takes place. This weakens the C–O bond further by pumping more electron density into the formally empty carbonyl π* orbital. This increases the M–CO bond strength making it more double-bond-like, that is, the resonance structure M=C=O becomes more important (Fig. 3.3).

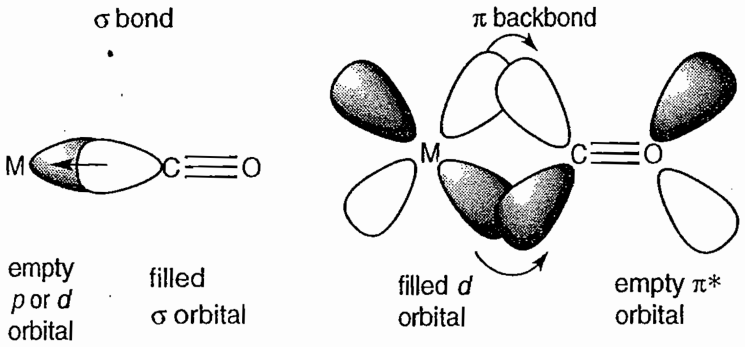


Fig. 3.3 Orbital overlap for σ and π bonding in metal carbonyls

Table 3.1 Variation in ν_{CO} (cm^{-1}) of the first row transition metal carbonyls[13]

CO^+ 2184	free CO 2143	$BH_3{:}CO$ 2164
$Cu(CO)_4^+$ 2202		
$Ni(CO)_4$ 2057		
$Co(CO)_4^-$ 1890		$Co_2(CO)_8$ 2044(av, ter)
$[Fe(CO)_4]^{2-}$ 1815	$[Fe(CO)_6]^{2+}$ 2204	$Fe(CO)_5$ 2030
$[Mn(CO)_4]^{3-}$ 1600, 1790	$Mn(CO)_6^+$ 2098	$Mn_2(CO)_{10}$ 2013 (av)
$[Cr(CO)_4]^{4-}$ 1462, 1657	$Cr(CO)_6$ 2000	
	$V(CO)_6^-$ 1860	$V(CO)_6$ 1976
	$Ti(CO)_6^{2-}$ 1747	

The ν_{CO} values given in Table 3.1 clearly illustrate the effect of charge, and thereby electron density on the extent of metal to CO π-backbonding. Although some additional factors such as electronegativity and size of the metal are being projected as influencing the electronic effects, they are minimal and contribute less to the observed CO stretching frequencies.

The donor/acceptor ability of the ligands on a metal has considerable effect on the absolute amount of electron density on that metal. This naturally affects the ν_{CO} infrared stretching frequencies of metal carbonyls when other ligands are present on the same metal centre. Ligands which are *trans* to a CO can have a particularly large effect on the ability of the CO ligand to effectively π-backbond to the metal. Thus two *trans* π-backbonding ligands will compete for the metal's *d* orbital electron density, weakening each others' effective M–L π-backbonding.

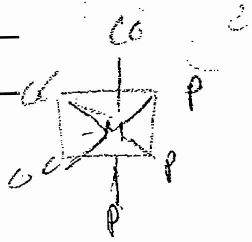
If the ligand *trans* to a CO is a σ-donor ligand, it will increase the M–CO bond strength by allowing unrestricted metal-to-CO backbonding. Table 3.2 shows the effect of a series of *trans* ligands on the ν_{CO} infrared stretching frequencies of *fac* isomers of $Mo(CO)_3L_3$. Pyridine and other amines are not very strong σ-donors, and they are even worse π-backbonding ligands. So the CO has virtually no competition for π-backbonding, which results in lower ν_{CO} values.

Two interesting trends are observed in the infrared spectra of carbonyl complexes that are both consistent with the concept of π-backbonding.

Table 3.2 Effect of different co-ligands on ν_{CO} (cm^{-1}) of $Mo(CO)_3L_3$[14]

Complex (fac isomers)	ν_{CO} cm^{-1}
$Mo(CO)_3(PF_3)_3$	2090, 2055
$Mo(CO)_3(PCl_3)_3$	2040, 1991
$Mo(CO)_3[P(OMe)_3]_3$	1977, 1888
$Mo(CO)_3(PPh_3)_3$	1934, 1835
$Mo(CO)_3(NCCH_3)_3$	1915, 1783
$Mo(CO)_3(dien)$*	1898, 1758
$Mo(CO)_3(Py)_3$	1888, 1746

* dien = diethylenetriamine (tridentate)



- With each negative charge added to the metal centre, the CO stretching frequency decreases by approximately 100 cm^{-1}.
- The better the σ donating capability (or poorer the π acceptor ability) of the other ligands on the metal, the lower the CO stretching frequency.

The following ligands can be ranked in order of their π-acceptor abilities based on infrared spectral data available on metal carbonyls substituted by them.

$$NO > CO > PF_3 > RN{\equiv}C > PCl_3 > P(OR)_3 > PR_3 > RC{\equiv}N > NR_3$$

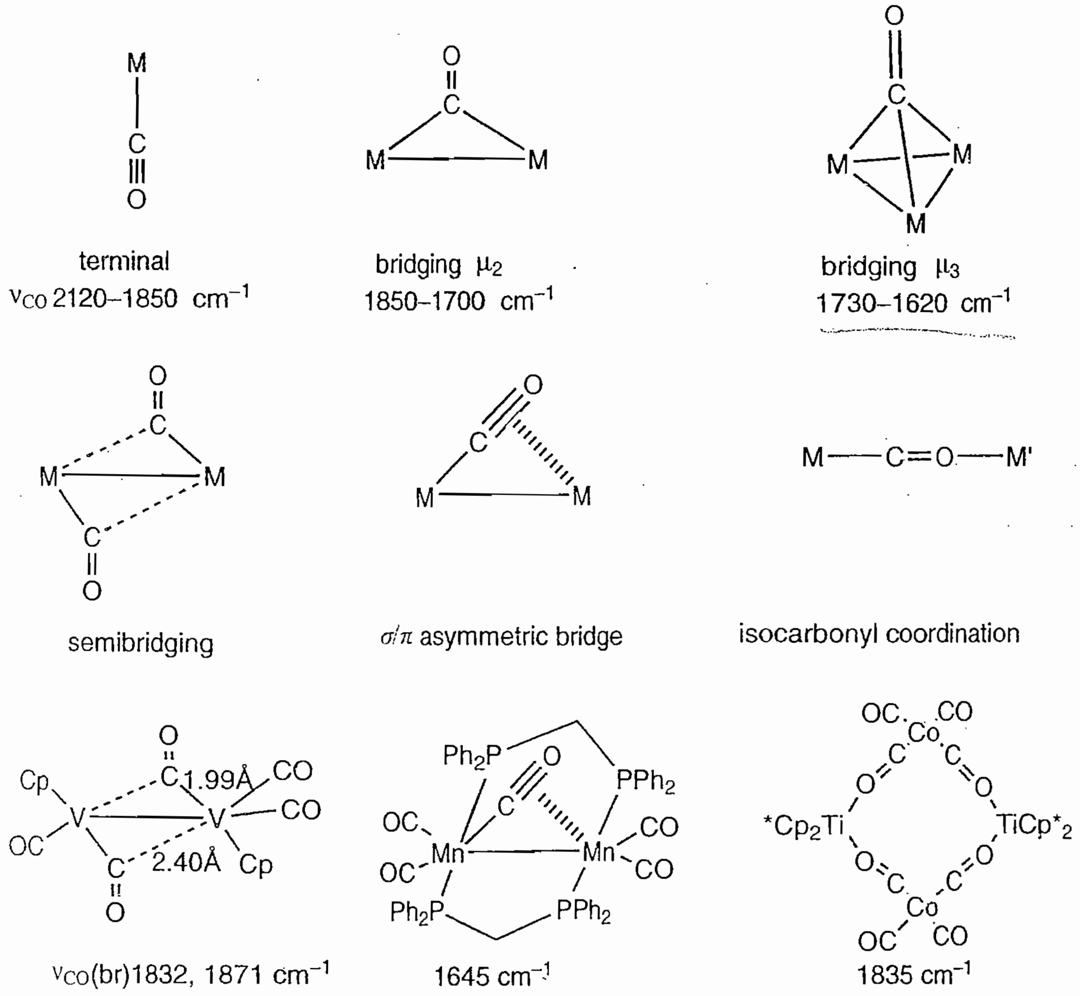
In addition to these two significant factors, the effect of electronegativity and size of the metal are also considered. The former has a marginal effect (Table 3.3) and the latter has no effect on the ν_{CO} stretching frequencies. [$Cr(CO)_6$: 2000cm^{-1}; $Mo(CO)_6$: 2004 cm^{-1}; $W(CO)_6$: 1998 cm^{-1}].

Table 3.3 Relationship between electronegativities of the metal and carbonyl stretching frequencies

Metal carbonyl	$V(CO)_6$	$Cr(CO)_6$	$Mn_2(CO)_{10}$	$Fe(CO)_5$	$Co_2(CO)_8$	$Ni(CO)_4$
ν_{CO} (cm^{-1})	1976	2000	2013 (av)	2023 (av)	2044 (av)	2057
Electronegativity of the metal (Pauling)	1.6	1.6	1.6	1.8	1.9	1.9

3.2 BONDING MODES OF CO

CO typically bonds in an end-on fashion through carbon (Fig. 3.4). However, bridging carbonyls are not uncommon and often undergo exchange with terminal carbonyls.



terminal
ν_{CO} 2120–1850 cm^{-1}

bridging μ_2
1850–1700 cm^{-1}

bridging μ_3
1730–1620 cm^{-1}

semibridging

σ/π asymmetric bridge

isocarbonyl coordination

ν_{CO}(br)1832, 1871 cm^{-1}

1645 cm^{-1}

1835 cm^{-1}

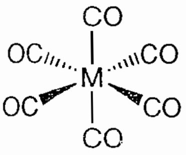
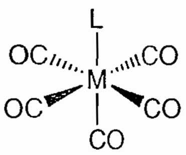
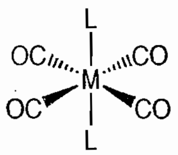
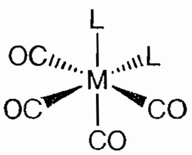
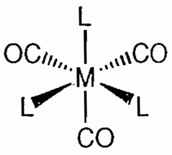
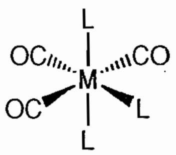
Fig. 3.4 Various bonding modes of CO

Different types of symmetrical and unsymmetrical bridging are observed within the bridging carbonyls. Among bridging carbonyls, μ_2-CO is most often encountered and it is noteworthy that μ_2-CO is not a dimetallaketone. The bond angle in M_2CO is much more acute (77–90°) than in R_2CO (120°) and is also highly delocalised. Bridging of three metal centres (or capping of the triangular face of a polyhedron) is also observed with many clusters of metal carbonyls [for example, $Rh_6(CO)_{16} = Rh_6(CO)_{12}(\mu_3\text{-}CO)_4$]. A variant of a bridging carbonyl is the 'semi-bridging' carbonyl, in which the M–CO–M bond is asymmetric rather than symmetric. These can be considered as being intermediate between terminal and bridging carbonyls. In another unsymmetrical form called the σ/π bridge, CO acts as a four or six electron donor, and shows a side-on coordination similar to the coordination of vinyl complexes. Isocarbonyl coordination through the oxygen atom of a coordinated CO to metals such as titanium, aluminum and the lanthanides is also observed, but very rarely. The typical ν_{CO} stretching frequency ranges of neutral metal carbonyls are as given in Fig. 3.4.

3.3 SYMMETRY OF METAL CARBONYLS

The local symmetry around the central metal atom of metal carbonyls decides the number and intensity of the carbonyl stretching bands in their IR spectra. The number of IR active bands possible for a specific isomer can be arrived at by using group theory. By simply counting the number of IR bands present, one can deduce the symmetry of most of the substituted metal carbonyls. Table 3.4 shows the symmetry and number of IR bands for common isomers of substituted octahedral metal carbonyl complexes. The same analysis is applicable to tetrahedral and trigonal bipyramid metal carbonyls.

Table 3.4 Relationship between symmetry and number of carbonyl stretching bands[15, 16]

					
	Mono	Trans	Cis	Fac	Mer
Oh (T_{1u})	C_{4v} ($2A_1 + E$)	D_{4h} (E_u)	C_{2v}($2A_1 + B_1 + B_2$)	C_{3v} ($A_1 + E$)	C_{2v} ($2A_1 + B_2$)
One	Three*	One	Four*	Two	Three*

*The number of bands expected is based on formal selection rules. In some cases, fewer bands are observed. In $ML(CO)_5$ if the four-fold array of CO ligands lies in the same plane, only two bands will be observed. In the cases of *cis* $ML_2(CO)_4$ and *mer* $ML_3(CO)_3$ if the *trans* CO ligands are collinear, one band less will be observed.

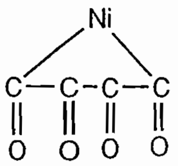
3.4 SYNTHESES OF METAL CARBONYLS

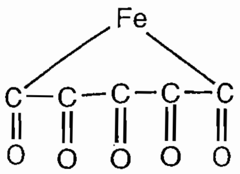
In 1868, Schutzenberger prepared the first metal carbonyl compound, $[PtCl_2(CO)]_2$, by the reaction of $PtCl_2$ with carbon monoxide.

$$PtCl_2 + CO \longrightarrow [PtCl_2(CO)]_2 + \textit{Cis}\ PtCl_2(CO)_2 \qquad (3.1)$$

The first metal carbonyls[17, 34]

Although Schutzenberger was the first to make a metal carbonyl, the chemistry community considers Ludwig Mond as the father of metal carbonyl chemistry. The serendipitous discovery of $Ni(CO)_4$ (1890) by Mond and coworkers was followed by discoveries of a few more metal carbonyls such as $Fe(CO)_5$ (1891), $Co_2(CO)_8$ and $Mo(CO)_6$ (1910) by the same group. Mond, who was also the founder of the famous Imperial Chemical Industry (England) was smart enough to notice the industrial potential of his nickel carbonyl and obtained a British patent for making pure nickel by the Mond process in 1890. His 'Mond nickel company' was making over 3000 tons of nickel in 1910 with a purity level of 99.9%. It is to be noted that $Ni(CO)_4$, a clear liquid which boils at 42°C and decomposes around 180°C to pure nickel is extremely toxic and Mond's ingenuity has to be complimented as he was able to handle this compound in large quantities successfully at that time. The BASF company in Germany, by using a similar procedure, nowadays manufactures more than 10,000 tons of $Fe(CO)_5$ per year for making iron oxide pigments used in magnetic tape manufacture. It may be of interest to note that it was during this period of discovery of metal carbonyls that Alfred Werner's theory of bonding in metal complexes was being proposed (1893) and chemists had no idea about the actual shape of metal carbonyls. Indeed the original formulae of $Ni(CO)_4$ and $Fe(CO)_5$ given in common chemistry textbooks (see below) published around 1925 reflect the perception at that time.


$Ni(CO)_4$


$Fe(CO)_5$

Simple homoleptic or binary metal carbonyls are made by two basic methods—direct reaction of the metal with CO and reductive carbonylation in which a metal salt reacts with CO in the presence of a reducing agent.

3.4.1 Direct Carbonylation

This method is applicable to the synthesis of only a few metal carbonyls; $Ni(CO)_4$ is the classic example which was discovered by Ludwig Mond in 1890 and has since then been utilised in the refining of nickel as well.[17]

$$Ni + 4\,CO \xrightarrow[1\text{ bar, }25^\circ C]{} Ni(CO)_4 \quad \text{colourless} \quad \text{mp } -17^\circ C\text{, bp } 42^\circ C \tag{3.2}$$

$$Fe + 5\,CO \xrightarrow[100\text{ bar, }150^\circ C]{} Fe(CO)_5 \quad \text{pale yellow} \quad \text{mp } -20^\circ C\text{, bp } 103^\circ C \tag{3.3}$$

3.4.2 Reductive Carbonylation

Reductive carbonylation is the most commonly utilised method for the preparation of binary metal carbonyls. Reducing agents such as aluminium, sodium, zinc, trialkylaluminium and Grignard reagents are used in the reaction with a metal halide or acetate along with carbon monoxide at high pressures and temperatures. Representative reactions are given below.[18–22]

$$CrCl_3 + Al + 6\,CO \xrightarrow[300\text{ bar, }140^\circ C]{C_6H_6,\ AlCl_3} Cr(CO)_6 + AlCl_3 \tag{3.4}$$

$$MoCl_5 + 5\,Na + 6\,CO \xrightarrow[62\text{ bar, }-10-25^\circ C]{\text{diglyme}} Mo(CO)_6 + 5\,NaCl \tag{3.5}$$

$$VCl_3 + 4\,Na + 6\,CO \xrightarrow[300\text{ bar}]{\text{diglyme}} [Na(diglyme)_2][V(CO)_6] \xrightarrow{H_3PO_4} V(CO)_6 \tag{3.6}$$

$$WCl_6 + 3\,Zn + 6\,CO \xrightarrow[50\text{ atm}]{Et_2O,\ 67^\circ C} W(CO)_6 + 3\,ZnCl_2 \tag{3.7}$$

$$RuCl_3.\,3H_2O + CO + H_2 \xrightarrow[\substack{80\text{–}135^\circ/1\text{ atm}\\ KOH,\ 75^\circ C,\ Zn}]{\text{2-ethoxyethanol}} Ru_3(CO)_{12} \xrightarrow[160^\circ C]{CO,\ 200\text{ atm}} Ru(CO)_5\ \text{(unstable)} \tag{3.8}$$

$$2\,Mn(OAc)_2 + 10\,CO + AlEt_3 \xrightarrow[207\text{ bar, }80\text{–}100^\circ C]{(iso\text{-}Pr)_2O} Mn_2(CO)_{10} + Al(OAc)_3 + C_4H_{10} \tag{3.9}$$

$$2\,Mn(OAc)_2 + 4\,Na + 10CO \xrightarrow[165^\circ C,\ 240\text{ bar}]{DME} Mn_2(CO)_{10} + NaOAc \tag{3.10}$$

$$3\,Ru(acac)_3 + 12\,CO + 4.5\,H_2 \xrightarrow[150^\circ C,\ 155\text{ atm}]{MeOH} Ru_3(CO)_{12} + 9\,MeC(O)CH_2C(O)Me \tag{3.11}$$

In the case of metal oxides, carbon monoxide itself acts as a reducing agent and gets converted to CO_2 in the process. The reaction conditions are relatively more drastic for such reactions.

$$OsO_4 + CO \xrightarrow[125^\circ C/75\text{ atm}]{MeOH} Os_3(CO)_{12} + 4\,CO_2 \tag{3.12}$$

$$Re_2O_7 + 17\,CO \xrightarrow[290^\circ C]{215\text{ atm}} Re_2(CO)_{10} + 7\,CO_2 \tag{3.13}$$

$$RuO_2.\,x\,H_2O + CO \xrightarrow[20\text{ atm, }160^\circ C]{\text{toluene}} Ru_3(CO)_{12} + CO_2 \tag{3.14}$$

$$CoO + CO \xrightarrow[80^\circ C]{1900\text{ atm}} Co_2(CO)_8 + CO_2 \tag{3.15}$$

$$Fe_2O_3 + CO \xrightarrow[225^\circ C]{2000\text{ atm}} Fe(CO)_5 + CO_2 \tag{3.16}$$

$$MoO_3 + CO \xrightarrow[300^\circ C]{2000\text{ atm}} Mo(CO)_6 + CO_2 \tag{3.17}$$

$$2\,CoCO_3 + 2H_2 + 8\,CO \xrightarrow[240\text{ bar}]{100\text{–}150^\circ C} Co_2(CO)_8 + 2\,CO_2 + 2\,H_2O \tag{3.18}$$

There are also a variety of other methods, however, they are specific to a few metal carbonyls, clusters and industrially useful carbonyls.

$$Na_3IrCl_6 + CO \xrightarrow[\text{reflux, 1atm}]{\text{MeOH}} Ir_4(CO)_{12} \tag{3.19}$$

$$RhCl_3.\,3H_2O + CO \xrightarrow[\text{100°C, 1atm}]{\text{MeOH}} [Rh(CO)_2Cl]_2 \xrightarrow[\text{CO, H}_2\text{O, NaHCO}_3]{\text{heptane}} Rh_4(CO)_{12} \tag{3.20}$$

$$RhCl_3.\,3H_2O + CO \xrightarrow[\text{60°C, 40–50 atm}]{\text{MeOH}} Rh_6(CO)_{16} \tag{3.21}$$

$$WMe_6 + \text{excess } CO \xrightarrow{\qquad} W(CO)_6 + 3Me_2CO \tag{3.22}$$

$$RhCl(PPh_3)_3 + RCHO \xrightarrow[\text{(deinsertion)}]{} RhCl(CO)(PPh_3)_2 + RH \tag{3.23}$$

$$[Ru(NH_3)_5H_2O]^{2+} \xrightarrow{\text{CO}} [Ru(NH_3)_5(CO)]^{2+} \tag{3.24}$$

$$2\,Fe(CO)_5 \xrightarrow[\text{sunlight}]{\text{AcOH, hv}} Fe_2(CO)_9 + CO \tag{3.25}$$

$$3\,Fe(CO)_5 + 6\,OH^- \xrightarrow[-3HCO_3^-]{} 3[HFe(CO)_4]^- \xrightarrow{3\,MnO_2} Fe_3(CO)_{12} + 3\,OH^- + 3\,MnO \tag{3.26}$$

$$2\,Co_2(CO)_8 \xrightarrow[\text{70°C}]{} Co_4(CO)_{12} + 4\,CO \tag{3.27}$$

3.5 REACTIONS OF METAL CARBONYLS

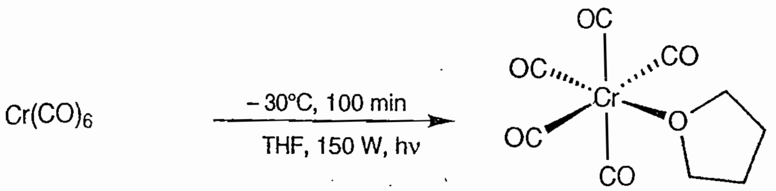
Depending upon whether the metal carbonyl is an 18 electron species or not, dissociative and associative pathways are observed in substitution reactions. For example, a 16 or 17 electron containing metal carbonyl can react by an associative mechanism and it will be much faster than the reactions on an 18 electron metal carbonyl which proceeds by a dissociative mechanism.

Substitution of carbonyl groups under thermal and photochemical conditions constitutes the most common reaction of metal carbonyls. In addition, reactions such as disproportionation, oxidative decarbonylation, reduction and addition of nucleophiles on the carbon monoxide also can be carried out on metal carbonyls.

3.5.1 Activation of Metal Carbonyls

Lewis bases, olefins and arenes are some of the ligands which can be thermally substituted on metal carbonyls. A complete substitution of all carbonyl groups is rarely accomplished. One method that is usually adopted is the activation of a metal hexacarbonyl by the intermediate introduction of a relatively more labile ligand that is replaced later by other ligands under mild conditions.[23]

Some of the $M(CO)_n$ transfer reagents are $(THF)Mo(CO)_5$, $(CH_2Cl_2)Cr(CO)_5$, $M(CO)_4$(norbornadiene) (where M = Mo, W) and $Fe(CO)_3$(cyclooctadiene). These are prepared by direct reaction of the homoleptic metal carbonyl with the solvent or reagent, under thermal or photochemical conditions.



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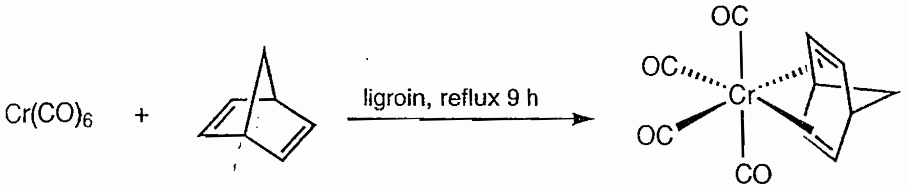

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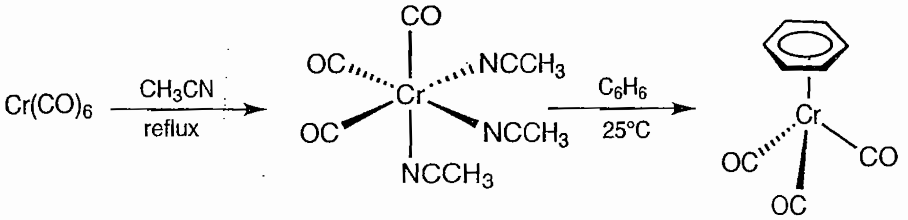


(3.30)

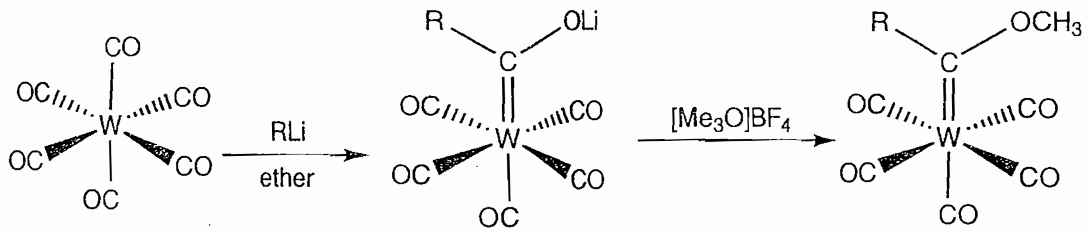
3.5.2 Disproportionation

Some multi-metal carbonyls can undergo disproportionation in the presence of suitable ligands often leading to carbonyl anions.

$$3\ Mn_2(CO)_{10} + 12\ Py \xrightarrow[-10\ CO]{120°C} 2[Mn(py)_6]^{2+} + 4\ [Mn(CO)_5]^-$$ (3.31)

3.5.3 Nucleophilic Addition to CO

Nucleophilic addition to the electron deficient carbon atom of a metal coordinated carbonyl group has become a powerful tool in organometallic chemistry; it is commonly called the *Hieber base reaction*. Fischer carbenes can be prepared by the addition of alkyllithium to metal carbonyls followed by methylation. Carbenes are important reagents as well as catalysts for a host of organometallic transformations.[23]

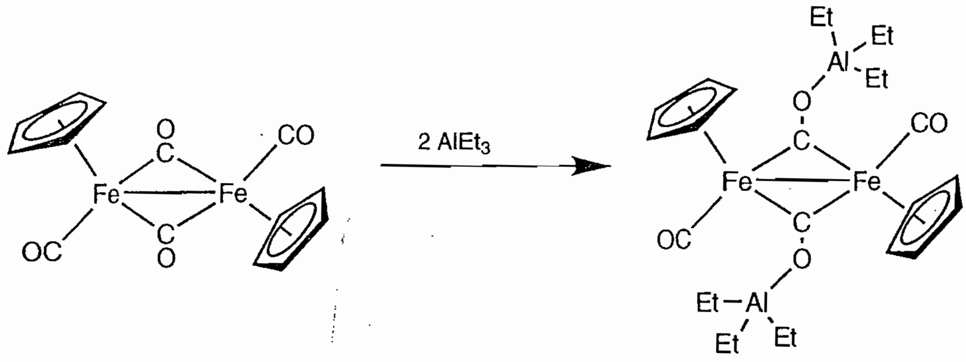


(3.32)

Fischer carbene

3.5.4 Electrophilic Addition to the Carbonyl Oxygen

Lewis acids such as $AlEt_3$ can attach to the oxygen-end of a coordinated carbonyl group. Only bridging carbonyl groups are nucleophilic enough to undergo this reaction as far as neutral metal carbonyls are considered. Addition of electrophiles becomes more facile with anionic carbonyl metallates.[24]



(3.33)

3.5.5 Carbonyl Anions, Cations and Hydrides

Carbonyl anions are also formed by reduction or by reactions with strong nucleophiles.[25,26]

$$Mn_2(CO)_{10} + 2Na \longrightarrow 2\,Na[Mn(CO)_5] \quad (3.34)$$

$$Co_2(CO)_8 + 2Na \longrightarrow 2\,Na[Co(CO)_4] \quad (3.35)$$

$$Fe(CO)_5 + NaOH \xrightarrow[-CO_2]{} Na[HFe(CO)_4] \xrightarrow{NaH} Na_2Fe(CO)_4 \quad (3.36)$$

While reduction with common reducing agents such as Na amalgam results in mono- or dianionic species, with strong reducing agents such as Na/liq. NH_3 or Na/HMPA, they can be further reduced with the formal oxidation states of the metal reaching even −4.

$$Na[Mn(CO)_5] + 3\,Na \xrightarrow[\text{liq. } NH_3]{\text{HMPA}} Na_3\,[Mn(CO)_4] + 1/2\ Na_2C_2O_2 \quad (3.37)$$

$$K[Co(CO)_4] + 3\,K \xrightarrow[\text{liq. } NH_3]{} K_3\,[Co(CO)_3] + 1/2\,K_2C_2O_2 \quad (3.38)$$

Carbonyl cations are prepared mostly by oxidative carbonylation. Lewis acids in anhydrous HF or superacids such as HF–SbF_5 along with an external oxidant are found to be ideal for realising carbonyl cations.

$$Fe(CO)_5 + XeF_2 + 4SbF_5 \xrightarrow[\text{HF–}SbF_5\text{, 50°C, 2 d}]{\text{CO (1 atm)}} [Fe(CO)_6][Sb_2F_{11}]_2 \quad (3.39)$$

$$Mn_2(CO)_{10} + 2HF + 2BF_3 + 2CO \xrightarrow[\text{RT, 10 d}]{\text{CO (0.6 bar)}} 2\,[Mn(CO)_6]BF_4 + H_2 \quad (3.40)$$

Carbonyl hydrides are prepared from carbonyl anions, carbonyl halides and dimeric carbonyls. The term hydride is assigned based on the formal oxidation state; however, the properties of the organometallic hydrides vary from hydridic to protic in character. Based on the nature of the metal and the ligands, the acidity of these complexes varies significantly.

Table 3.5 Synthesis of carbonyl hydrido complexes[28]

Methods of synthesis	pKa	Comparable acidity
$[Co(CO)_4]^- + H^+ \longrightarrow HCo(CO)_4$	1	HCl
$I_2Fe(CO)_4 + NaBH_4 \xrightarrow[150°C]{200\ bar} H_2Fe(CO)_4$	4.7	CH_3COOH
$Mn_2(CO)_{10} + H_2 \longrightarrow 2HMn(CO)_5$	7	H_2S
$Fe(CO)_5 + OH^- \longrightarrow [HFe(CO)_4]^-$	14	H_2O

3.5.6 Collman's Reagent

$Na_2Fe(CO)_4$, called Collman's reagent, has found many applications in organic synthesis. Organic halogen compounds can be functionalised in many ways via reaction with the Collman's reagent (Fig. 3.5).[28–30]

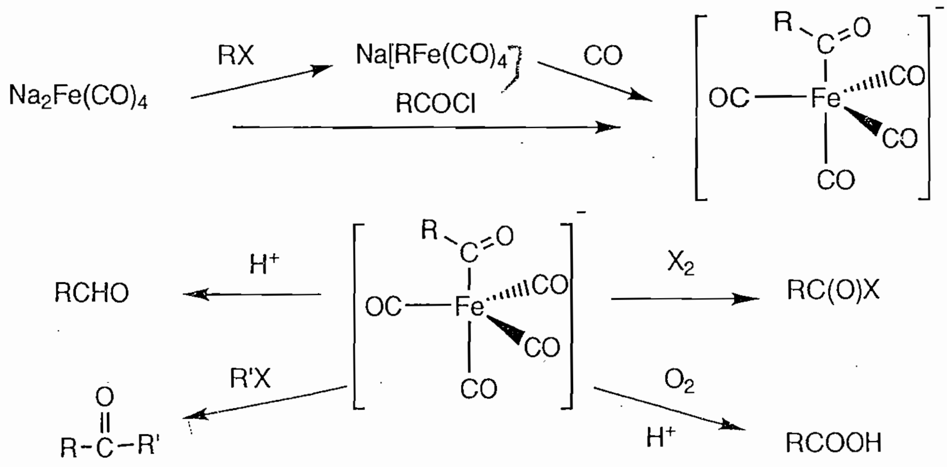
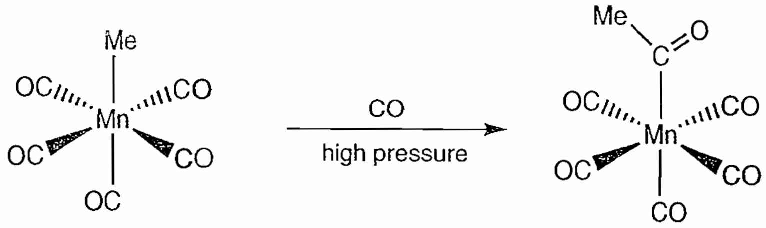


Fig. 3.5 Uses of Collman's reagent

3.5.7 Migratory Insertion of Carbonyls

The ability of metal carbonyls, especially metal carbonyl anions, to undergo migratory insertion has been utilised in organic synthesis for the preparation of acyl substituted metal carbonyls. These are good precursors for a host of carbonyl containing organic molecules.



(3.41)

3.5.8 Oxidative Decarbonylation

Carbonyl metal halides are prepared by oxidative decarbonylation and are good reagents for reactions with metallated reagents. In addition, substituted metal carbonyls can be converted to metal oxides by oxidative decarbonylation.

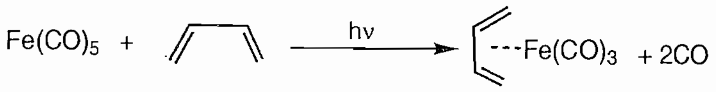
$$\mathrm{Mn_2(CO)_{10}} + \mathrm{I_2} \longrightarrow 2\,\mathrm{Mn(CO)_5I} \xrightarrow[-2\mathrm{CO}]{\mathrm{Na\,Cp}} \mathrm{Cp\,Mn(CO)_3} \tag{3.42}$$

$$\mathrm{Fe(CO)_5} + \mathrm{I_2} \longrightarrow \mathrm{Fe(CO)_4I_2} \tag{3.43}$$

3.5.9 Photochemical Substitution

Photochemical substitutions are the most common photoreactions in organometallic chemistry. Kinetic studies have shown that the rate constant for the dissociation of one CO unit which precedes the entrance of a new ligand is increased upon photochemical excitation by a factor of 10^{16}.[31, 32]

$$\mathrm{W(CO)_6} + \mathrm{PPh_3} \xrightarrow{h\nu} \mathrm{W(CO)_5(PPh_3)} + \mathrm{CO} \tag{3.44}$$



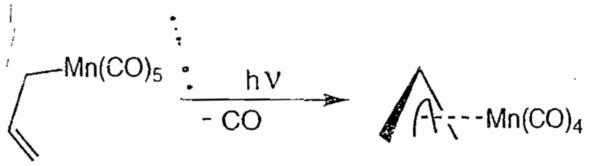
(3.45)

Photochemical substitution of CO by monodentate ligands often results only in the displacement of one carbonyl unit. This is because, photochemical excitation of a metal carbonyl with a coordination sphere of mixed substituents causes the dissociation of the ligand which is the most weakly bonded in the ground state. Therefore, attempts to substitute a second carbonyl from an $\mathrm{M(CO)_5L}$ species results in the displacement of L itself. If ligands of comparable ligand strength are used, one can displace all the carbonyl groups.

$$\mathrm{M(CO)_6} \xrightarrow[\mathrm{THF}]{h\nu} \mathrm{M(CO)_5THF} \xrightarrow{h\nu} \mathrm{M(CO)_5} + \mathrm{THF} \tag{3.46}$$

$$\mathrm{Mo(CO)_6} \xrightarrow[\mathrm{P(OMe)_3}]{h\nu} \mathrm{Mo[P(OMe)_3]_6} + 6\,\mathrm{CO} \tag{3.47}$$

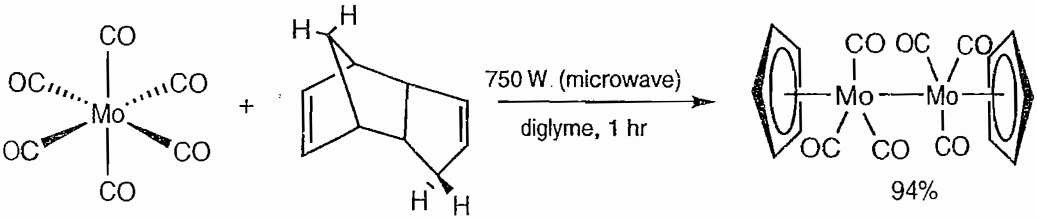
If after the dissociation of a ligand, no suitable free ligands are present, the free coordination site generated through photochemical dissociation of CO may get closed by dimerisation. The gap may also be filled internally by rearrangement of a ligand such as allyl or cyclopentadienyl from η^1 to η^3 or η^3 to η^5.



(3.48)

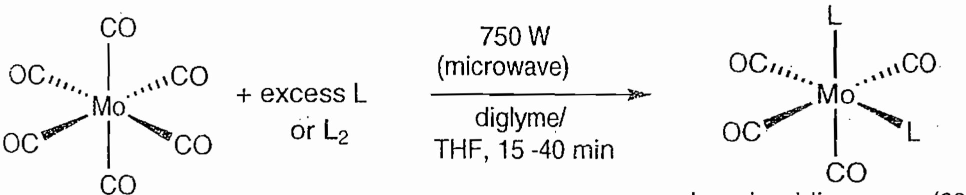
3.5.10 Microwave Assisted Carbonyl Substitution

Carbonyl substitution reactions under thermal conditions can often be improved, accelerated and simplified by carrying out the reaction in a microwave oven. The reactions can be carried out in a dedicated microwave oven using teflon reactors or a conventional oven fitted with a facility for inserting a water circulated reflux condenser. Reactions quite often proceed without the need for an inert atmosphere, are clean and give high yields. Usually a solvent such as diglyme or diglyme/THF mixture is used. For example, the reaction of $Mo(CO)_6$ with dicyclopentadiene affords a simple one step synthesis of $[CpMo(CO)_3]_2$ in 94% yield in one hour. In contrast, the conventional methods to synthesise this compound involve (i) the preparation of NaCp and its reaction with $Mo(CO)_6$ giving $Na[CpMo(CO)_3]$, followed by oxidation with iron (III) ammonium sulphate or (ii) the preparation of $Mo(CO)_3(CH_3CN)_3$ and its reaction with freshly prepared 'C_5H_5' obtained by cracking of dicyclopentadiene.[33]



(3.49)

The microwave assisted method is also useful for high yield synthesis of a variety of *cis* substituted $M(CO)_4L_2$ complexes from $M(CO)_6$ within an hour.



(3.50)

L = piperidine	(83 %)
pyridine	(50 %)
L_2= phenanthroline	(91 %)
bipyridine	(94 %)
dppe	(96 %)

3.6 METAL NITROSYLS

NO contains one more electron than CO in a N–O π* orbital and thus can act as a three electron donor. In electron counting terms, 3CO = 2NO. However, NO can also act as a one electron donor when the lone pair resides on the nitrogen and the geometry is in the bent form. In the oxidation state counting method, the ligand is viewed as a coordinated nitrosyl ion, NO^+, when in the linear form and as a coordinated NO^- when bent. It is a two electron donor in both the forms. Although either atom in NO is a potential donor, the nitrogen atom coordinates preferentially avoiding a large formal positive charge on the more electronegative oxygen atom.

Nitrosyl complexes are readily formed by the replacement of carbon monoxide with nitric oxide. Only a few organometallic compounds containing nitrosyl ligands alone are known but many mixed carbonyl–nitrosyl complexes obeying the 18 electron rule are known. One problem in the synthesis of nitrosyl complexes by direct reaction with NO is that excess nitric oxide at high temperatures and pressures can cause unfavourable oxidation and decomposition. So, many current synthetic routes use reagents such as nitrosyl chloride (NOCl), nitrites and nitrosonium salts.

· Like carbonyl complexes, nitrosyl complexes are also characterised using IR spectroscopy. The unpaired electron in NO resides in a π^* antibonding orbital and is easily removed to give NO^+ (as in $NO^+PF_6^-$). NO^+ is isoelectronic with CO. Infrared stretching frequencies of free NO is observed at 1896 cm^{-1}, free NO^+ at 2250 cm^{-1} and M–NO in the range of 1600–1900 cm^{-1}. Bridging nitrosyls are also known, for example, $CpCr(NO)_2Cl$ on treatment with $NaBH_4$ gives $[CpCr(NO)(\mu\text{-}NO)]_2$. The terminal nitrosyls in this compound are observed at 1672 cm^{-1} while the bridging NO is observed at 1505 cm^{-1} (Fig. 3.6).

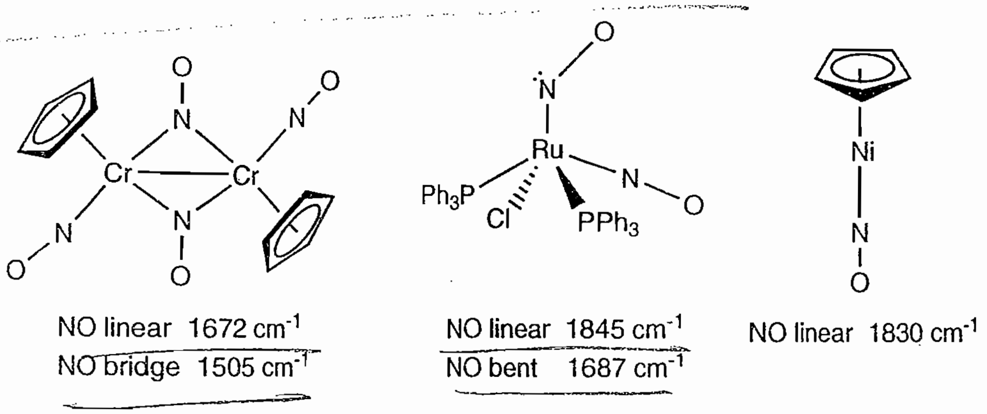


Fig. 3.6 Examples of metal nitrosyl complexes

Problems and Exercises

3.1. The V–C bond distances in $V(CO)_6^-$ and $V(CO)_6$ are 1.93 and 2.00Å respectively. Justify the difference in bond distances in these compounds.

3.2. In a carbonyl complex having a linear (OC)–M–(CO) group, indicate how ν_{CO} will change when (a) one CO is replaced by Et_3N, (b) a positive charge is placed on the complex and (c) a negative charge is placed on the complex.

3.3. Considering NO as a 3e donor, give the formula of the corresponding neutral metal carbonyls which are isoelectronic with $Cr(NO)_4$, $Mn(CO)(NO)_3$, $Co(NO)_3$ and $Fe(CO)_2(NO)_2$.

3.4. $V(CO)_6$ readily reacts with Na to give $Na[V(CO)_6]$. Why?

3.5. N_2 and CO are isoelectronic molecules but M–N_2 complexes are much weaker compared to M–CO complexes. Offer a reasonable explanation.

3.6. What happens to ν_{CO} when CO gets coordinated to BH_3 or $Ni(CO)_3$?

3.7. In LnM–CO complexes, if CO gets coordinated to a Lewis acid A and becomes LnMCO–A, what will happen to its ν_{CO} value? Justify your answer. (Ln = non π acid ligand)

3.8. The infrared spectrum of $[\eta^5\text{-CpFe(CO)}_2]_2$ when measured at room temperature indicated three bands at 2005, 1961 and 1795 cm^{-1} and when measured at high temperature gave a different spectrum with three bands at 2015, 1973 and 1938 cm^{-1}. In contrast, the infrared spectrum of $[\eta^5\text{-CpOs(CO)}_2]_2$ gave bands at 2040, 1986 and 1948 cm^{-1} when measured both at room temperature and high temperature. Both the compounds obey the 18 electron rule. Draw possible structures of the compounds explaining this phenomenon.

3.9. Photolysis of $[\eta^5\text{-CpFe(CO)}_2]_2$ at −78°C results in the loss of a colourless gas and formation of an iron containing product having a single carbonyl band at 1785 cm^{-1} and containing 14.7% oxygen by mass. Suggest a structure for the product.

3.10. Arrange the following in the decreasing order of back donation.

$Cr(CO)_6$; $[Ti(CO)_6]^{2-}$; $[Mn(CO)_6]^+$; $[Ir(CO)_6]^{3+}$; $[V(CO)_6]^-$

3.11. The complex $[Cr(CO)_4(PPh_3)_2]$ has one very strong IR absorption at 1889 cm^{-1} and two other very weak bands in the CO stretching region. What is the probable structure of this compound?

3.12. Suggest a sequence of reactions for the selective preparation of *cis*-$Fe(PPh_3)_2(CO)_3$. You are given Fe metal, CO, Ph_3P. Use any reagent of your choice.

3.13. Suppose you are given a series of metal tricarbonyl compounds having the respective symmetries C_{3v}, D_{3h} and C_s. Which of these should display the greatest number of CO stretching bands?

3.14. Refluxing $W(CO)_6$ in butryonitrile (C_3H_7CN) gives three products—$W(CO)_5(NCC_3H_7)$, $W(CO)_4(NCC_3H_7)_2$ and $W(CO)_3(NCC_3H_7)_3$. The following ν_{CO} (cm^{-1}) values are observed.

$W(CO)_5(NCC_3H_7)$ 2077, 1975, 1938

$W(CO)_4(NCC_3H_7)_2$ 2017, 1898, 1842

$W(CO)_3(NCC_3H_7)_3$ 1910, 1792

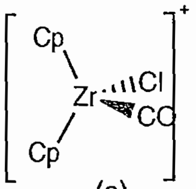
On the basis of the number of bands, determine the likely isomers of $W(CO)_4(NCC_3H_7)_2$ and $W(CO)_3(NCC_3H_7)_3$ and justify the changes in ν_{CO} as the number of butyronitrile groups increases.

3.15. On the basis of the given information on the ν_{CO} band, which ligand among the following pairs of complexes, (CO or CSe and NS or NO) is the better π acceptor ligand. Explain briefly.

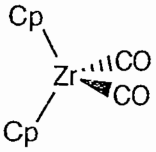
(a) $\eta^5\text{-CpRe(CO)}_3$ 2024, 1937 cm^{-1} and $\eta^5\text{-CpRe(CO)}_2\,CSe$ 2035, 1946 cm^{-1}

(b) $\eta^5\text{-CpCr(CO)}_2\,(NS)$ 2033, 1962 cm^{-1} and $\eta^5\text{-CpCr(CO)}_2\,(NO)$ 2028, 1955 cm^{-1}

3.16. Among the given two complexes (a) and (b), which will show a lower carbonyl stretching frequency? Give reasons for your answer.



(a)



(b)

3.17. Which one of the given complexes (a) and (b) will undergo ligand substitution faster with PPh_3? Why?

(a) $V(CO)_6$ (b) $[V(CO)_6]^-$

3.18. A first row transition element M forms a homoleptic carbonyl complex A with the empirical formula $M(CO)_5$. A reacts with Na/Hg in tetrahydrofuran solvent to give a compound B whose empirical formula is C_5O_5MNa. Treatment of B with MeI followed by excess of CO at high pressure resulted in a compound C with the empirical formula $C_7H_3O_6M$. Unlike A and B, compound C had in its infrared spectrum, an extra band in the range 1600–1700 cm^{-1}. Define the metal M and write the structures of A, B and C. Compound A on reaction with I_2 followed by reaction with NaCp loses a colourless gas and gives a stable organometallic compound D with the empirical formula $C_8H_5O_3M$ (a derivative of compound D has applications in the petroleum industry). Suggest the structure of D.

3.19. Select the best choice in each of the following and briefly justify the reason for your choice.

(a) Complex with the shortest C–O bond $Ni(CO)_4$, $[Co(CO)_4]^-$, $[Fe(CO)_4]^{2-}$

(b) Complex with the lowest C–O stretching frequency $Cr(CO)_6$, $V(CO)_6^-$, $Fe(CO)_6^{2+}$

3.20. The compound $(\eta^5\text{-}C_5H_5)Co(CO)_2$ (A) upon UV irradiation, resulted in the evolution of a gas and formation of a new compound, B. While the infrared spectrum of A showed absorptions around 1988 cm^{-1}, the spectrum of B showed absorptions only at 1798 cm^{-1}. Compounds A and B obey the 18 electron rule and both have the cyclopentadienyl group in the η^5 mode. Draw the structure of compound B.

3.21. An organometallic compound A with the empirical formula MC_4O_4 reacts with nitric oxide to give a new compound B with the empirical formula MC_3NO_4. B on further reaction with excess of NO under drastic conditions gave a new compound C with the molecular formula MN_3O_3. Compounds A, B and C are stable and neutral and one among them contains more than one metal atom. Draw the structures of A, B and C.

3.22. The compound $Re(CO)_5Br$ upon UV irradiation resulted in the evolution of an equimolar amount of a colourless gas and the formation of a new stable complex, X. The infrared spectrum of compound X indicated the absence of any metal–metal bond and showed bands in the range of 2040–1965 cm^{-1}. The starting material $Re(CO)_5Br$ also showed bands in the same spectral range. Draw the structure of compound X.

3.23. $[\eta^5\text{-}CpFe(CO)]_4$ is a dark green stable compound. Its infrared spectrum shows a single CO stretching band at 1640 cm^{-1}. The ^1H NMR spectrum shows a single line even at low temperature. Propose a structure for this compound based on the given data.

3.24. In the given pair of complexes pick out the complex having lower energy CO stretching frequency in its infrared spectrum. Rationalise your choice.

(a) $Mo(CO)_6$ or $Mo(CO)_5PPh_3$ (b) $Fe(CO)_5$ or $Fe(CO)_4Br_2$

3.25. Provide a plausible explanation for the differences in infrared wave numbers between each of the pairs (a) $Mo(PF_3)(CO)_3$, 2043 and 1991 cm^{-1} vs $Mo(PMe_3(CO)_3$ 1945, 1851 cm^{-1} (b) $MnCp(CO)_3$ 2023, 1939 cm^{-1} vs $MnCp^*(CO)_3$ 2017, 1928 cm^{-1}.

3.26. When compound A is heated, CO gas is driven off. The product B so formed, readily reacts with CO and reverses the reaction. Infrared spectral studies indicate the ν_{CO} value of A at 1960 cm^{-1} and B at 1850 cm^{-1}. Draw the structures of A and B.

$$\underset{\text{A}}{[\eta^5\text{-CpMo(CO)}_3]_2} \underset{+\,2CO}{\overset{-2CO}{\rightleftharpoons}} \underset{\text{B}}{[\eta^5\text{-CpMo(CO)}_2]_2}$$

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CHAPTER

4

NEUTRAL SPECTATOR LIGANDS: PHOSPHINES AND N-HETEROCYCLIC CARBENES

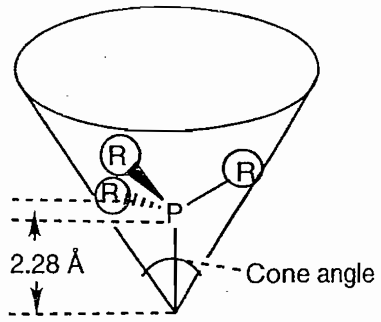
Spectator ligands are ligands which are present on the metal centre but do not take part in a reaction although their properties (mainly steric and electronic) alter the reactivity of the metal centre. They often play a role in the formation of the intermediate complex in a reaction and may also influence the rate of a reaction. Phosphines are some of the most widely used spectator ligands.

4.1 PHOSPHINES: STERIC AND ELECTRONIC PARAMETERS

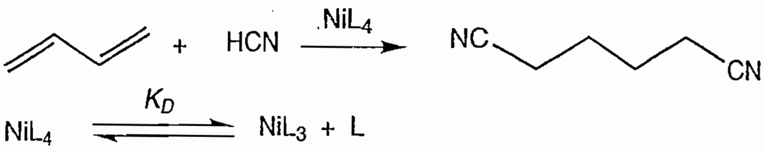
Phosphine (PH_3), the parent compound of the enormous range of trivalent phosphorus compounds known in chemical literature, was first reported in 1783 by Genembre as a spontaneously inflammable gas obtained by the reaction of phosphorus with caustic potash. Like amines, the phosphines have a pyramidal structure and can function both as nucleophiles and as bases. Depending on the number of hydrogen atoms replaced by organic groups in PH_3, phosphines are classified as primary, secondary or tertiary. Tertiary phosphines are one of the most important ligands used in organometallic chemistry as their steric and electronic properties can be easily modified to fine-tune the catalytic activity of the metal they are bound to. Phosphines are excellent soft donor ligands (which are large and polarisable) with a variety of substituents which differ in steric and electronic properties. Variation of the three R groups can effect:

- significant changes in the steric size of the phosphine (from small to enormous),
- changes in the basicity and nucleophilicity of the phosphine which in turn results in large changes in its donor/acceptor properties (from excellent donor/poor π-acceptor and vice versa), and
- preparation of a variety of multidentate polyphosphines (bi, tri, tetra, penta, hexa or cyclo) that can assume different coordination geometries and stereochemistry (chelating, bridging, chiral, *cis*-enforcing or facial).

In 1977, Chadwick Tolman (Dupont Chemicals) developed the steric and electronic parameters for phosphines to explain the ligand effects of L_4Ni-catalysed hydrocyanation



of butadiene. This study forms the cornerstone for analysing the steric and electronic effects of phosphines. He published a classic review article covering the methods that he developed for arranging a wide variety of phosphine ligands in order of their electron-donating ability and steric bulk. It was shown that ligand dissociation from the tetrakisphosphine complex NiL_4 was the crucial step in understanding the activity of the metal complex as a catalyst in the hydrocyanation reaction (Eq. 4.1). Tolman compared his steric and electronic parameters with the equilibrium dissociation constant (K_D) of the dissociation. The size or steric bulk of a phosphine ligand was determined from simple 3-D space-filling models of the phosphine ligands.[1,]



(4.1)

The steric parameter θ for a symmetrical phosphine was taken as the apex angle of a cylindrical cone, centered 2.28 Å from the centre of the phosphorus atom which just touches the van der Waals radii of the outermost atoms of the model. Real M–P bond lengths vary from 2.12–2.55 Å. Tolman coined the name *cone angle* for the steric parameter to indicate the approximate amount of 'space' that the ligand occupied about the metal centre. Cone angles of some of the well known phosphines are given in Table 4.1.[1, 2]

The electron donating ability of a phosphine ligand was determined by reacting one equivalent of the phosphine (monodentate) with $Ni(CO)_4$ to make a $Ni(CO)_3$(phosphine) complex. The ν_{CO} stretching frequency (the very sharp a_1 high energy mode in the infrared spectrum) of the $Ni(CO)_3$(phosphine) complex was then measured. The more the electron

Table 4.1 Cone angles of selected phosphines

PR_3	Cone angle (°)	PR_3	Cone angle (°)
PH_3	87	$PEtPh_2$	140
PF_3	104	PPh_3	145
$P(OMe)_3$	107	$P(i\text{-}Pr)_3$	160
PMe_3	118	PCy_3	170
PCl_3	124	$P(O\text{-}t\text{-}Bu)_3$	175
$P(OPh)_3$	128	$P(t\text{-}Bu)_3$	182
PBr_3	131	$P(C_6F_5)_3$	184
PEt_3, PPr_3	132	$P(o\text{-}Tol)_3$	194
$P(CF_3)_3$	137	$P(mesityl)_3$	212

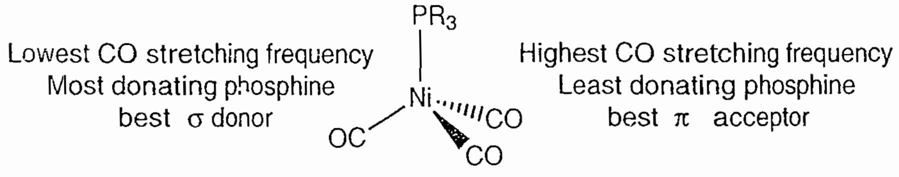
density donated by the phosphine ligand to the metal centre, the more was the π-backbonding to the carbonyl ligands, weakening the CO triple bond, thus lowering the ν_{CO} stretching frequency.

Tolman defined the electronic parameter χ (Table 4.2) simply as the difference in the ν_{CO} carbonyl stretching frequencies of the $Ni(CO)_3$(phosphine) complex and the $Ni(CO)_3P(t\text{-}Bu)_3$ complex. Later on, Crabtree also computed the electronic parameters using quantum calculations and compared the same with Tolman's experimentally determined electronic parameters. A good correlation was obtained (except for PCl_3), which helped to theoretically predict the relative donor capabilities of phosphines as well as non-phosphorus based ligands such as H_2O and halides which do not form stable complexes with $Ni(CO)_3$.[3]

Table 4.2 The ν_{CO} infrared stretching frequencies of $Ni(CO)_3$(phosphine) and Tolman's electronic parameters (χ) of selected phosphines

Electronic Parameter

PR_3	ν_{CO} (cm^{-1})	χ (cm^{-1})	PR_3	ν_{CO} (cm^{-1})	χ (cm^{-1})
$P(t\text{-}Bu)_3$	2056.1	0.0	$PPh_2(C_6F_5)$	2074.8	18.7
PCy_3	2056.4	0.3	$P(O\text{-}i\text{-}Pr)_3$	2075.9	19.8
$P(i\text{-}Pr)_3$	2059.2	3.1	$P(OEt)_3$	2076.3	20.2
PEt_3	2061.7	5.6	$P(p\text{-}C_6H_4\text{-}CF_3)_3$	2076.6	20.5
$P(NMe_2)_3$	2061.9	5.8	$PPhH_2$	2077.0	20.9
PMe_3	2064.1	8.0	$P(OMe)_3$	2079.5	23.4
PBz_3	2066.4	10.3	$PPh(OPh)_2$	2079.8	23.7
$P(o\text{-}Tol)_3$	2066.6	10.5	PPh_2Cl	2080.7	24.6
$PMePh_2$	2067.0	10.9	PH_3	2083.2	27.1
$P(m\text{-}Tol)_3$	2067.2	11.1	$P(OPh)_3$	2085.3	29.2
PPh_3	2068.9	12.8	$P(C_6F_5)_3$	2090.9	34.8
$P(p\text{-}C_6H_4\text{-}F)_3$	2071.3	15.2	PCl_3	2097.0	40.9
PPh_2H	2073.3	17.2	PF_3	2110.8	54.7
$PPh_2(OPh)$	2074.6	18.5	$P(CF_3)_3$	2115.0	58.9



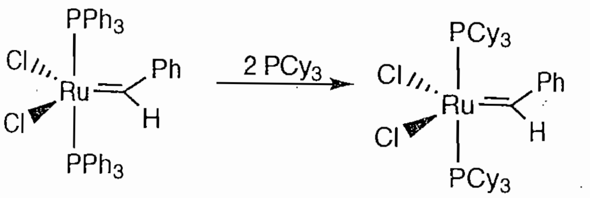
4.2 BASICITY OF PHOSPHINES

While Tolman's electronic parameter helps one to classify phosphines as good σ donors and good π acceptors, it should be remembered that what one observes experimentally is the combined outcome of these two effects. A relatively lower σ donor capability of a ligand can get masked by its high π acceptor capability. To get an idea about the σ donor capability of a phosphine exclusively, one can compare the pK_a values of phosphines. The pK_a value is typically used as a measure of the σ donor ability of phosphines coordinated to metals. Generally, phosphines are less basic compared to amines (pKa of NEt_3 = 10.87 while that of PEt_3 = 8.69). Table 4.3 lists the pK_a values (in water) of a variety of phosphines.[4–6]

Table 4.3 Basicities of selected phosphines

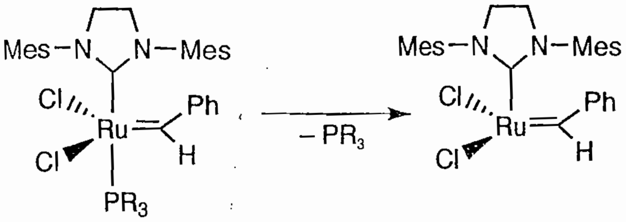
R_3P	pK_a	R_3P	pK_a
$(Bu^t)_3P$	11.40	$P(4\text{-}MeOC_6H_4)_3$	4.57
Cy_3P	9.70	$P(4\text{-}MeC_6H_4)_3$	3.94
Et_3P	8.69	$P(3\text{-}MeC_6H_4)_3$	3.30
Me_3P	8.65	$P(2\text{-}MeC_6H_4)_3$	3.08
$(Pr^n)_3P$	8.64	PPh_3	2.73
$(Bu^n)_3P$	8.43	Ph_2POMe	2.69
$PhPMe_2$	6.49	$P(4\text{-}FC_6H_4)_3$	1.97
$PhPEt_2$	6.25	$P(4\text{-}ClC_6H_4)_3$	1.03

There are many examples of reactions where a phosphine or amine bound to a metal is displaced by another phosphine. For example, in the synthesis of Grubbs first generation catalyst, the two PPh_3 units (θ = 145°, $\chi = 12.8\ cm^{-1}$ and $pK_a = 2.73$) bound to the precursor complex are easily displaced by two PCy_3 units (θ = 170°, $\chi = 0.3\ cm^{-1}$ and $pK_a = 9.70$) (Fig. 4.2). It may be noted that PR_3 ligands that are less electron donating than PPh_3 cannot be used for substitution in such a reaction.[7]



(4.2)

Dissociation of a phosphine ligand from a metal complex is often a very important step in the formation of the active species of many homogeneous catalysts. Both steric and electronic perturbations affect the dissociation of a phosphine from a complex. A representative example involves the studies carried out by Grubbs on the rate of dissociation of various phosphines from the Grubbs second generation catalyst. The rate of dissociation of $P(n\text{-}Bu)_3$ (θ = 132°) from the ruthenium complex is less (0.006 times) compared to the rate of dissociation of Cy_3P (θ = 170°) although both have comparable electronic parameters. Here, the steric factors seem to play an important role. However, the rate of disssociation of $PPh_2(OMe)$ (θ = 132°) is 13 times faster than that of PCy_3. In this case, the lower donor strength of $PPh_2(OMe)$ ($pK_a = 2.69$) compensates for its smaller size. The dissociation of aryl phosphines in general is faster in these reactions [PPh_3 is 58 times faster and $P(4\text{-}ClC_6H_4)_3$ is 138 times faster than PCy_3]. One can conclude that from a metal complex which is not electron rich and in which the metal is in a relatively high oxidation state, a weak donor phosphine dissociates faster than a strong donor phosphine. Aryl phosphines when compared to alkyl phosphines dissociate faster.[8]



(4.3)

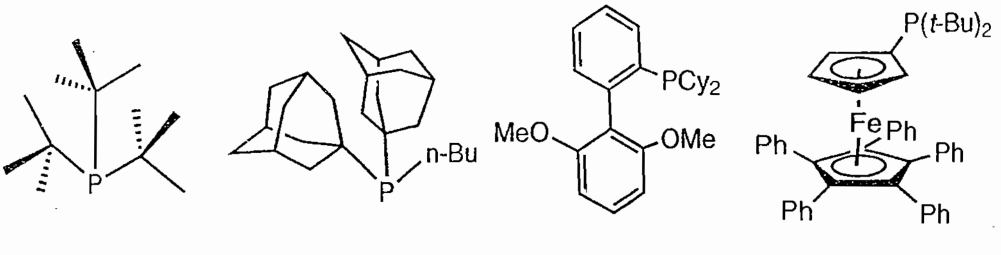
The situation can be different for a metal complex which is electron rich and has the metal in the zero or negative oxidation state. For example, in the case of $Ni(PR_3)_4$, the most stable complexes are those where the PR_3 corresponds to phosphites. Phosphites being good π acceptors are more effective in bonding with electron rich metal centres.

4.3 MONODENTATE PHOSPHINES

Triphenylphosphine is the most widely used monodentate phosphine as it is air and moisture stable and is an easily accessible solid phosphine. Almost all alkyl phosphines are fairly to highly air-sensitive, get oxidised to phosphine oxide on exposure to air and some are also pyrophoric. They are strong σ donors, usually colourless liquids and foul smelling (unless they have very high molecular weight and are nonvolatile). The σ donor ability increases from $PMePh_2$ to $P(t\text{-}Bu)_3$ which is in concordance with the χ values as shown by Tolman (see Table 4.2).

The phosphites on the other hand are relatively poor σ donors, but can be fairly good π acceptor ligands (about half as good as CO). Low molecular weight compounds are usually colourless liquids and higher molecular weight compounds are white solids. Phosphites are usually air-stable but moisture sensitive. Phosphites can also undergo the Arbusov rearrangement forming the pentavalent tetracoordinate phosphorus compound with a P=O bond. The formation of the P=O bond is the driving force for many reactions involving phosphorus (III) compounds and oxygen containing reagents. PF_3 is a very strong π acceptor ligand and is almost as good as CO in its acceptor properties.

Recent years have witnessed an added interest in the design, synthesis and use of bulky as well as electron rich phosphines, especially in palladium catalysed cross coupling reactions. Aryl chlorides which generally have poor reactivity in cross coupling reactions can be made to react under mild conditions to give good yields of cross coupled products by using such phosphines along with palladium. The basic difference that these phosphines bring about is in the nature of the palladium complex which becomes tricoordinate due to the steric bulkiness. Some of the bulky phosphines used in such reactions are shown in Fig. 4.1. Water soluble phosphines find use in cases where catalyst recovery is important by means of biphasic catalysis.



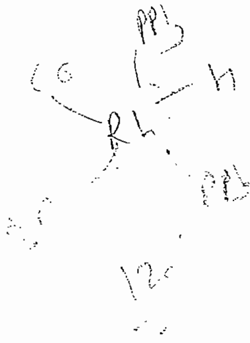
P(t-Bu)$_3$ cataCXium A S-Phos Q-Phos

Fig. 4.1 Sterically hindered and electron rich tertiary phosphines

4.4 MULTIDENTATE PHOSPHINES

Among multidentate phosphines, bidentate phosphines are the most important as they find applications in many catalytic reactions. Some of the most widely used bidentate phosphines are described below. Being bulky ligands, two monodentate phosphine units on a metal centre generally prefer an orientation *trans* to each other. The important characteristic of bidentate ligands is that they are *cis* enforcing and thereby, one can fine tune the catalytic activity of a metal centre. Chiral biphosphines are very important as they can induce chirality on the metal bound by them.

A very important feature of the biphosphines, chiral and non-chiral, which helps one to select the best phosphine for a specific application, is their natural P–M–P bite angles. Natural bite angles along with electronic and steric properties are varied on biphosphines bound to metal catalysts to get better selectivity of products. For example, one of the problems associated with hydroformylation of alkenes using a rhodium catalyst, HRh(CO)(PPh$_3$)$_3$, is that one gets a mixture of linear and branched aldehydes as products (see Chapter 13). In 1987, the Texas Eastman company patented the rhodium catalyst having BISBI, a biphenyl derived biphosphine which gave excellent selectivity to the linear aldehyde compared to other phosphine ligands. The high selectivity observed with BISBI was attributed to the active catalyst species RhH(BISBI)(CO)$_2$ with the BISBI having a natural bite angle of 120° (Fig. 4.2). Later, detailed studies on a series of xanthphos biphosphines having a natural bite angle varying from 102–123° further confirmed the



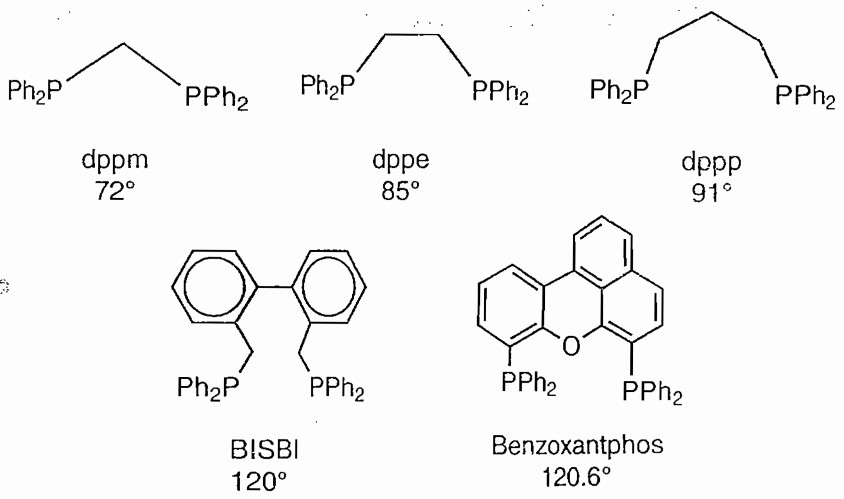


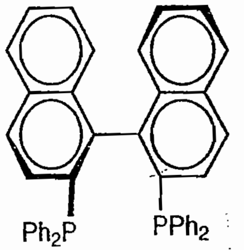
Fig. 4.2 Bite angles of selected biphosphines

high selectivity for linear aldehydes, when biphosphines having a natural bite angle very close to 120° were used.[9]

Some of the other important chiral and achiral biphosphines and their specific applications are given below.

BINAP

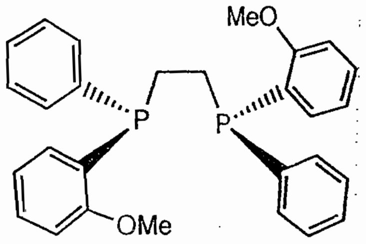
This is a chiral biphosphine with a bite angle of 92° and has been used in a variety of asymmetric catalysis reactions. Introduced by Noyori in 1980 (Nobel prize 2001) both the R and S isomers have been separated and used. Along with rhodium, it is used in the industrial synthesis of menthol, a chiral aromatic substance. Later Noyori used it along with ruthenium for the asymmetric hydrogenation of ketones. One of the well known processes in which BINAP is used is in the production of (R)-1,2-propanediol for the industrial synthesis of the antibiotic *levofloxacin*.[10]



(S) BINAP

DIPAMP

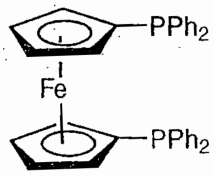
This was the first chiral biphosphine to have found use in an industrial process. William Knowles (Nobel prize 2001) used it in the asymmetric hydrogenation of methyl-(Z)-α-acetamidocinnamate which was then used for the synthesis of L-dihydroxy phenylalanine. L-DOPA (Levodopa) is used as a prodrug to increase the dopamine levels in the treatment of Parkinson's disease, since it is able to cross the blood-brain barrier where dopamine cannot. Once levodopa has entered the central nervous system, it is metabolised to dopamine.[11]



DIPAMP

DPPF

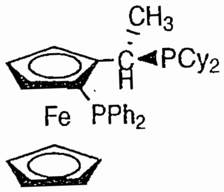
This biphosphine has a bite angle close to that of BINAP (96°) and has been used in many reactions as a cheaper substitute for the costly chiral BINAP. It has been extensively used in palladium catalysed cross coupling reactions. PdCl$_2$dppf when used in the Kumuda–Hayashi coupling (coupling of aryl bromides with Grignard reagents) gives excellent selectivity of products. DPPF has been used to achieve good yields and selectivity in palladium catalysed reactions such as the Suzuki and Buchwald–Hartwig C–N coupling reactions.[12]



DPPF

JOSIPHOS

This is one of the examples of ferrocene-derived chiral biphosphine having both normal and planar chirality that is industrially useful. The biphosphine has been used efficiently in enantioselective hydrogenation of enamines leading to chiral β-amino acids. Industrially, it has also been used in stereoselective hydrogenation steps leading to the synthesis of biotin. Biotin, also known as vitamin H or B$_7$ (biotin, coenzyme R),

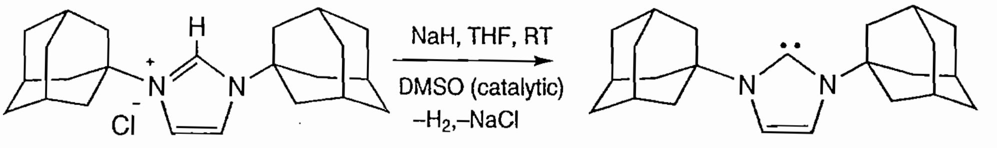


JOSIPHOS

is a water soluble B-complex vitamin. Biotin is used in cell growth, the production of fatty acids, and in the metabolism of fats and amino acids.[13]

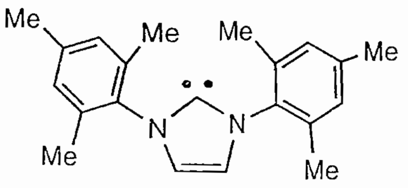
4.5 N-HETEROCYCLIC CARBENES

The importance of phosphines as spectator ligands is exemplified in many reports of highly efficient homogeneous catalytic systems in terms of yields and selectivity of a structural or stereo isomer when applied to processes such as hydrogenation, hydroformylation or palladium catalysed coupling reactions. However, their disadvantages are (i) high cost of producing tertiary (especially chiral) phosphines and (ii) high tendency to get oxidised to phosphine oxides. Except triphenyl phosphine and a few aryl phosphines, the rest are highly sensitive to oxidation and some are even pyrophoric in nature. N-Heterocyclic carbenes (NHCs) have been found to be attractive alternatives to tertiary phosphine ligands in organometallic and coordination chemistry. The field of stable carbene research was initiated in 1991 by the discovery of N,N'-diadamantyl-imidazol-2-ylidene by the research group of Anthony J Arduengo III, who managed to isolate and obtain an X-ray structure of this stable carbene.[14]

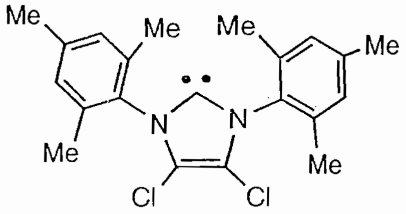


(4.4)

Such carbenes were first proposed by Breslow in 1957, first prepared by Guy Bertrand in 1989, and finally isolated as a crystalline solid by Arduengo. It was found to be indefinitely stable at room temperature (in the absence of oxygen and moisture), and melted at 240–241°C without decomposition. Another interesting feature of this molecule was a characteristic resonance in the ^{13}C NMR spectrum at 211 ppm for the carbenic carbon. The X-ray structure revealed longer N–C (carbene) bond lengths in the ring of the carbene than in the parent imidazolium compound (Eq. 4.4), indicating that there was very little double bond character to these bonds. Later, in 1997, Arduengo synthesised an air and moisture stable carbene having two chlorines substituted on the imidazole ring.



δ_C (Carbenic C), 245 ppm
Air sensitive



δ_C(Carbenic C), 220 ppm
Air stable

Typically, normal carbenes are very reactive short lived molecules that cannot be isolated, and are usually studied by observing the reactions they undergo. However, NHCs are quite stable. In many cases, these carbenes are thermodynamically stable in the absence of moisture and oxygen, can be isolated and indefinitely stored. Some NHC carbenes dimerise slowly over days, while the least stable triplet state carbenes have half lives that can be measured in seconds. The main advantage as observed in several reactions is their greater electron donating capability over the most basic phosphines. Several beneficial uses of NHC substituted organometallic complexes over the conventional phosphine complexes have been reported. The most visible among these are in the olefin metathesis reaction using Grubbs catalysts. NHCs have also shown better performance compared to phosphines in iridium catalysed hydrogenation, platinum catalysed hydrosilylation and palladium catalysed cross coupling reactions.

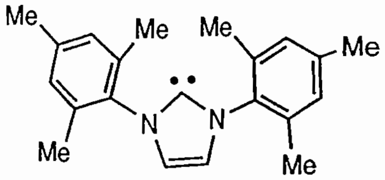
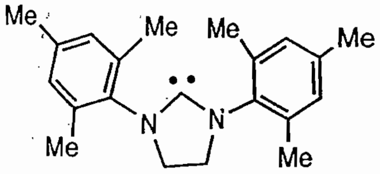
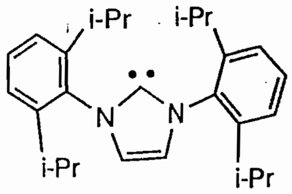
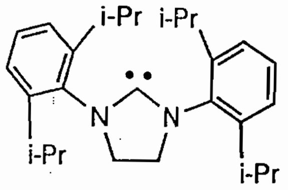
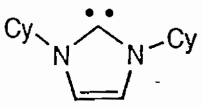
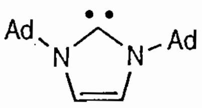
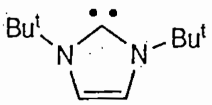
A wide range of NHC ligands are now commercially available which exhibit high activities in various important organic transformations when combined with metal pre-catalysts. NHC imidazolidine ligands with sterically encumbering groups such as mesityl, isopropyl and adamantyl have been used in many reactions. The most commonly used NHCs are listed in Table 4.4. Some of the advantages of NHC as ancillary ligands are:

- they are stronger donors than phosphines and can readily displace other ligands *trans* to them by the well known *trans effect*,
- the strong metal-carbenic bond of the NHC complex favours reaction kinetics which involves less of NHC dissociation from the metal complex,
- the presence of sterically hindered groups bound to the N-atoms facilitate reductive elimination of the product from the metal during catalysis, and
- the activity of the NHC ligands can be modified by introducing electronically different substituents on the nitrogen atoms in the ring.

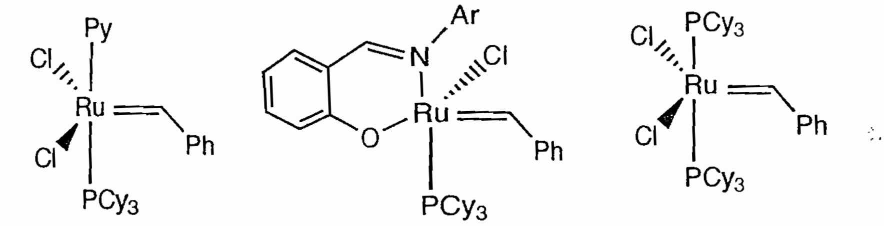
In 2005, Steven Nolan reported the first systematic study comparing the electronic properties of widely used NHCs and phosphines. He carried out reactions of seven NHCs with $Ni(CO)_4$ and prepared complexes where carbonyl groups were replaced by NHCs. The ν_{CO} stretching frequency of the new complexes were measured in dichloromethane for a one on one comparison with phosphines. The data indicate that N-heterocyclic carbenes are as good or better σ donors than the most basic alkyl phosphine $P(t\text{-}Bu)_3$. The saturated NHCs were slightly less electron donating than their unsaturated analogues.[15]

The superiority of NHCs over phosphines is best exemplified in the Grubbs catalysts used in olefin metathesis reactions. The Grubbs catalysts are ruthenium carbene complexes having two spectator neutral ligands *trans* to each other along with two chloride ligands. Grubbs had initially prepared carbene complexes with two PPh_3 units which were later modified to create the Grubbs first generation catalyst having two PCy_3 ligands in a *trans* orientation (Fig. 4.3). This complex was stable but its activity was much lower compared to Schrock's molybdenum based catalysts. Later on, Grubbs came up with his second generation catalysts possessing one NHC group (SIMes) *trans* to PCy_3. Since NHC ligands are much more basic ligands, they increase the reactivity of the catalyst by making it easier to push the *trans* PCy_3 ligand off the metal (*trans effect*). This correlates well with the proposed dissociation mechanism as well as the higher basicity

Table 4.4 The ν_{co} infrared stretching frequencies of important $Ni(CO)_3NHC$ complexes [16]

	Ligand	Structure	Complex	ν_{CO} (cm^{-1}), (CH_2Cl_2)
1.	IMes		$Ni(CO)_3(IMes)$	2050.7
2.	SIMes		$Ni(CO)_3(SIMes)$	2051.5
3.	IPr		$Ni(CO)_3(IPr)$	2051.5
4.	SIPr		$Ni(CO)_3(SIPr)$	2052.2
5.	ICy		$Ni(CO)_3(ICy)$	2049.6
6.	IAd		$Ni(CO)_2(IAd)$ (tricoordinate)	2007.2 (hexane)
7.	IBu^t		$Ni(CO)_2(IBu^t)$ (tricoordinate)	2009.7 (hexane)
8.	$P(Bu^t)_3$		$Ni(CO)_3(PBu^t_3)$	2056.1
9.	PCy_3		$Ni(CO)_3(PCy_3)$	2056.4
10.	PPh_3		$Ni(CO)_3(PPh_3)$	2068.9

of NHCs observed from Nolan's studies with $Ni(CO)_3NHC$ complexes. It is important to note that the increased reactivity of the second generation catalyst can now help to bring about metathesis on tri and tetra substituted double bonds, which was possible only by molybdenum based Schrock's olefin metathesis catalysts. The introduction of the NHC ligand makes the ruthenium catalysts as reactive as the molybdenum catalysts. Also, it is important to note that the second generation catalysts are tolerant to the presence of many functional groups on the alkenes involved in olefin metathesis.[17–19]

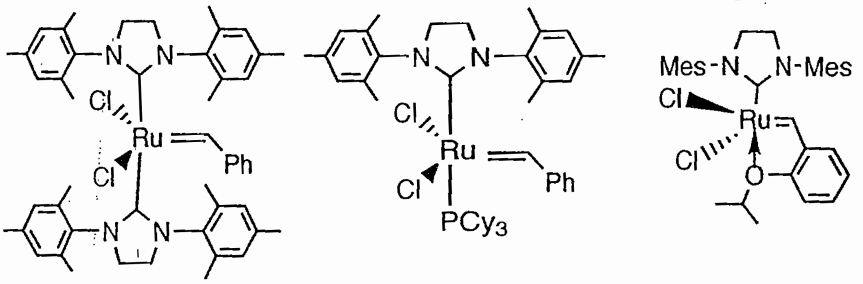


unstable, high activity

stable, low activity

stable, low activity

Grubbs first generation catalyst



stable low activity

stable, high activity

stable, high activity
recyclable

Grubbs second
generation catalyst

Grubbs–Hoveyda catalyst

Fig. 4.3 N-Heterocyclic carbenes and olefin metathesis catalysts

4.5.1 Synthesis of NHCs

NHCs with saturated carbene rings have been prepared with five, six or seven membered rings. Initially, these were prepared by the reaction of acyclic diamines (or diimines) with a formyl unit to close the ring (Fig. 4.4). However, this method was found to be low yielding and had problems while preparing functionalised NHCs. A recent method uses the reverse methodology wherein a formamidine fragment is first prepared and the ring is closed with a dibromo or diiodo hydrocarbyl unit using a base. This potentially useful method is high yielding as well.[20]

As the deprotonation of the halide can sometimes lead to partial decomposition, the halide ions were exchanged for tetrafluoroborate ions, and the resulting salts were easily purified by crystallisation and readily converted to the free carbene.

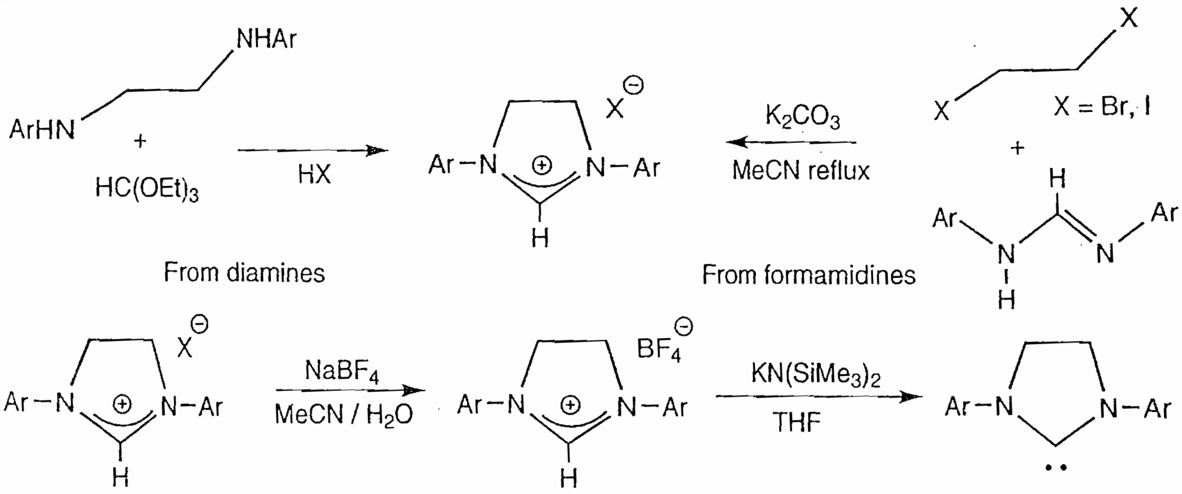


Fig. 4.4 Synthesis of NHCs with saturated carbene rings

Synthesis of NHCs with unsaturated carbene rings such as 1,3-bis(2,6-diisopropylphenyl) imidazoliumchloride (IPrHCl) has been carried out as follows. Glyoxal on addition to 2, 6-diisopropylaniline in absolute ethanol with a catalytic amount of formic acid results in the formation of a diazabutadiene in the form of a yellow solid. This compound reacts with paraformaldehyde and HCl in toluene to form 1,3-bis(2,6-diisopropylphenyl) imidazoliumchloride (IPrHCl) in moderate yields. The free carbene IPr is generated when IPrHCl is reacted with potassium *tert*-butoxide in THF.[21]

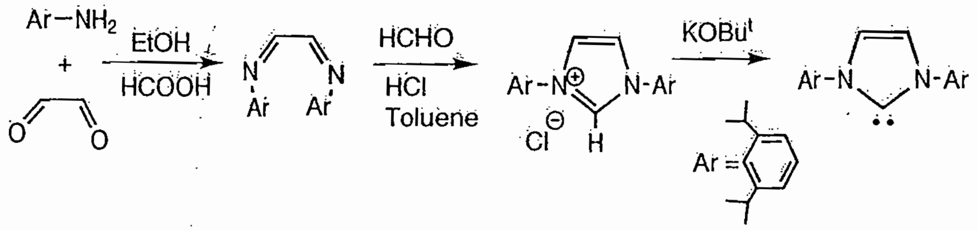


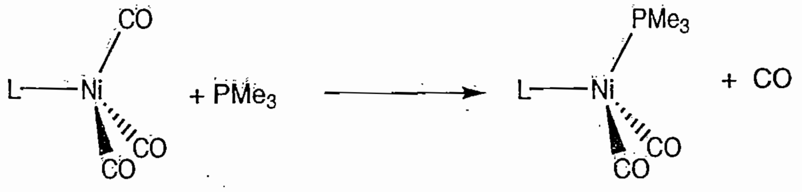
Fig. 4.5 Synthesis of NHCs with unsaturated carbene rings

Problems and Exercises

4.1. Arrange the following ligands in the order of increasing σ donor capability.

PCy$_3$, SIMes, PMe$_3$, P(OEt)$_3$, PPh$_3$, PF$_3$

4.2. Consider the following reaction. Show in which case the ligand substitution reaction occurs faster: when L = CO or when L = PMe$_3$?



4.3. If a highly substituted complex, Mo(CO)$_3$L$_3$ is desired, which of the ligands PMe$_3$ or P(^{t}Bu)$_3$ would be preferred and why? Name the isomer formed from that reaction.

4.4. Among Cr(CO)$_5$(PF$_3$) and Cr(CO)$_5$(PMe$_3$), which one do you think will have

(a) the stronger C–O bonds (b) the stronger Cr–C bonds?

4.5. Which among the following pairs of metal complexes will have the higher CO stretching frequency? Give reasons.

(a) TiO$_2$(PEt$_3$)$_2$(CO)$_2$ and Cp$_2$Ti(CO)$_2$

(b) {Rh(CO)$_2$[P(OPh)$_3$]$_2$}$^+$ and Rh(CH$_3$)$_2$(CO) dmpe

(c) (η^3-allyl)Co[P(OMe)$_3$](CO)$_2$ and (η^3-1,3-dimethyl-allyl)Co(PMe$_3$)(CO)$_2$

(d) Os(CF$_3$)$_2$(CO)$_2$ [P(OMe)$_3$]$_2$ and Fe(CH$_3$)$_2$(CO)$_2$ (PMe$_3$)$_2$

4.6. Arrange the following in the decreasing order of Rh–C bond lengths.

(a) Rh(CO)Cl(PPh$_3$)$_2$ (b) Rh(CO)Cl(PEt$_3$)$_2$ (c) Rh(CO)Cl[P(C$_6$F$_5$)$_3$]$_2$

4.7. The rhenium complex Re(Cl)(N$_2$)(PMe$_2$Ph)$_4$ on heating loses a colourless gas and forms a new complex.The new complex obeys the 18 electron rule, does not possess metal–metal bonds and its ^{31}P NMR chemial shift values are comparable to that of the parent compound. Suggest a possible strucutre for this complex.

4.8. The ν_{CO} stretching frequency (a_1 high energy mode) values obtained for a series of *cis*-$L_2Mo(CO)_4$ complexes where L = PR_3 are given below in the increasing order. Given that the trends of the electronic parameters of *cis*-$L_2Mo(CO)_4$ are similar to that of $LNi(CO)_3$, match the phosphines with the streching frequency values.

2013, 2015, 2022, 2037, 2046, 2092

[PR_3 = PF_3, PMe_3, PPh_3, $P(OPh)_3$, PEt_3, $P(OMe)_3$]

4.9. From the given list of phosphines choose the most suitable one to use along with the metal catalyst for the reactions provided [dppe, dppf, BISBI, $P(^tBu)_3$, $P(OPh)_3$, PMe_3] (for reactions, see chapters 12, 13 and 16).

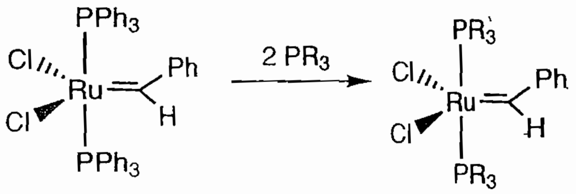
(a) Hydrocyanation of butadiene (b) Hydrogenation of propylene

(c) Kumada–Hayashi coupling (d) Suzuki coupling of aryl chlorides

(e) Hydroformylation of propene

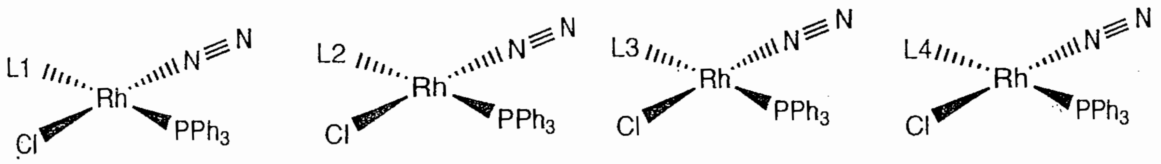
4.10. Which among the given phosphines is most likely to give a positive reaction in the given scheme?

PR_3: R = (a) 4-FC_6H_4 (b) Bu^t (c) Et (d) 4-$MeOC_6H_4$



4.11. If Tolman's electronic parameters were to be applied to N-heterocyclic carbenes, indicate the range in which the χ values of the NHCs will appear.

4.12. Place the following dinitrogen complexes in order of their increasing N–N bond length.



L1 = Ph_3P L2 = Me_3P L3 = F_3P L4 = $(MeO)_3P$

4.13. Consider the following data and explain the observed trend in reaction rates.

$$Mo(CO)_4L_2 + CO \longrightarrow Mo(CO)_5L + L$$

L = $PhPMe_2$ $< 1 \times 10^{-6}$ s^{-1}

= Ph_2PMe 1.3×10^{-5} s^{-1}

= Ph_3P 3.2×10^{-3} s^{-1}

Supplementary reading

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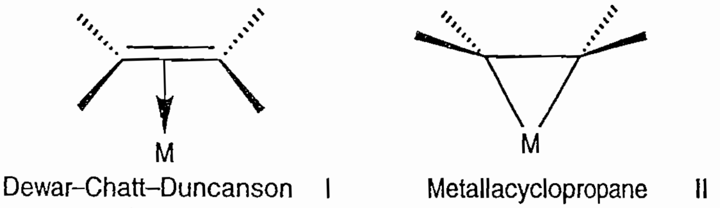
ALKENES AND ALKYNES AS LIGANDS

CHAPTER

5

5.1 MODELS OF ETHYLENE–METAL BONDING

Complexes between metal salts and alkenes have been known since the beginning of organometallic chemistry. The most well known example is Zeise's salt which was discovered in 1827, and obtained by the reaction of $[PtCl_4]^{2-}$ and ethanol. However, its structure was only determined about 150 years later. One of the unique features of this complex is that the ethylene molecule occupies the fourth coordination site of the square planar complex with its C–C axis perpendicular to the platinum–ligand plane.



(5.1)

Relative to the free ethylene, the C–C bond in the complex is lengthened slightly and the hydrogens are slightly tilted back from the planar arrangement. There are two major bonding models (features) known for complexes of alkenes with metals. At one extreme is the *Dewar–Chatt–Duncanson model* (I) and at the other extreme, the *metallacyclopropane model* (II). Actual structural studies on a large number of alkene complexes have shown that they fall in between these two extremes depending on the metal and the substituents on the carbon atoms.[1, 2]

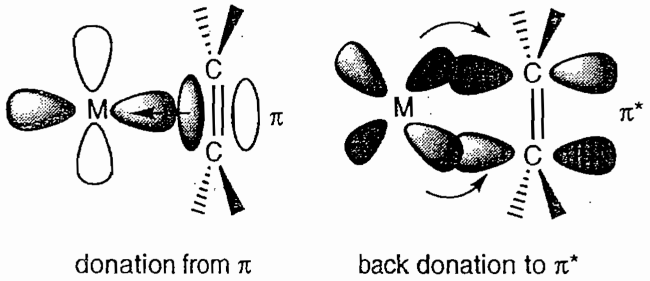


Fig. 5.1 Orbital overlap in the Dewar–Chatt–Duncanson Model

For Zeise's salt, the best bonding picture is given by the Dewar–Chatt–Duncanson model (Fig. 5.1). This involves the donation of the π electrons of the C=C to an empty σ orbital of the metal, accompanied by back donation from a filled metal *d*π orbital into an empty C=C π* orbital. As the back donation from the metal is important to stabilise the complex, usually only soft metals that are capable of back donation bind alkenes.[3–5]

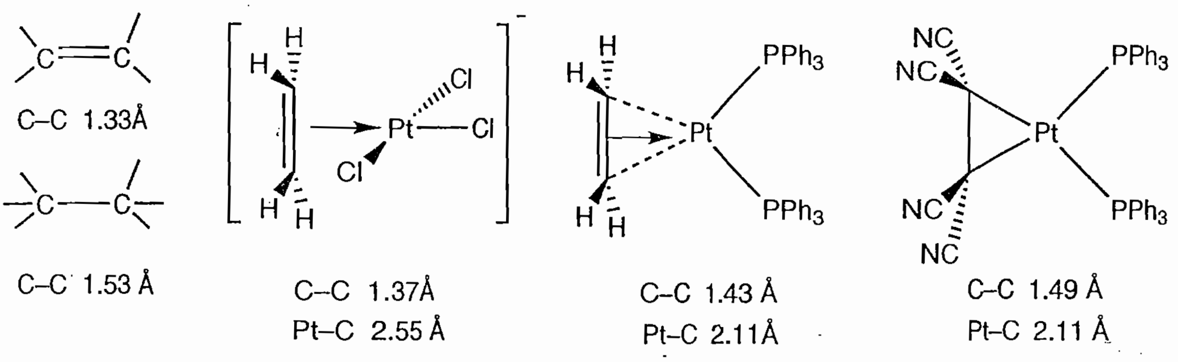


Fig. 5.2 Bond distances of few platinum–alkene complexes

In the metallacyclopropane model, the substituents on the carbon are strongly folded back, away from the metal, and the alkene carbons rehybridise from *sp*^{2} to *sp*^{3}. In this process, the metal gets oxidised and its formal oxidation state increases by two units; the C–C bond becomes more of a single bond (Fig. 5.2). The η^2-Pt and Pd complexes of C_{60} also fall under this category (Fig. 5.3).[6]

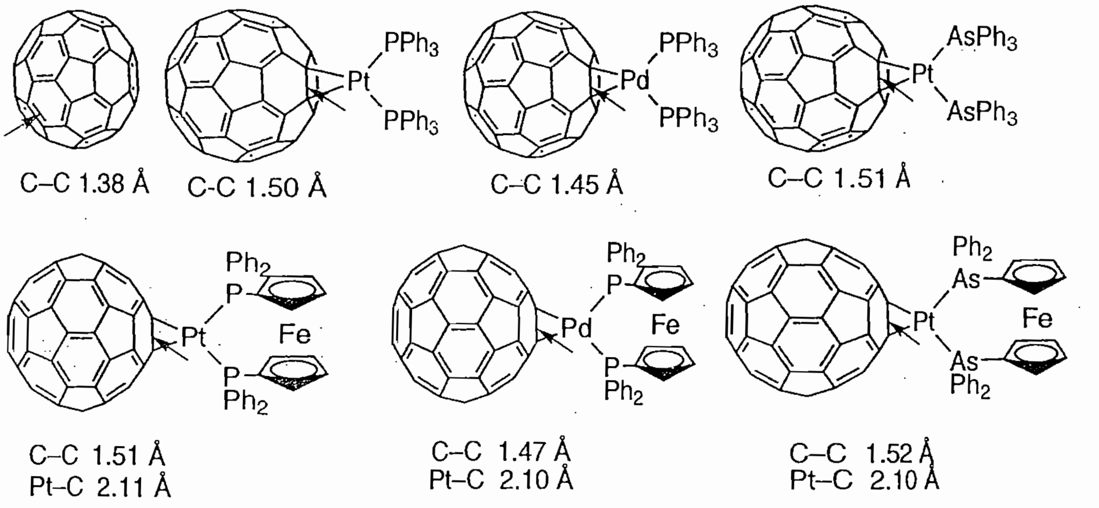


Fig. 5.3 C–C and Pt–C bond distances of η^2-C_{60} complexes of platinum and palladium

When the back bonding from the metal to the alkene is small, the substituents on the alkene are bent only slightly away from the metal and the C–C bond is lengthened marginally from the free alkene (type I). With electron withdrawing substituents on the alkene, the back donation is greater and the structure of the complex becomes close to type II.

An interesting comparison is shown in Fig. 5.4 where different types of alkenes are coordinated to the metal. The electron withdrawing fluoro groups in $F_2C=CF_2$ as well as the cyano groups of $(NC)_2C=C(CN)_2$ make them better π-acceptor ligands. This effect weakens the C=C bond but strengthens the alkene–metal bond.[7,8]

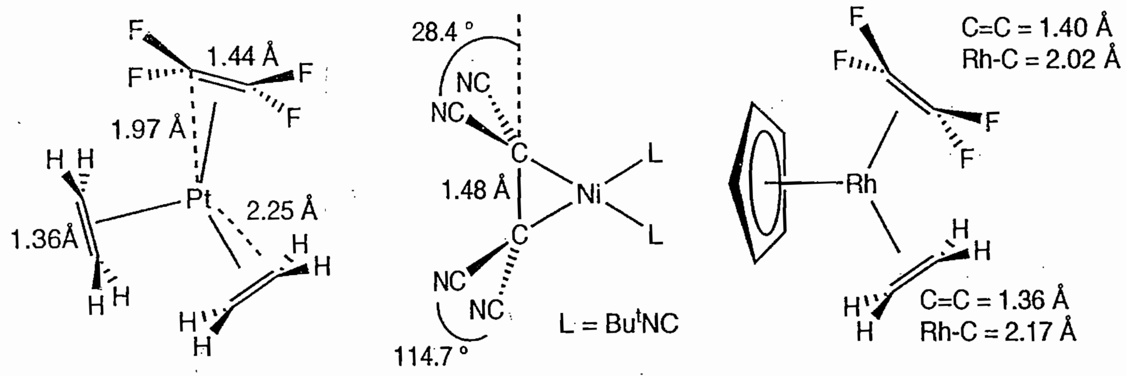


Fig. 5.4 Examples of complexes with alkenes having electron withdrawing groups

Alkene ligands are able to rotate with respect to the alkene–metal axis if sufficient energy is provided. The magnitude of this rotational barrier depends on the extent of back bonding. The rotational barrier is around 40–50 kJ mol^{-1} for Zeise's salt while it is around 100 kJ mol^{-1} in complexes with excessive back bonding. The hindered rotation of alkenes around the metal–alkene axis can be monitored by variable temperature NMR spectroscopy. The possibility of the alkene rotating around its own axis has been ruled out by variable temperature studies of chiral alkene complexes. It has also been observed that when both C_2H_4 and C_2F_4 are present in a complex, the rotation about the M–C_2F_4 axis sets in at a higher temperature as the metal to alkene back bonding is larger in M–C_2F_4 complexes. Both σ donation and π back bonding weaken the C=C bond resulting in lower $\nu_{C=C}$ stretching frequencies compared to the free alkene in the infrared spectra. Some of the $\nu_{C=C}$ values for ethylene complexes are: $Fe(CO)_4(CH_2{=}CH_2)$ 1551 cm^{-1}, $Pd_2Cl_4(CH_2{=}CH_2)_2$ 1525 cm^{-1}, $Pt_2Cl_4(CH_2{=}CH_2)_2$ 1506 cm^{-1} and $CpRh(CH_2{=}CH_2)_2$ 1493 cm^{-1}.[9]

One can monitor three parameters to classify the alkene complex as Dewar-Chatt-Duncanson type or metallacyclopropane type.

(i) Lengthening of the C=C bond (free C–C: 1.532 Å; C=C: 1.335 Å).
(ii) C=C stretching frequencies in the infrared spectra (free C_2H_4: 1623 cm^{-1}).
(iii) Reduction of the angles around C [from 120 (sp^2) to 107 (sp^3) (difficult to monitor in angles involving C–H bonds].

In metal–alkene complexes it is generally observed that

- the more stable complex is almost always formed by the *cis*-alkene (due to steric factors) in cases of complexes where *cis–trans* isomerism is possible,
- the presence of electron withdrawing groups on the alkene increases the strength of the metal–alkene bonding while electron-donating groups decrease the stability,
- chelating dienes such as cyclooctadiene (COD) and norbornadiene (NBD) show stabilisation resulting from the chelate effect. However, it may be noted that these can be displaced from the metal by stronger coordinating ligands such as phosphines,
- complexes of cycloalkenes which have strained rings (for example, cyclopropene), display increased stability. The ring strain increases the energy of the cycloalkene ring

compound making it a better donor to the metal centre. The changes in hybridisation on binding releases the strain in the alkene, for example norbornene binds strongly to the metals compared to cyclooctadiene.

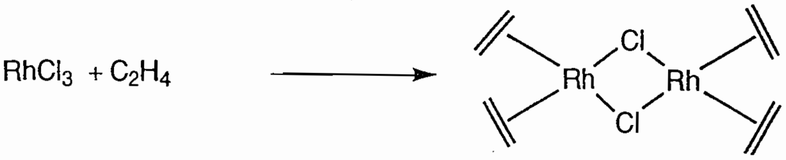
To summarise, the same factors that lead to lowering of ν_{CO} in the infrared spectra of metal carbonyls also lead to greater metallacyclopropane character in alkene complexes; for example, strong donor co-ligands (non-π acid ligands) on the metal, a net negative charge on the complex ion, and particularly a low oxidation state for the metal will lower the $\nu_{C=C}$ stretching frequencies. This means Pd(II), Hg(II), Ag(I) and Cu(I) alkene complexes tend to be type I (Eq. 5.1) while those of Ni(0), Pd(0) and Pt(0) complexes tend to be type II. In addition, the presence of electron withdrawing substituents on the alkene favours the type II structure.[10]

5.2 SYNTHESIS OF METAL—ALKENE COMPLEXES

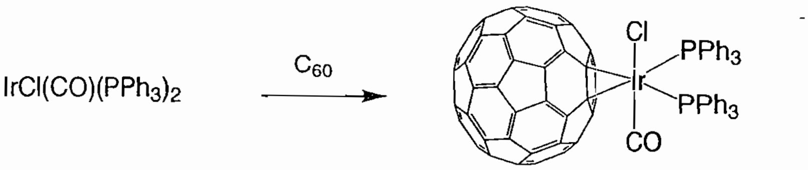
Synthetic methods adopted for the preparation of a few acyclic and cyclic alkene complexes are given in Eqs 5.2 to 5.9.[11–15]

$$Cp_2Co + K + C_2H_4 \longrightarrow CpCo(C_2H_4)_2 + KCp \qquad (5.2)$$

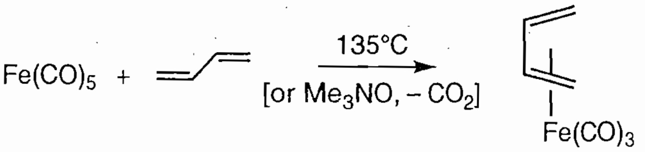
$$CpCo(CO)_2 + COD \longrightarrow CpCo(COD) + 2CO \qquad (5.3)$$



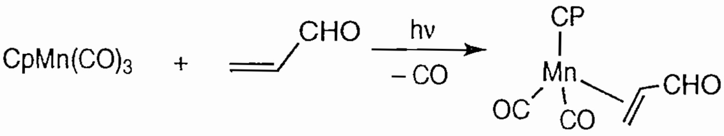
(5.4)



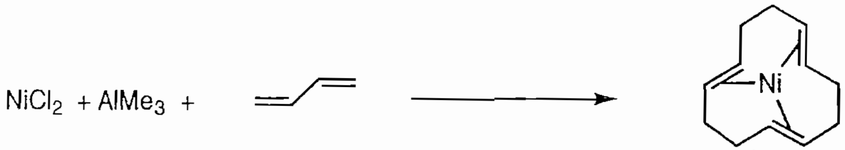
(5.5)



(5.6)

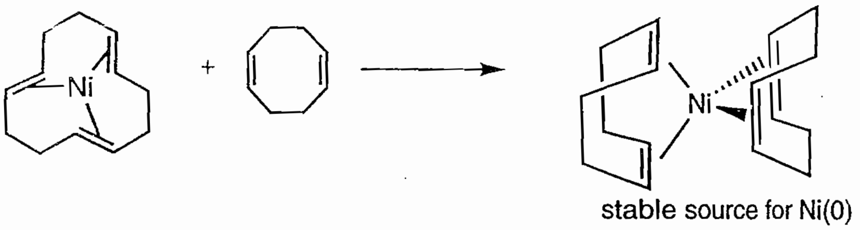


(5.7)



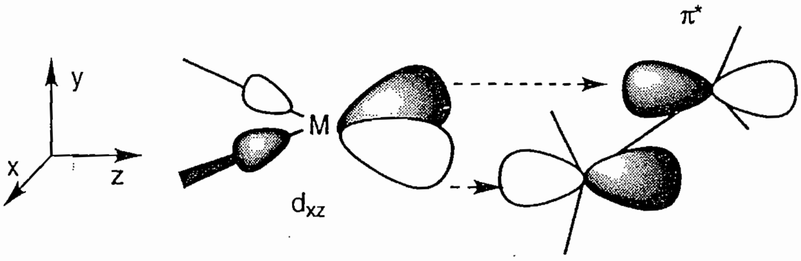
trans- trans- trans-
cyclododecatriene Ni(0)

(5.8)



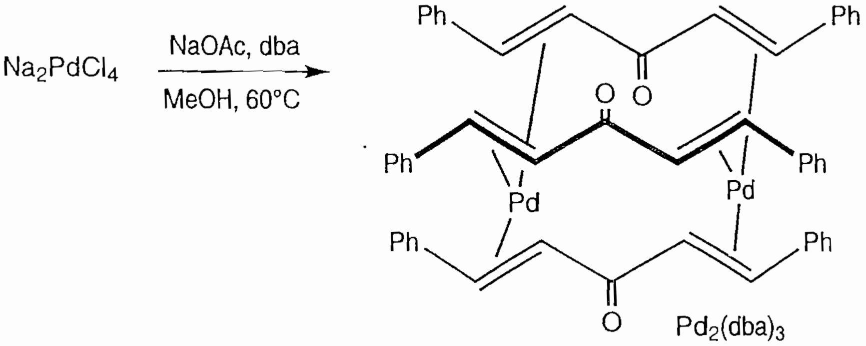
(5.9)

It is observed that the alkene complexes, M(alkene)$_3$, of zero-valent Ni and Pt (d^{10}) as well as a host of similar compounds such as L$_2$M(alkene) (L = phosphine/phosphite) M = Ni, Pd or Pt (including η^2 complexes of C$_{60}$), adopt a conformation which has the alkene ligands coordinated in the metal–ligand plane. In contrast, the complexes of d^8 metal ions such as the Zeise's salt, have the alkene bonded perpendicular to the coordination plane to minimise steric interactions. The difference is found to be due to the difference in the energies of the d_{xz} and d_{yz} orbitals in an angular ML$_2$ fragment. The energetically high occupied d_{xz} orbital of d^{10} metal ions, leads to more efficient back bonding. As a result of this, the alkene ligand has to adopt an in-plane bonding to maximise its overlap with the d_{xz} orbital.

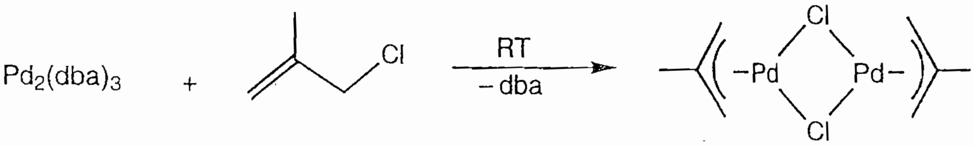


Compared to monoolefins, dienes have energetically low lying π* orbitals and are therefore more powerful π acceptors. In fact, monoolefin complexes with Ti(0) are unknown while complexes can be prepared with butadiene, for example, Ti(dmpe)(C$_4$H$_6$)$_2$. Upon bonding, the diene often adopts a *cis* conformation and the structure varies from a half-sandwich model to a metallacyclopentene depending on the electronic factors.

Complexes of 1,5-cyclooctadiene (COD) and dibenzylideneacetone (dba) often form air stable alkene complexes with many metals. These are often useful for providing the free metal (naked metal) which is highly reactive (Eqs 5.10 to 5.11).[16, 17]



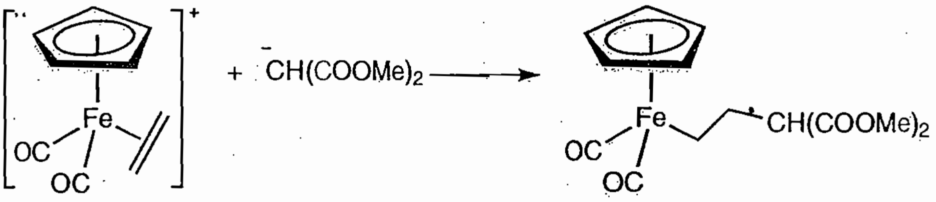
(5.10)



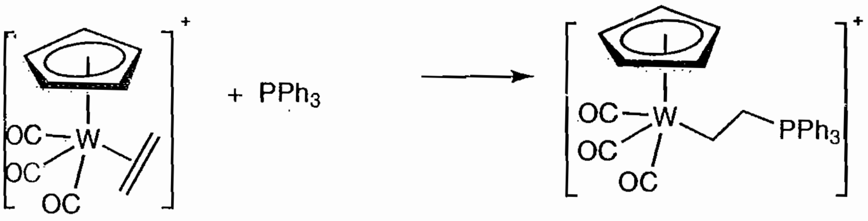
(5.11)

5.3 REACTIONS OF METAL BOUND ALKENES: THE CONCEPT OF UMPOLUNG

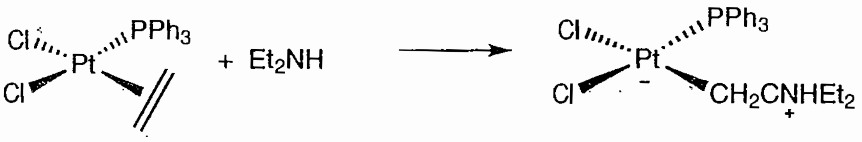
A very interesting outcome of the bonding of an alkene to the metal is reflected in the reactivity of the coordinated alkene. Many simple alkenes in the free state are easily subjected to electrophilic attack but do not undergo nucleophilic attack. However, because of the depleted electron density on the alkene (as a result of the σ donation to the metal), the alkenes bound to the metal are prone to nucleophilic attack rather than an electrophilic attack. So the effect of the binding plays an important role in deciding the reactivity of the alkene and this inversion of the chemical character of the alkene is called *umpolung* (a German term meaning reversal of polarity).[18, 19]



(5.12)

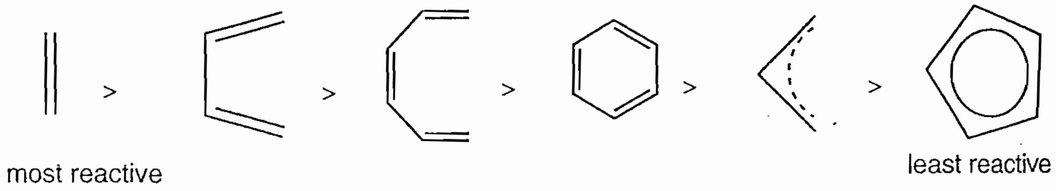


(5.13)

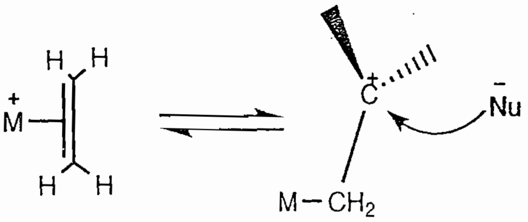


(5.14)

The organic chemistry of benzene is dominated by electrophilic substitution but as a coordinated ligand, it undergoes nucleophilic substitution. A metal fragment with good π accepting ligands and/or positive charge will be a good candidate for activating an unsaturated hydrocarbon towards nucleophilic attack. Of course, not all unsaturated hydrocarbons are equally reactive. While ethylene and benzene are quite reactive, cyclopentadienyl is one of the least reactive ligands towards nucleophiles when it is coordinated to a metal.



The reason why coordination activates the alkene for nuclophilic substitution can be understood from the fact that the alkene moiety is not rigidly bound to the metal but oscillates around its equilibrium position. If



an ethylene ligand shifts sideways as shown, the C–C bond becomes polarised. In an extreme case, the carbon atom at one end could be thought to assume cationic character which enhances the susceptibility towards a nucleophilic attack. The attack can be from a nucleophile that is already bound to the metal or from outside. For example, in the Wacker process, the alkene bound to the Pd unit undergoes nucleophilic attack by a water molecule from outside. More details of this process will be understood when we look into migratory insertion (Chapter 8).

5.4 ALKYNES: MODES OF BONDING TO METALS

Alkynes are quite similar to alkenes in their coordination behaviour but have another perpendicular pair of π-electrons. Consequently, they can act as neutral 2 or 4e donors. Because of the second set of π-electrons, their bridging ability is also much better (Fig. 5.5).

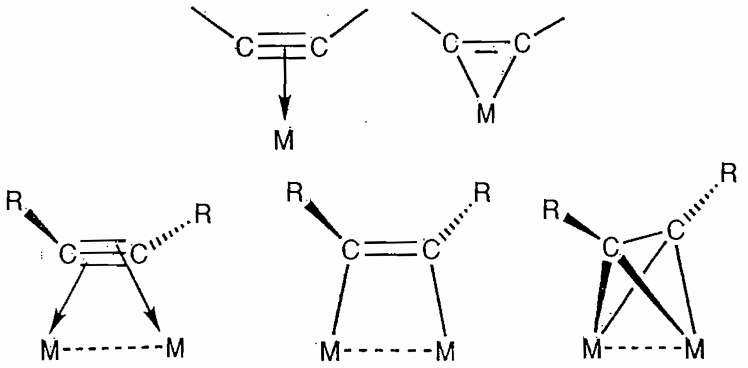
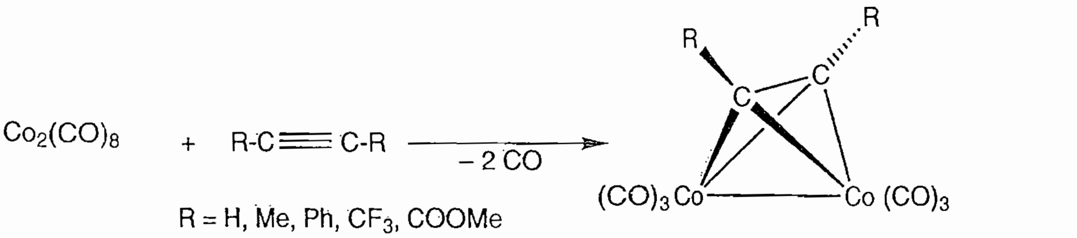


Fig. 5.5 Possible modes of bonding of alkynes to metals

Alkynes coordinate far more readily than alkenes to a metal due to steric (more open, less hindered) and electronic (better donor, 2 or 4e- bonding) reasons. They are also more reactive in C–C coupling and other similar reactions. Similar to the alkenes, the bonding of alkynes to metal centres also shows different orientations with respect to the plane of the metal complex. For example, in the Pt(II) complex $PtCl_2(ArNH_2)(Bu^tC{\equiv}CBu^t)$, the orientation of the alkyne is perpendicular to the square plane of the molecule while in the Pt(0) complex $Pt(PPh_3)_2(PhC{\equiv}CPh)$, there is in-plane bonding of the alkyne.[20-23]

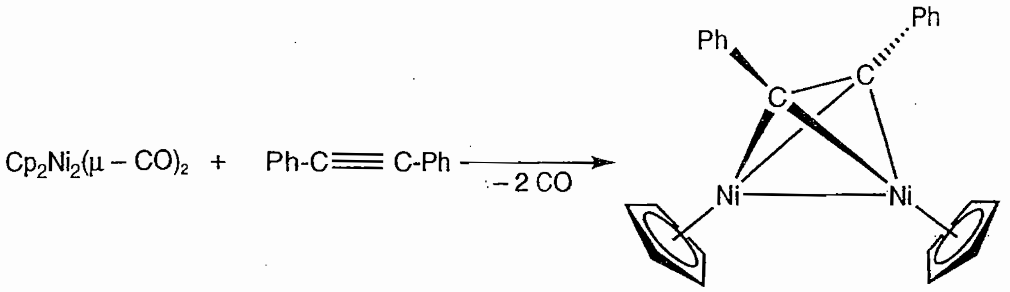
The following synthetic methods show how different types of bonding of metal to alkynes can occur.



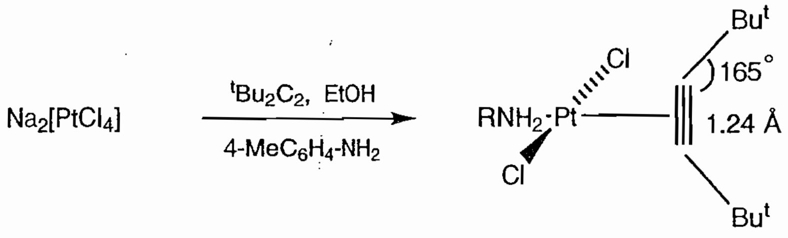
(5.15)

$\nu_{C\equiv C}$ H≡H 1974 cm^{-1} $\qquad$ ν_{C-C} of complex 1403 cm^{-1} (R = H)

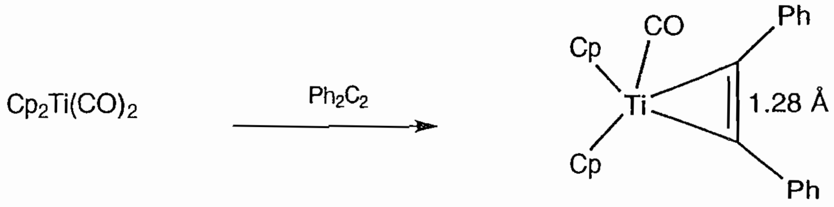
Me≡Me 2055 cm^{-1} $\qquad$ 1633 cm^{-1} (R = Me)



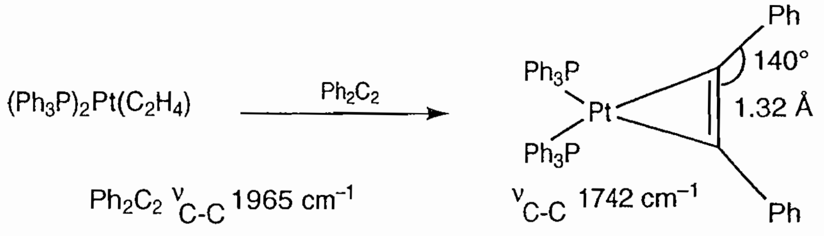
(5.16)



(5.17)

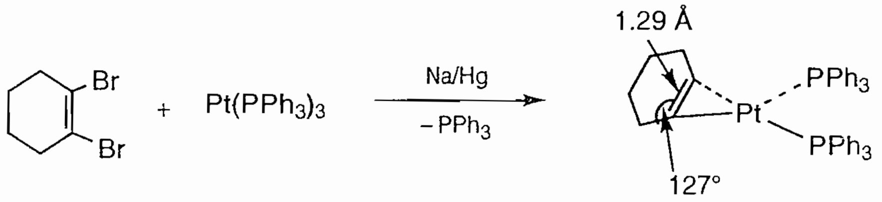


(5.18)

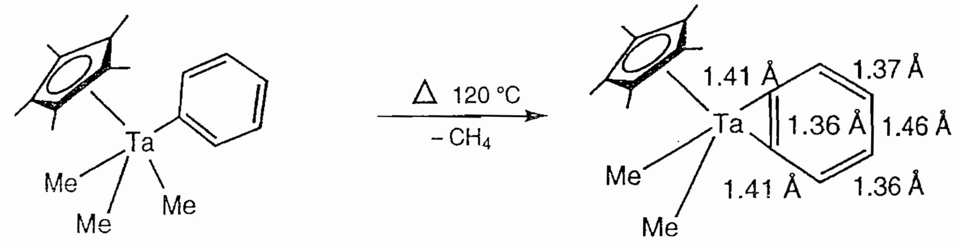


(5.19)

Though benzynes are generally difficult to isolate, alkyne coordinated organometallic compounds like $Cp^*Ta(CH_3)_2(C_6H_4)$ can be made in principle. Similarly, strained cyclic alkynes which are unstable can be stabilised by coordination to a metal. For example, cyclohexyne is unstable as a free molecule but can be obtained in the metal coordinated form. Like alkenes, alkynes readily insert into metal–hydride bonds to give vinyl complexes.[24, 25]



(5.20)



(5.21)

5.5 REACTIONS OF METAL COMPLEXES OF ALKENES AND ALKYNES

With many cobalt and palladium complexes, alkynes dimerise to give cyclobutadiene compounds (Fig. 5.6).[26,27]

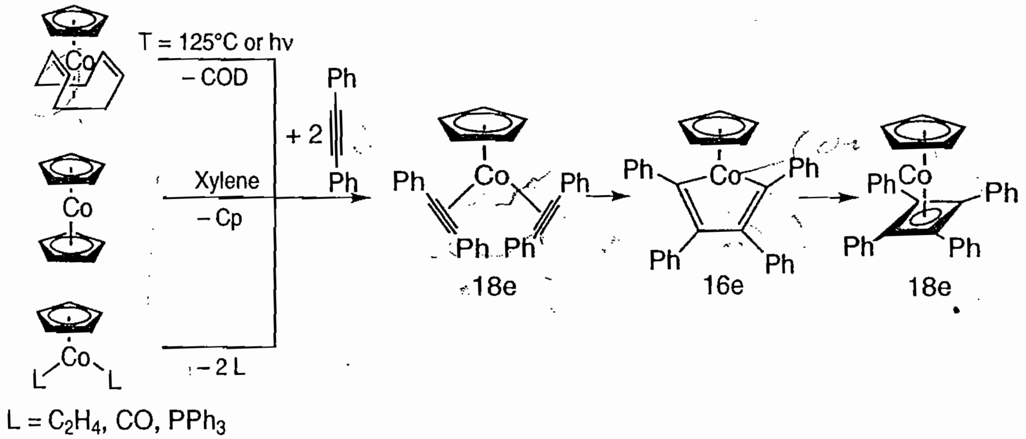
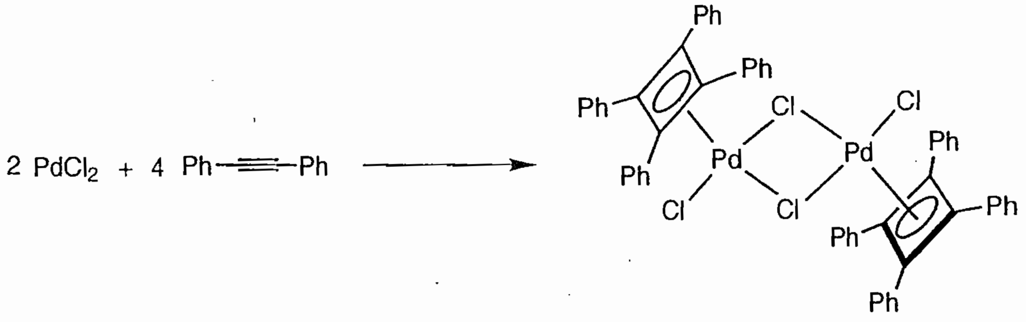
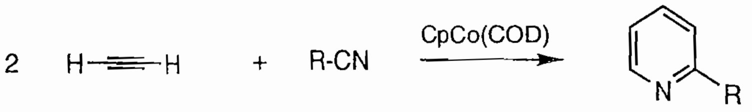


Fig. 5.6 Dimerisation of alkynes to cyclobutadiene with CpCo based reagents

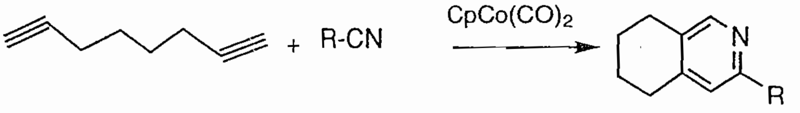


(5.22)

The most interesting reaction of alkynes with organometallic reagents is their trimerisation to aryl compounds. For example, acetylene and substituted acetylenes trimerise to benzene or its derivatives in the presence of catalysts like $CpCo(COD)$ or $CpCo(C_2H_4)_2$.[28,29]

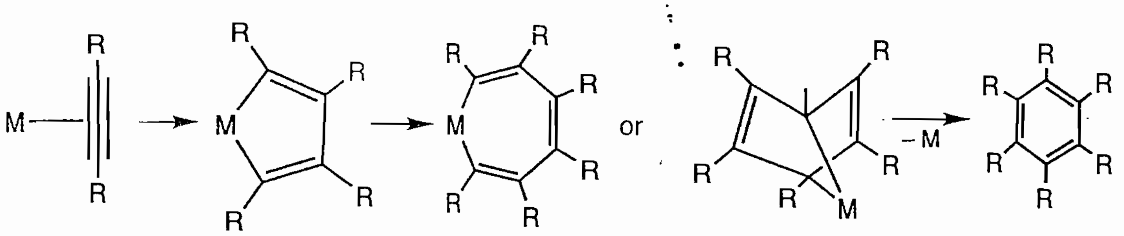


(5.23)

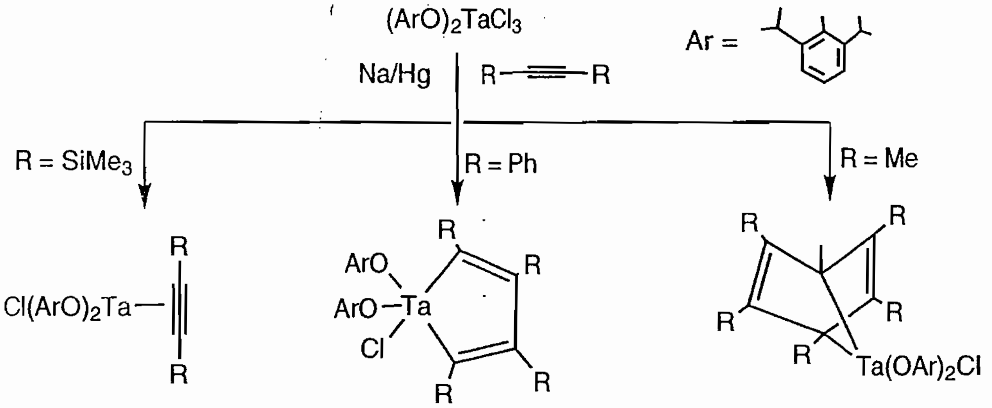


(5.24)

Trimerisation reactions also occur with a combination of alkynes and nitriles or analogous compounds to yield pyridine derivatives. While gain in aromaticity is the driving force for many of these reactions, it is also possible to prepare trimeristion products with two alkynes and an alkene resulting in cyclohexadiene derivatives. Trimerisation reactions have also been catalysed by Nb and Ta chlorides. The reaction is thought to proceed stepwise.

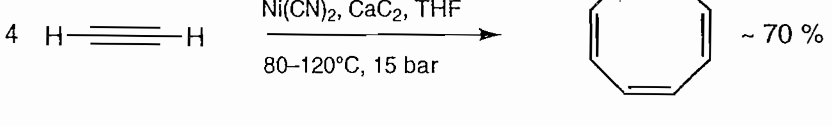


The mechanistic evidence for this reaction has been obtained by isolating and characterising some of the possible intermediates by a careful control of the R groups (Eq. 5.25).[30]



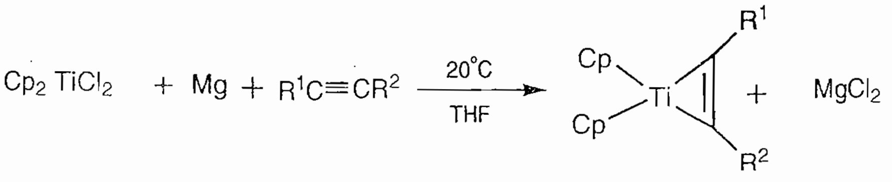
(5.25)

Acetylene and a few other monosubstituted alkynes have also been found to undergo tetramerisation leading to cyclooctatetraene (COT) or its derivatives. This was first reported by Reppe in 1946 where a nickel catalyst such as $Ni(CN)_2$ or $Ni(acac)_2$ along with CaC_2 was used for this reaction.[31] Benzene is also obtained as a side product in this reaction. The mechanism of this reaction has been subjected to investigations since many reactions are possible, such as addition of alkyne to benzene, dimerisation of the cyclobutadiene ligand, and a concerted mechanism or a step wise addition of alkynes to metallacycles leading to COT. Mechanistic studies have ruled out the first two possibilities and it is presumed that the reaction proceeds by a concerted process (having four alkynes and two ligands bound simultaneously to nickel forming an octahedral complex) or by the stepwise addition which involves intermediates such as metallalcycloheptatrienes or metallacyclononatetraenes.



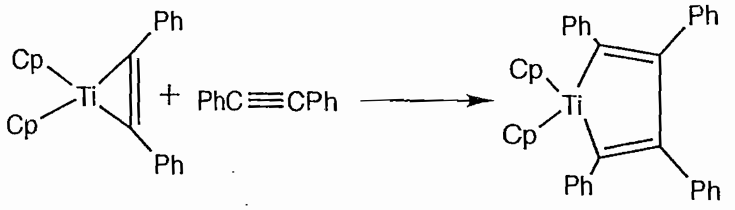
(5.26)

Many examples of metallacycles, formed as a result of reactions of alkynes with organometallic reagents are known and most of these are precursors for a variety of organic molecules. The first acetylene based metallacycle of titanocene without additional ligands was prepared by the interaction of Cp_2TiCl_2 with equimolar amounts of magnesium and diphenylacetylene. The metallacyclopropene acetylene complex has also been prepared and structurally characterised.[32]



(5.27)

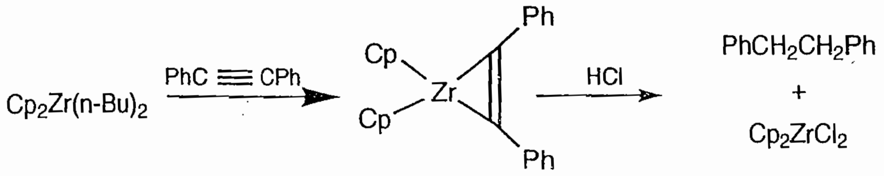
The diphenylacetylene complex of titanocene (metallacyclopropene) on further reaction with diphenylacetylene gives a stable metallacyclopentadiene.



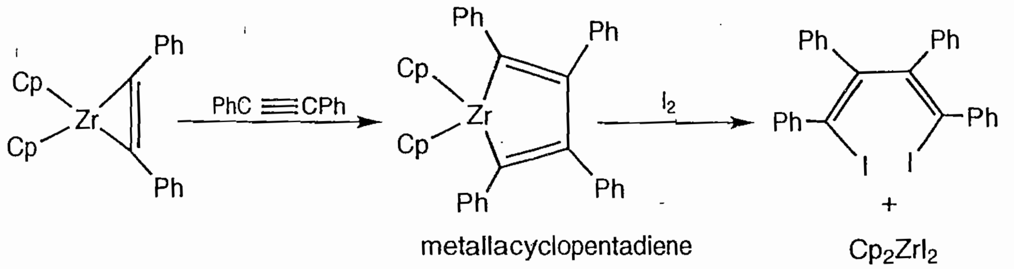
(5.28)

Treatment of Cp_2ZrCl_2 with two equivalents of n-BuLi gives $Cp_2Zr(n\text{-}Bu)_2$ (Negishi's reagent) which is very reactive and is often considered to give a reactive species '$ZrCp_2$'. Treatment of this with two moles of diphenylacetylene gives the zirconium analogue of the metallacyclopentadiene, a useful precursor for making substituted butadienes.[33]

$$\mathrm{Cp_2ZrCl_2} \xrightarrow{\text{2 n-BuLi}} \mathrm{Cp_2Zr(n\text{-}Bu)_2} \qquad (5.29)$$

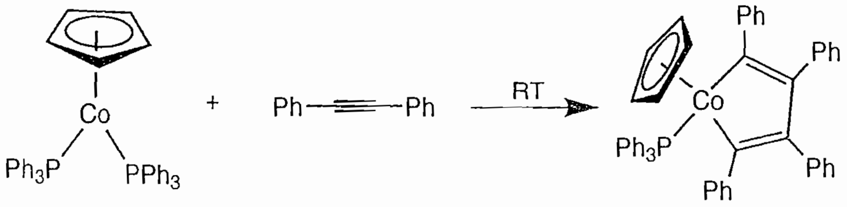


(5.30)



(5.31)

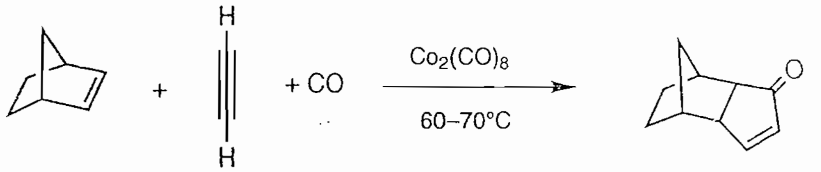
The first and the most well known example of a cobalt based metallacycle was prepared by Yamazaki in 1967 by the reaction of $CpCo(PPh_3)_2$ with diphenylacetylene at room temperature. The complex and its analogues obey the 18 electron rule and are quite stable. They are also precursors for a host of aromatic molecules, especially substituted pyridines and similar heterocyclic compounds.[34]



(5.32)

5.5.1 Pauson-Khand Reaction

A related reaction of significant synthetic importance in organic chemistry is the Pauson-Khand reaction which involves the catalytic addition of an alkyne, alkene and carbon monoxide in the presence of cobalt catalysts to yield substituted cyclopentanones.[35]



(5.33)

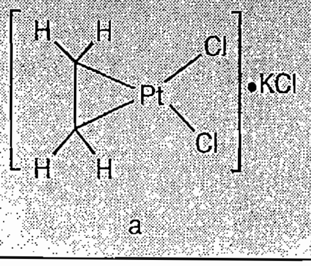
The discovery of Zeise's salt[36, 37]

The first organometallic compound containing a transition metal to be discovered was a relatively stable platinum ethylene complex $K[(C_2H_4)PtCl_3].H_2O$, well known as the Zeise's salt. The discovery of this compound in 1827 by William Christopher Zeise, a Danish pharmacist who later on became a professor at the University of Copenhagen has been vividly described by Prof. Dietmar Seyferth as follows.

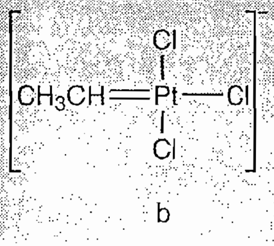
'The breakthrough, the isolation of a pure, crystalline compound came when Zeise added potassium chloride to a concentrated $PtCl_4$/ethyl alcohol reaction solution and evaporated the resulting solution. Beautiful lemon yellow crystals, often one half inch or more in length were isolated. On longer exposure to air and light, they gradually became covered with a black crust. They contained water of hydration, which was lost when they were kept over concentrated sulfuric acid in vacuo or when heated to around 100°C. Chemists in those days often reported how the compounds that they had prepared tasted. Zeise described the taste of this potassium salt as metallic, astringent and long lasting.'

On strong heating, the Zeise's salt gave off gaseous HCl and an inflammable gas. Because of this property, Zeise called his salt '*sal kalicoplatinicus inflammabilis*', meaning inflammable potassium platinum salt. The determination of the actual structure of this compound went through different stages with Brinbaum (a) and Chatt (b) initially suggesting possible structures based on their experiments. The actual structure (c), of the molecule was obtained after a series of studies which began in 1954 with an X-ray diffraction and confirmed with a neutron diffraction study in 1975, almost 150 years after the discovery of the compound.

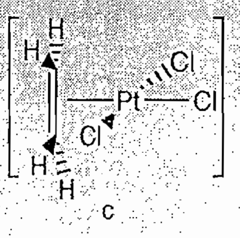
Zeise is also well known for his original contributions in organosulphur chemistry and was the first person to discover the malodorous thiols (mercaptans) in 1832 which earned him the bad reputation of a 'smelly' chemist. He was once ordered out of the royal theatre as his foul smelling clothes were unbearable for his fellow listeners in the theatre!



a



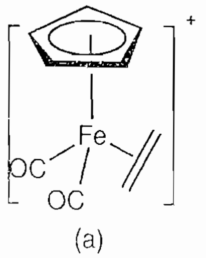
b



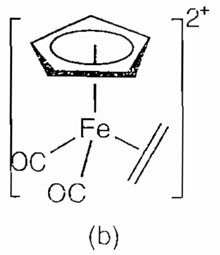
c

Problems and Exercises

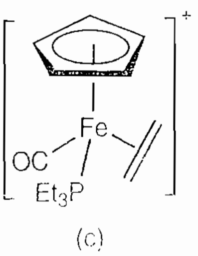
5.1. Arrange the following compounds in the increasing order of ethylene C–C bond length.



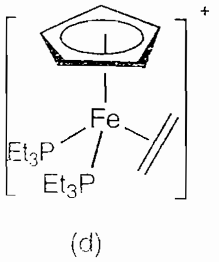
(a)



(b)



(c)



(d)

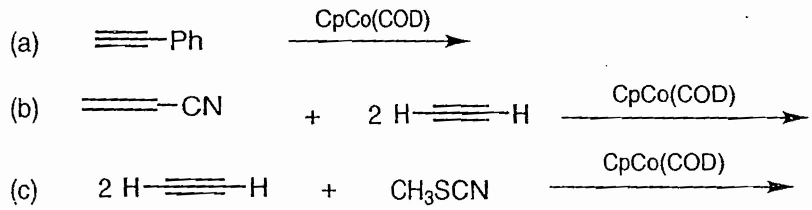
5.2. Which among the following alkenes will bind most strongly to a metal? Give reasons.

(a) COD (b) ethylene (c) norbornene (d) cyclohexene

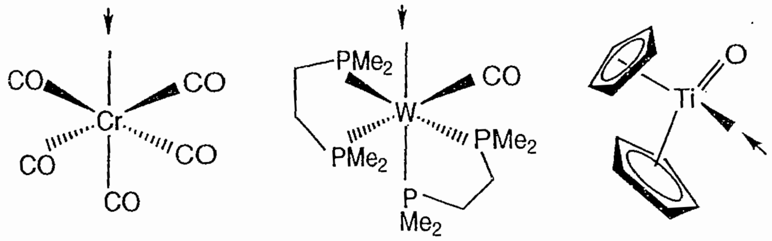
5.3. The alkene complex $Fe(PMe_3)_4(\eta^2\text{-propene})$ at low temperature shows four peaks in its ^{31}P NMR spectrum. Draw the structure of this complex. When the sample is warmed, the four peaks in the ^{31}P NMR spectrum coalesce to two peaks with equal intensity. Explain this phenomenon.

5.4. When acetylene is bubbled through a refluxing solution of 2-cyanopyridine in THF in the presence of CpCp(COD), a new compound A with an empirical formula C_5NH_4 was formed. Compound A, in the presence of ferric ions, was found to give an intense red coloured solution indicating the formation of another new compound B. Write the structures of A and B.

5.5. Predict the product(s) in the following reactions.



5.6. To which of the following structures will trifluoroethylene ($F_2C{=}CHF$) bind most and least strongly?



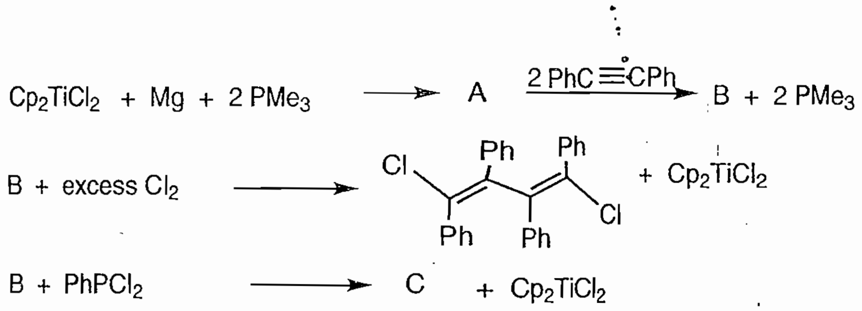
5.7. When one mole of $(PPh_3)_2Pt(C_2H_4)$ is treated with two moles of BF_3, ethylene is quantitatively released and the BF_3 is completely consumed. The unusual product obtained consists of a single compound and is square planar and monomeric in dichloromethane solution. Formulate the product and explain the bonding, also draw the structure of $(PPh_3)_2Pt(C_2H_4)$ (*Inorg. Chem*, 1976, Vol. 15, 490).

5.8. If an olefin has to bind to a transition metal, say Cr, which of the olefins, *cis*-cyclooctene or *trans*-cyclooctene will form the stronger complex and why?

5.9. Which of the following metal alkene complexes do you think will look most like a metallacyclopropane? Explain your answer.

(a) $(CH_2{=}CH_2)Ni(PPh_3)_2$ (b) $(CH_2{=}CH_2)Fe(CO)_4$

5.10. Draw the structures of A, B and C in the following reactions.



Supplementary reading

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CHAPTER

6

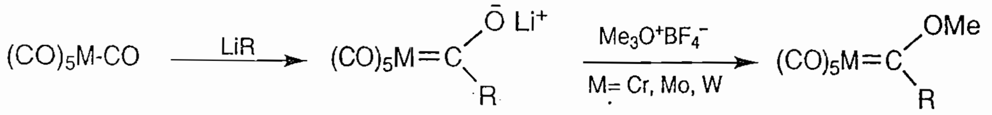
Carbenes and Carbynes: Complexes with Metal–Carbon Double and Triple Bonds

6.1 Metal Carbenes

Carbenes, :CR$_2$, are species which are highly reactive and rarely stable in the free state. Generally there are two types of carbenes—singlet (↑↓) and triplet (↑↑) carbenes. Singlet carbenes have a pair of electrons and an *sp*^{2} hybrid structure. Triplet carbenes have two unpaired electrons. They may possess either *sp*^{2} hybrid or linear *sp* hybrid structures. Carbenes as ligands in oragnometallic chemistry can be broadly classified under two categories—the Fischer and the Schrock types.

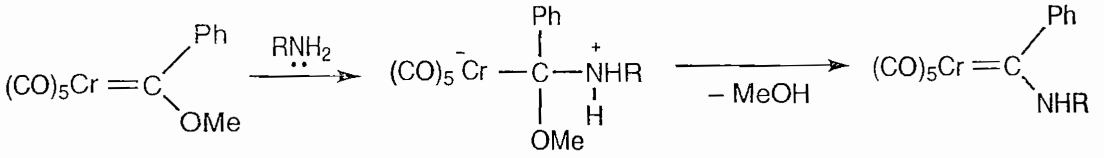
Compounds with metal–carbon double bonds were first discovered in 1964 by E O Fischer.[1] These compounds are of the type $(CO)_5M{=}C(R)(OR')$ (M = Cr, Mo, W), and as they are formally derived from the coordination of a carbene, :CR$_2$, to a metal centre, they have been named carbene complexes or more precisely as Fischer carbene complexes. The metal is in a low oxidation state and the bonding of the carbene is similar to that of CO. Complexes with M=C bonds having highly oxidised metal centres were subsequently prepared by Richard Schrock. These were called Schrock carbene complexes or metal alkylidene complexes, for example, $Cp_2(CH_3)Ta{=}CH_2$.[2]

6.1.1 Synthesis of Fischer Carbene Complexes



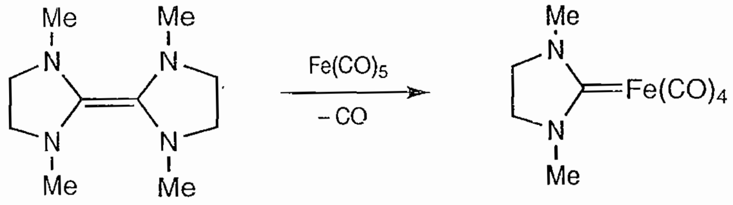
(6.1)

The methylation of the lithium salt can also be brought about by reagents such as MeI or MeOSO$_2$F. This is the most widely applied method of preparation for Fischer carbenes. Since the carbon is electron deficient, it undergoes nucleophilic attack. If Cr(CO)$_5$ is replaced by O in the following reaction, an interesting similarity to aminolysis of an ester to amide is observed.[3]



(6.2)

One can realise Fischer carbenes from electron rich olefins or by the addition of alcohols or amines to isocyanide complexes.[4, 5]



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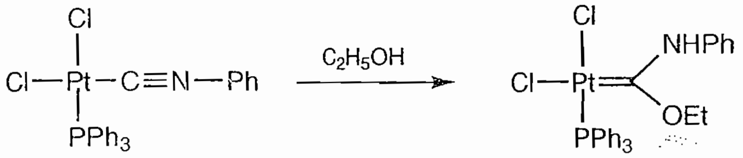
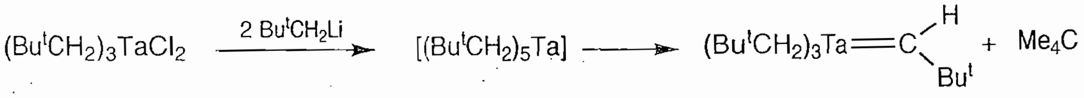


(6.4)

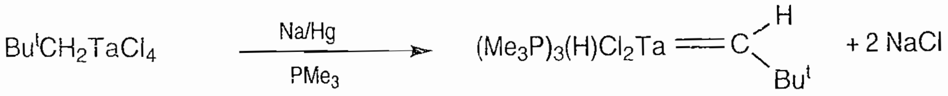
6.1.2 Synthesis of Schrock Carbene Complexes

Unlike electron rich noble metals, the early transition metals undergo α-H abstraction to reduce steric crowding and form alkylidene metal complexes. One can make $TaMe_5$ by the methylation of $TaCl_5$ with MeLi, but as the steric bulk of the alkyl groups increases, it becomes difficult to accommodate five alkyl groups around the metal. α-H abstraction can also be initiated by strong donor ligands like PMe_3 resulting in carbene complexes in high oxidation states; these have been named alkylidenes by Schrock.[6,7]

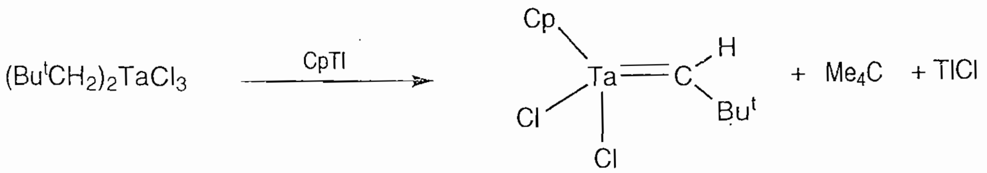
$$TaCl_5 + 1.5\,(Bu^tCH_2)_2Zn \longrightarrow (Bu^tCH_2)_3TaCl_2 \qquad (6.5)$$



$$(Bu^tCH_2)_3TaCl_2 \xrightarrow{2\,Bu^tCH_2Li} [(Bu^tCH_2)_5Ta] \longrightarrow (Bu^tCH_2)_3Ta{=}C(H)Bu^t + Me_4C \qquad (6.6)$$



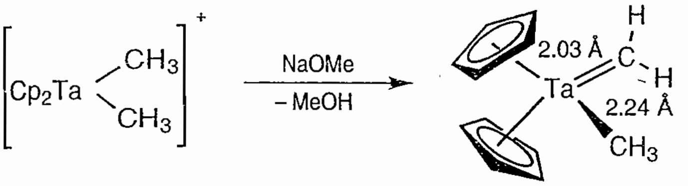
$$Bu^tCH_2TaCl_4 \xrightarrow[PMe_3]{Na/Hg} (Me_3P)_3(H)Cl_2Ta{=}C(H)Bu^t + 2\,NaCl \qquad (6.7)$$



(6.8)

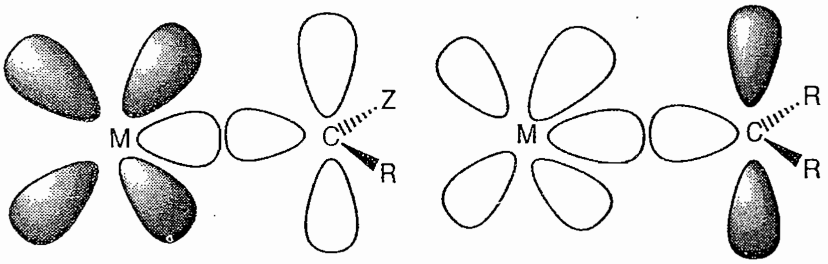
Such reactions are quite facile with tantalum; the methyl groups can even be deprotonated to give methylene complexes with a strong base such as sodium methoxide.[8]

$$TaMe_3Cl_2 \xrightarrow{2\ LiCp} Cp_2TaMe_3 \xrightarrow{Ph_3C^+BF_4^-} Cp_2TaMe_2^+ \qquad (6.9)$$



(6.10)

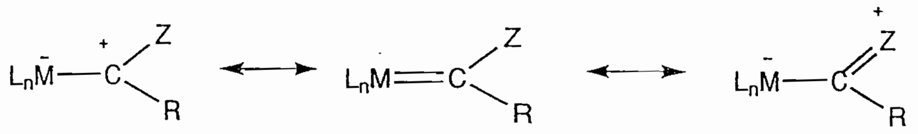
The properties and chemical behaviour of Schrock and Fischer carbenes are substantially different because of the differences in the nature of the metal–carbene bonding. As shown in Fig. 6.1, the metal in a Schrock carbene is electrophilic and is stabilised by electron donating ligands as well as by backbonding from an occupied *p*-orbital of the carbon atom. This results in a strong metal–carbon double bond. The overall bonding in the complex leaves the carbon atom electron rich.[9]

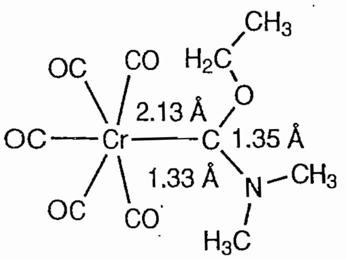


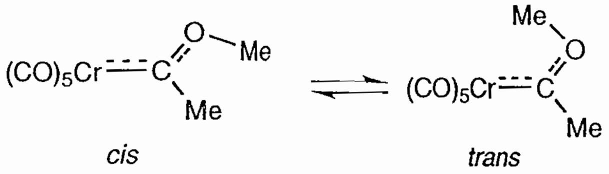
	Fischer carbene	Schrock carbene
Carbon:	electron deficient; stabilised by heteroatom/phenyl groups; attacked by nucleophiles.	electron rich; destabilised by heteroatom groups; attacked by electrophiles.
Metal:	present in low oxidation state; electron rich (usually d^6 with 18e); attacked by electrophiles; stabilised by electron accepting ligands.	present in high oxidation state; electron deficient (d^2/d^0 etc; 16 or 14 e); attacked by nucleophiles; stabilised by electron donating ligands.
M=C:	relatively weak; low rotational barrier.	relatively strong; large rotational barrier.

Fig. 6.1 Comparison of Fischer and Schrock carbenes

Fischer carbenes on the other hand, have nearly opposite properties. The metal is electron rich, in part because of coordinate donation of an electron pair from the carbene carbon atom and the CO ligands. The competition for the metal *d* electrons occurs between the electron withdrawing ligands like CO, and the empty *p* orbital on carbon. This in turn, is stabilised by overlap with electron pairs on the heteroatom substituents (NR_2, SR, OR or Ph). The resulting C=M multiple bond is weakened and has a low barrier to rotation. Many of the chemical properties of Fischer carbenes are ester-like. Nucleophilic substitution takes place by way of a tetrahedral intermediate. Also, α-hydrogen atoms, for example, $(CO)_5Cr{=}C(OCH_3)CH_3$, have enhanced acidity ($pK_a = 12.3$). The Fischer carbene can be described by the following resonance forms and the relative contribution of the individual form depends on the π-donor properties of the M, Z and R at the carbene carbon atom.[10, 11]







The effect of these resonance structures is reflected in the bond distances of the Fischer carbene, as observed in the X-ray crystal structure of $(CO)_5Cr{=}C(OEt)(NMe_2)$. The Cr–C bond distances are observed in the range of 2.0–2.2 Å while the C–O and C–N bond distances are 1.35 and 1.33 Å respectively. These are slightly shorter than the corresponding single bond distances. Conclusive proof for the partial double bond character of the C–heteroatom bond is obtained from NMR spectral studies. For example, the Fischer type methoxy(methyl) carbene complex adopts a *trans* configuration in the solid state while both *cis* and *trans* isomers are present in a solution at −40°C giving rise to four methyl peaks in the proton NMR. On bringing to room temperature, a pair wise coalescence takes place leading to two peaks as a result of rotation about the C–O bond. Similar observations are also seen in amino substituted Fischer carbenes.[12]

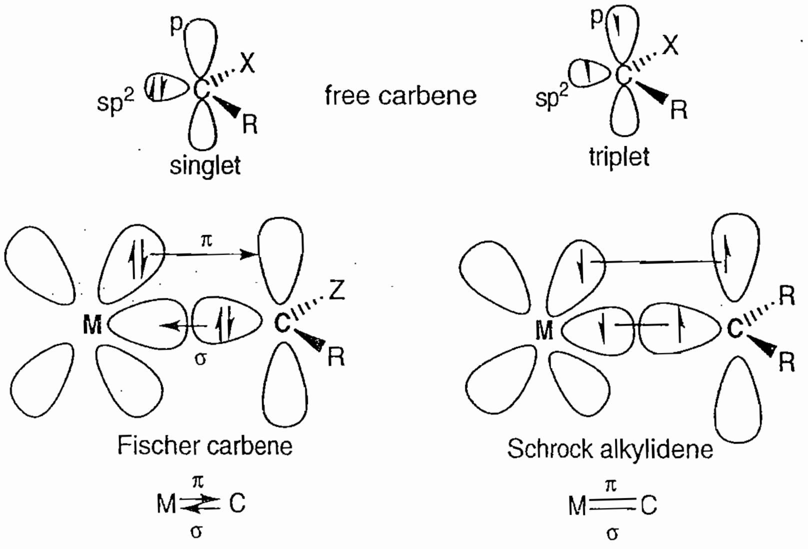
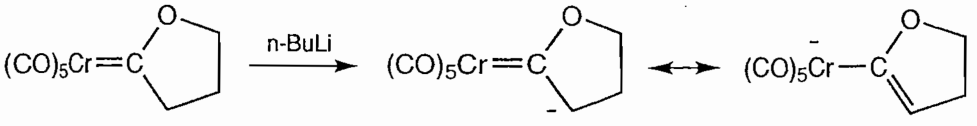


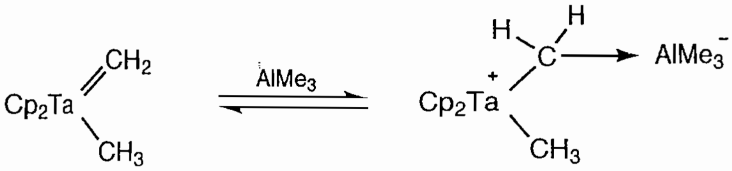
Fig. 6.2 Differences in bonding between Fischer and Schrock carbenes

Considerable similarity is observed between singlet carbenes and Fischer carbenes as well as triplet carbenes and Schrock carbenes. The bonding differences between Fischer and Schrock carbenes can be described as follows. In the Fischer carbene, donation of electrons from the carbon to the metal dominates (with some amount of back donation to the carbene carbon's *p* orbital) leaving the carbene carbon atom with a slight positive charge. In the Schrock carbene, two covalent bonds are envisaged between the metal and carbon, both of them polarised towards the carbon, giving it a slight negative charge (Fig. 6.2). The C–H acidity of a methyl group bound to a Fischer carbene carbon is considerably enhanced as the carbene can stabilise the carbanion formed upon deprotonation. This is reflected in the reactions of such carbene complexes with alkyl lithium reagents.[13]

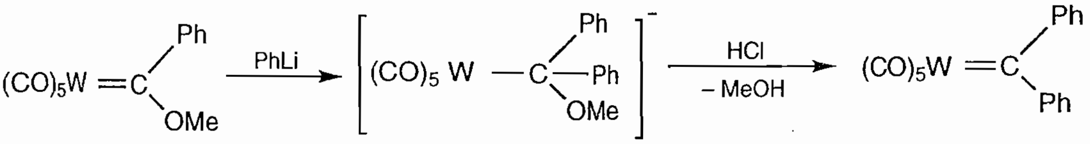


(6.11)

The electrophilic versus nucleophilic nature of the two different kinds of carbenes is indicated in the following reactions.[14]



(6.12)



(6.13)

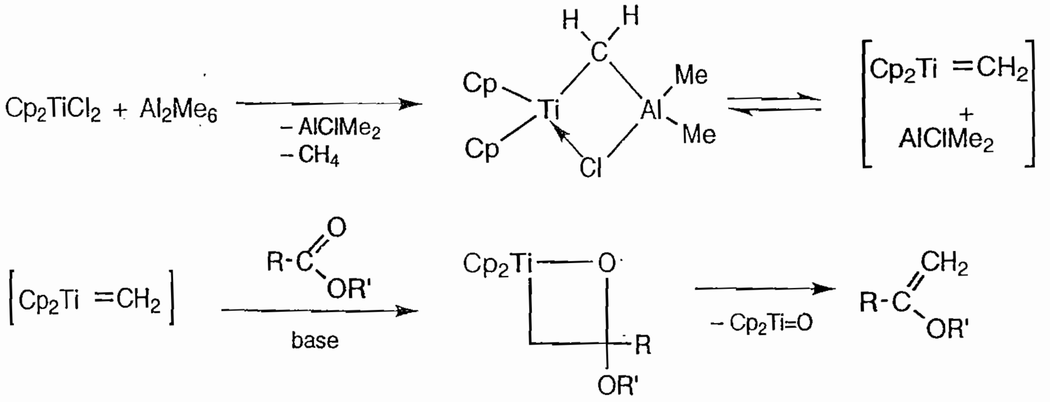
The reaction shown by the Schrock carbene with $AlMe_3$ is similar to that of a phosphorus ylide with $AlMe_3$. This analogy was instrumental in the discovery of the Tebbe's reagent.

6.1.3 Tebbe, Grubbs and Petasis Reagents

Many titanocene carbene based reagents have been developed for the conversion of carbonyl groups to alkenes. These reagents generate the unstable carbene $Cp_2Ti{=}CH_2$ which reacts with carbonyl groups; their reactions are complimentary to, and in many cases superior to the traditional Wittig reagent. These reagents have the unique advantage of being small in size and are therefore able to react with sterically hindered carbonyl groups. Their most noticeable advantage is that, the range of substrates they can react with is much wider than that of the Wittig reagent. They can be used, not only for the high yield conversion of carbonyl groups of aldehydes and ketones but also of esters, thioesters, amides, lactones and carbonates with tolerance of many functional groups. Among these reagents, the first to be developed was Tebbe's reagent followed by Grubbs' reagent. The most recent and versatile among such reagents is the Petasis reagent.

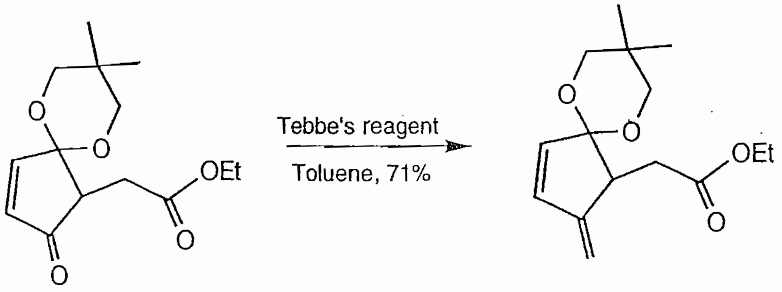
Tebbe's reagent

Tebbe's reagent is a four membered Ti–Al metallacycle prepared from Cp_2TiCl_2 and $AlMe_3$ (Eq. 6.14).[15] The reagent, commercially available as a solution in toluene is highly air and moisture sensitive, pyrophoric and has Lewis acidic character. The main advantage of Tebbe's reagent over other titanium carbene based reagents is that the reactive carbene species can be generated and reacted at low temperatures. The efficiency of this reagent is shown from the fact that methylenation of benzophenone with Tebbe's reagent gives 97% of $Ph_2C{=}CH_2$ while the yield is only 46% using the phosphorus ylide $Ph_3P{=}CH_2$. It methylenates a range of compounds—aldehydes, ketones, esters, thioesters, amides, carbonates and some lactones. However, it is not suitable for methylenation of carbonyl compounds such as acid chlorides, anhydrides, imides and β-lactones; such reactions lead to undesired products, mostly titanium enolates.



(6.14)

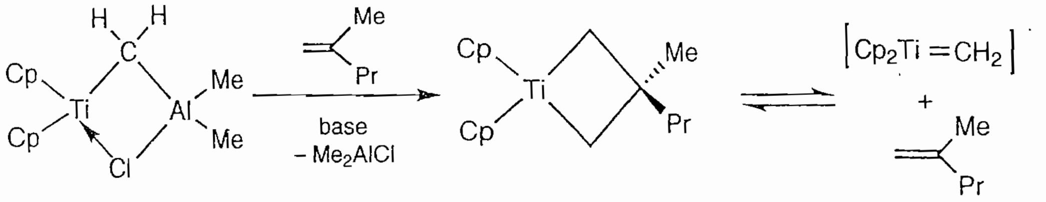
In the absence of a Lewis base such as pyridine or THF, the reactivity of the Tebbe's reagent with esters is sluggish but in the presence of such bases its reactivity and range of possible substrates increases considerably. This property has been made use of for selective methylenation of aldehydes and ketones in the presence of ester and amide groups (Eq. 6.15).



(6.15)

Grubbs' reagent

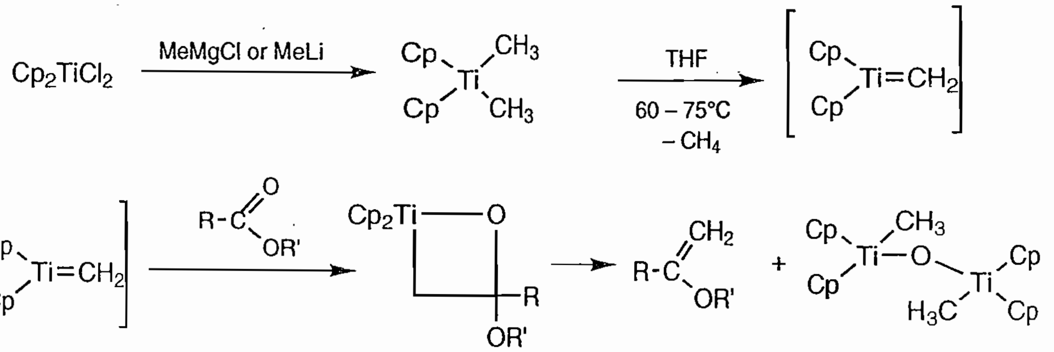
A variation of Tebbe's reagent has been prepared by Grubbs which involves a metallacycle generated from Tebbe's reagent.[16] This compound is relatively more air stable than Tebbe's reagent and the transfer reaction does not require a base. When this metallacycle is heated, the reactive carbene is generated (Eq. 6.16). This reagent has been relatively less utilised for organic reactions when compared to the other two.



(6.16)

Petasis reagent

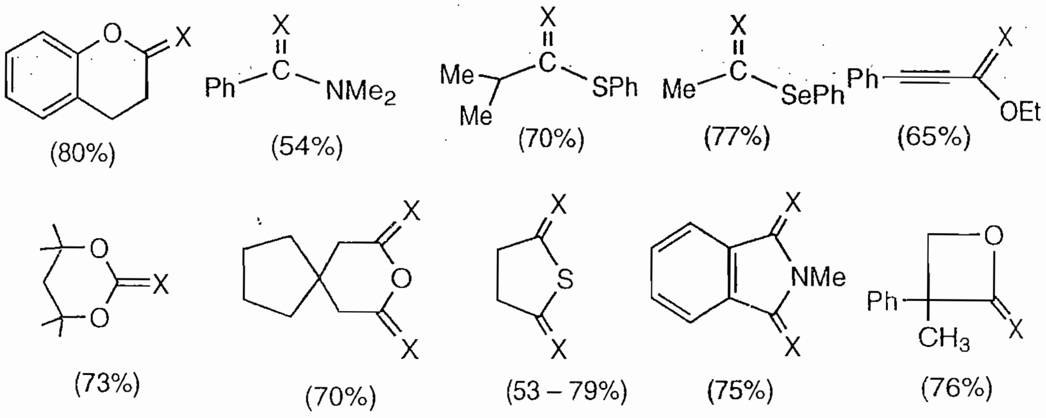
Petasis reagent is dimethyl titanocene, Cp_2TiMe_2 whose utility as a precursor for generating $Cp_2Ti{=}CH_2$ was first shown by Petasis and coworker, by heating the reagent in THF or toluene at 60–75°C with the carbonyl compound.[17] Cp_2TiMe_2 is easily prepared from Cp_2TiCl_2 and MeLi or MeMgBr and the compound is relatively stable to air and moisture and can be more easily handled than Tebbe's reagent. Its reactions can also be promoted by microwave irradiation. The methylenation of benzophenone with Petasis reagent gives 90% of $Ph_2C=CH_2$. An added advantage of this reagent is its recyclability; the dimeric titanocene based side product can be converted to Cp_2TiCl_2 by HCl in THF or toluene. The titanocene methylidene is generated by heat induced α-elimination which rapidly reacts with carbonyl compounds (Eq. 6.17).[18]



(6.17)

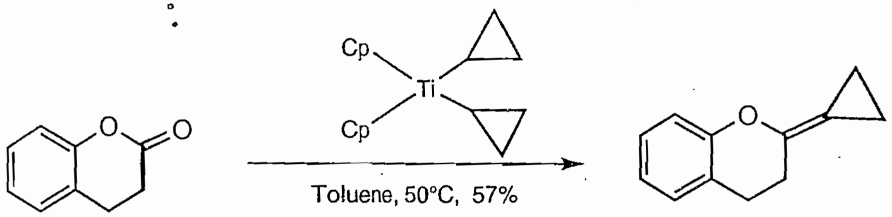
The popularity of Petasis reagent over the other titanocene based reagents is also due to the fact that the reaction conditions are non-basic and unlike Tebbe's reagent, no Lewis acid is involved. Therefore epimerisation of chiral centers is avoided and a wide range of functional groups is tolerated. The reaction with carbonyls is also clean and the titanium based side product is easily removed by precipitation and filtration. Acid anhydrides, thioanhydrides and imides undergo methylenation with Petasis reagent while they undergo titanium enolate formation with Tebbe's reagent. Methylenation of strained 4-membered β-lactones proceeds with excellent chemoselectivity with Petasis reagent while it is unsuccessful with Tebbe's reagent.

The figure below shows the range of substrates on which methylenation with Petasis reagent has been demonstrated and which does not take place with the Wittig reagent.[19, 20]



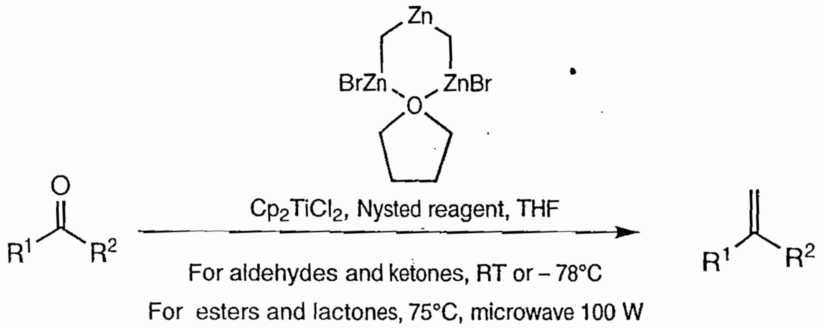
X = O (reactant) & CH_2 (product); yields in paranthesis

An added advantage of the Petasis reagent is that its scope can be extended beyond simple methylenation. A range of dialkyl titanocenes can be made and used for alkylidenation (for example, Eq. 6.18).



(6.18)

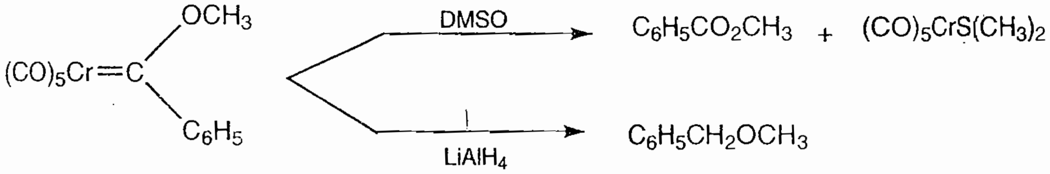
New variations of reagents that can generate $Cp_2Ti{=}CH_2$ in situ from Cp_2TiCl_2 are being discovered. Reactions of Cp_2TiCl_2 with Nysted reagent (Eq. 6.19) have been found to be quite useful for methylenations with $Cp_2Ti{=}CH_2$ generated at room temperature or under microwave conditions at 75°C.[21]



(6.19)

Removal of the metal component of a carbene by oxidation and reduction

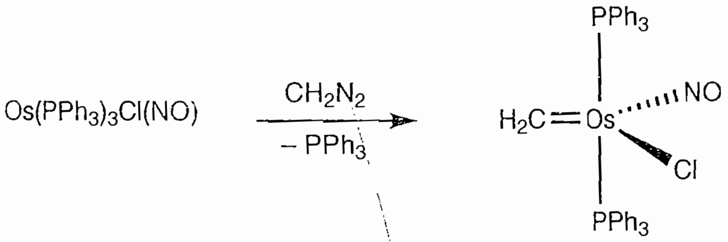
The metal component in a carbene can be removed in such a way that the carbene carbon can be reduced or oxidised.



(6.20)

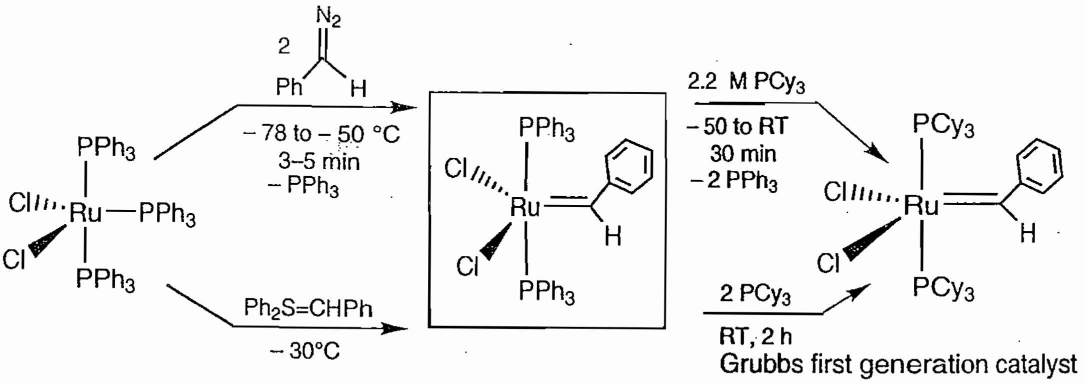
6.1.4 Carbenes that are Intermediate Between the Fischer and Schrock Types

There are also examples of carbenes which have properties intermediate between that of the Fischer and Schrock type carbenes. One of the well studied examples is an osmium complex $Cl(NO)(PPh_3)Os{=}CH_2$. The synthesis of this compound is given below where a carbene precursor is used.[22]



(6.21)

The Grubbs first generation catalyst is also synthesised using a carbene precursor. This compound, as well as his second generation catalyst, have properties intermediate between Fischer and Schrock type carbenes as mentioned by Grubbs himself (see box).[23]



(6.22)

Grubbs on his first generation ruthenium catalyst: 'Typically, high oxidation state metallaolefins are called alkylidene complexes while low oxidation state analogues are referred to as carbene complexes. The new complex described here does not show all of the characteristics of either of these two classes of complexes. The distinction between high- and low-oxidation state carbenes is misleading. I've tried to contend that there is a continuum of reactivity. The Fischer systems tend to be electron poor at the carbon centre while the Schrock systems tend to be electron poor at the metal centre, and they give different chemistries. I don't know where the ruthenium catalysts fit in between, but they work. If we had stuck with those oxidation state classifications, we would have been out of luck.'

(*J. Am. Chem. Soc.*, 1992, Vol. 114, 3974 and *C&E News*, 2002, Vol. 80, 34.)

Uses of metal carbene complexes

The most important and spectacular application of metal carbenes is in olefin metathesis reactions for which Robert Grubbs and Richard Schrock received the Nobel Prize in 2005.[24] Grubbs and his colleagues have discovered a ruthenium catalyst that affects ring closure reactions rapidly, cleanly and completely by means of olefin metathesis. What is noteworthy about the new catalysts is that they are stable in air, will tolerate water, and will operate at elevated temperatures compared to earlier ruthenium catalysts which were stable only at room temperature. This extra stability is the key to Grubbs's work and has been achieved by replacing one of the attached groups of the earlier catalysts (first generation) with an NHC group (second generation). The Schrock catalysts which are molybdenum based and air sensitive, are more active than the Grubbs first generation catalysts.[25]

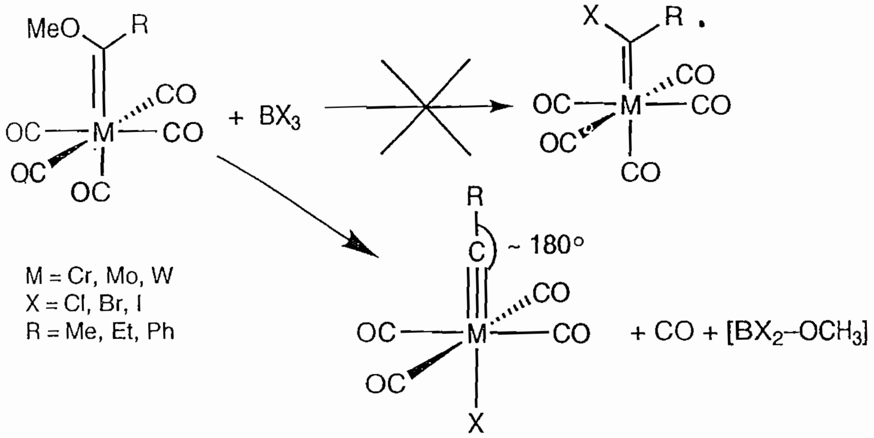
Olefin metathesis is the exchange reaction of two olefinic bonds which result in two new olefins, one of which is likely to be ethylene gas, and thereby easily removed. When the original two double bonds of the reactant are at the opposite ends of a chain of carbons, their reaction might be expected to form polymers, which is what often happens, but they might also interact with each other to produce a ring compound. The main types of reactions which are catalysed by Schrock and Grubbs catalysts are (i) cross metathesis, (ii) ring closing metathesis, (iii) ring opening metathesis, (iv) ring opening metathesis polymerisation, (v) acyclic diene metathesis polymerisation and (vi) enyne metathesis. Details of these olefin metatheses reactions will be described in detail in Chapter 15.

6.2 Metal Carbynes

Metal carbyne complexes having metal–carbon triple bonds are classified under the Fischer and Schrock types. E O Fischer accidentally prepared the first $M\equiv C\text{–}R$ triple bonded compound in 1973. He called this a carbyne after the alkyne, which refers to an $M\equiv C$ triple bond.[26]

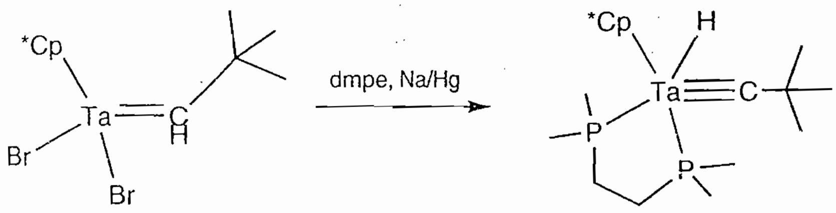
6.2.1 Synthesis of Metal–Carbyne Complexes

An attempted reaction to replace the OMe groups of a Fischer carbene by halogen using boron trihalides did not yield the halide substituted carbene, instead it resulted in the first Fischer carbyne compound.[26]

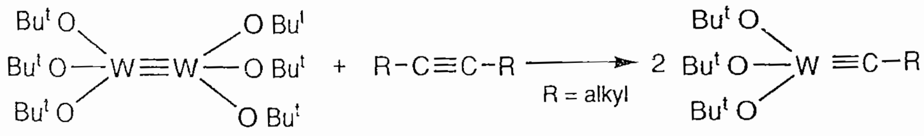


(6.23)

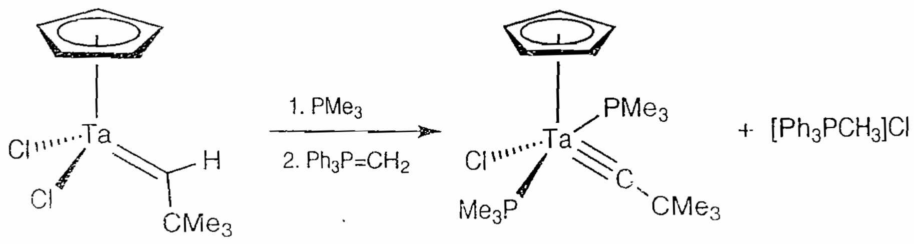
Early transition metal versions were first prepared by Schrock in 1978 via α-deprotonation of the alkylidene. These were named alkylidynes by Schrock. While there are some differences between these two classes of compounds, they can be treated basically as the same. Thus, one can simply treat carbynes and alkylidynes as trianionic (–3) 6e donating ligands. They are very strong donors as might be expected from the relatively low electronegativity of carbon and the –3 formal charge.[27–29]



(6.24)



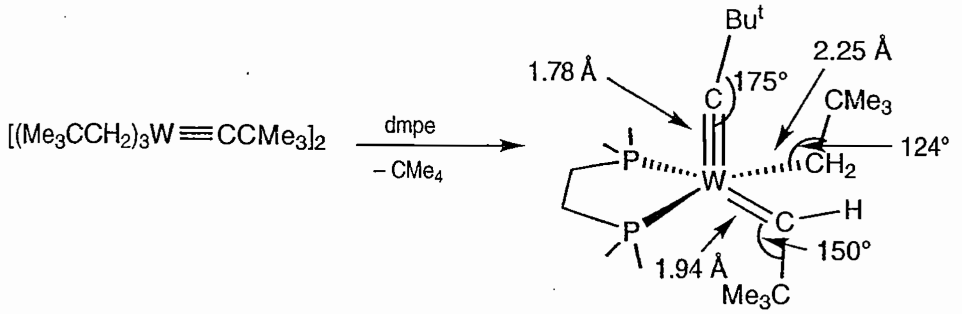
(6.25)



(6.26)

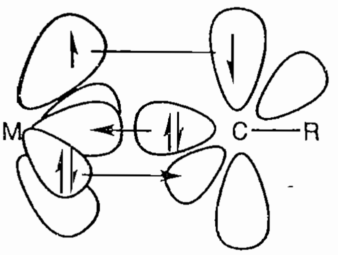
The M–C bond distance of the carbyne is considerably shorter than the analogous single and double bonds. The M–C–R bond axis is also linear or close to linear. A remarkable X-ray structure of one of Schrock's compounds that contains a W–C single bond, a W=C double bond, and a W≡C triple bond is shown below and it beautifully illustrates the dramatic and progressive shortening of the W-C bonds as the bond order is increased.[30, 31]

$$WCl_6 + 6\ Me_3CCH_2Li \longrightarrow [(Me_3CCH_2)_3W{\equiv}CCMe_3]_2$$

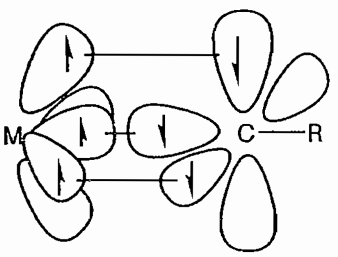


(6.27)

Similar to the singlet and triplet carbenes, in a bonding model, the free carbyne is considered as a doublet for the Fischer type and as a quartet for the Schrock type. A doublet carbon donates 2 electrons through its *sp* hybrid orbital and also forms an extra covalent bond between C and M. One of the *p* orbitals on the carbon is available to receive the back-donated electrons from the metal. A quartet carbyne forms three covalent bonds to a metal via three unpaired electrons.



Fischer carbyne

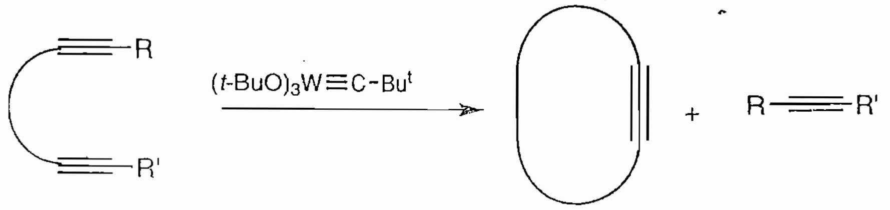


Schrock carbyne

6.2.2 Reactions of Metal–Carbyne Complexes

Two well known reactions of metal carbynes are substitution and alkyne metathesis. The strong *trans* directing effect of the carbyne ligand helps in substitution of the group *trans* to it. Carbonyl groups can also be displaced with Cp⁻. The metathesis reactions of alkynes can be carried out under mild conditions in the presence of tungsten alkylidyne complex $(t\text{-BuO})_3W{\equiv}C\text{-}t\text{-Bu}$, with the formation of metallcyclobutadiene as the intermediate. The reaction can also be applied to ring closing metathesis of two alkynes coupled together with the release of a volatile alkyne.[32]

$$trans\ X(CO)_4M{\equiv}CR \xrightarrow{Cp^-} (\eta^5\text{-}Cp)(CO)_2M{\equiv}CR + X^- + 2\,CO \qquad (6.28)$$



(6.29)

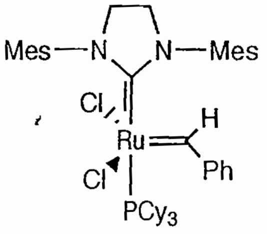
Problems and Exercises

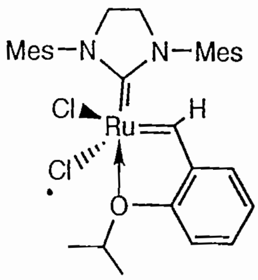
6.1. Given below are the actual (not the commonly depicted) figures of two well known ruthenium carbene catalysts.

(a) Which one of the carbene moieties in each complex takes part in the catalytic activity?

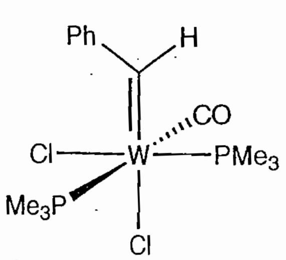
(b) Which one of the metal carbon bonds is longer in each complex? Justify.

(c) Classify the metal carbene units in each as Fischer, Schrock or the one in between the two.

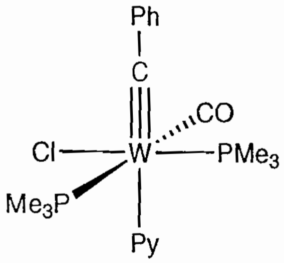




6.2. Using the given carbonyl stretching frequencies, compare the electronic properties of the carbene with the carbyne.

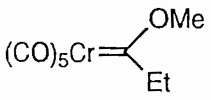


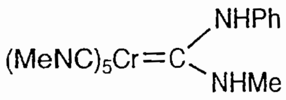
$\nu_{CO} = 1938\ cm^{-1}$



$\nu_{CO} = 1870\ cm^{-1}$

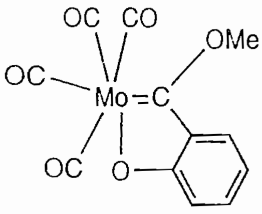
6.3. Starting with $Cr(CNMe)_6$ or $Cr(CO)_6$ show the minimum number of steps to make the following carbene complexes.



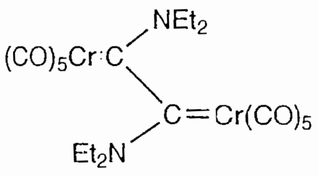


6.4. Although the definition of a Fischer carbene says that the carbene carbon should be bound to at least one heteroatom, many metal carbene complexes with the metal in the low oxidation state but having a phenyl group bound to the carbene carbon are also classified as Fischer type. Why? Justify your answer.

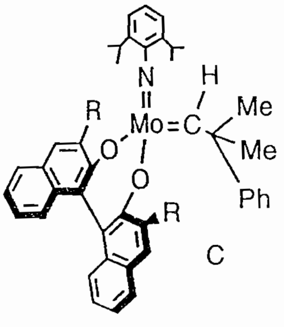
6.5. Classify the following carbenes as Fischer type, Schrock type or the one in between the two.



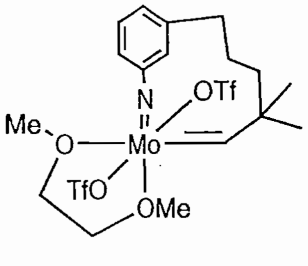
A



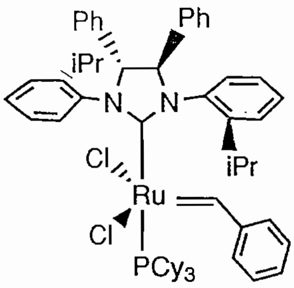
B



C



D



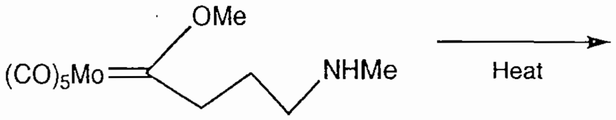
E

6.6. Indicate whether the statements given below describe a Fischer carbene, a Schrock carbene or neither. Write the statement and mark against each as *Fischer (F)*, *Schrock (S)* or *None.*

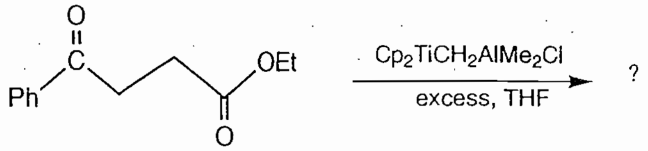
(a) It behaves like a phosphorus ylide in some of its reactions.
(b) The carbene carbon is nucleophilic in nature.
(c) It is synthesised from metal carbonyl precursors.
(d) It is a catalyst for cyclotrimerisation reactions.
(e) The metal atom is relatively electron rich.
(f) The Grubbs first generation catalyst is a typical example for this.
(g) The metal–carbon bond has a relatively low rotational barrier.
(h) It quite often does not obey the 18 electron rule.

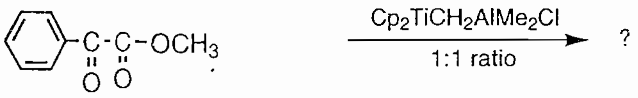
6.7. The room temperature ^{1}H NMR spectrum of $(CO)_5Cr{=}C(OMe)Ph$ shows a single resonance for the methyl protons. However, when the temperature is lowered, this peak first broadens and then splits into two peaks in the ratio 1:1. Explain the observation.

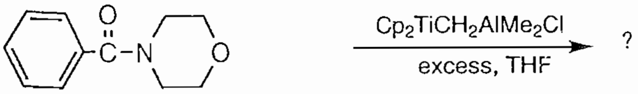
6.8. Predict the possible products from the proposed reaction.



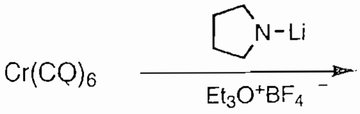
6.9. Predict the product in the following reactions.

(a)


(b)


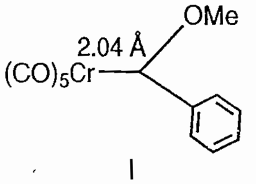
(c)


6.10. Give the product in the following reaction.

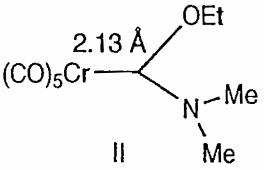


6.11. Write the most probable product when $Mo(CO)_6$ is treated initially with PhLi and is followed by a strong carbocation reagent, $CH_3OSO_2CF_3$.

6.12. Consider the following structures and explain why the Cr–C bond length is longer in II compared to I?



I

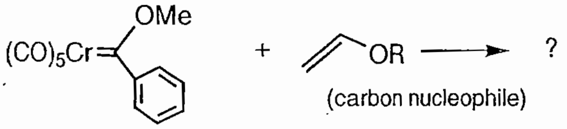


II

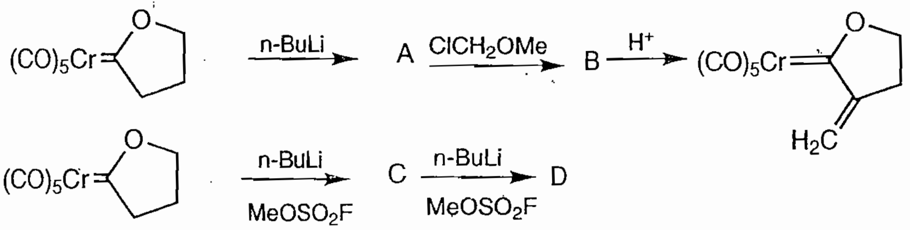
6.13. Write a plausible mechanism for the following (rather unusual) reaction and give reasons for your answer.

$$[Mn(CO)_5(CF_2)]^+ \quad + H_2O \longrightarrow [Mn(CO)_6]^+ + 2\,HF$$

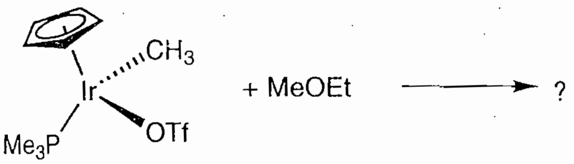
6.14. Write the possible product in the following reaction.



6.15. Write the structures of the species A–D in the following reactions.



6.16. The reaction of the given iridium complex with methylethyl ether resulted in the formation of a stable cationic carbene complex (with triflate as counter ion) along with the release of methane gas. Write the products obtained.



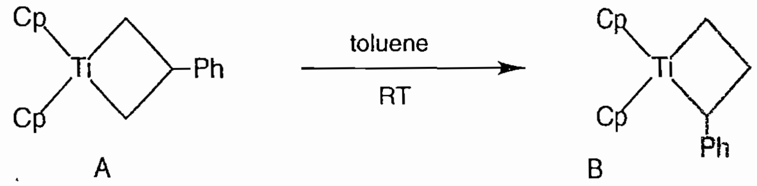
6.17. ΔG for three pairs of complexes is given below. Make a comparison within each pair and explain the relative value of ΔG for rotation around the M–carbene bond.

	Complex	ΔG_{rot} (kcal/mol)
I	$[\eta^5Cp(CO)_2(PPh_3)Mo{=}CH_2]^+$	< 6.3
	$[\eta^5Cp(CO)_2(PPh_3)W{=}CH_2]^+$	8.3
II	$[\eta^5Cp(CO)_2(PPh_3)W{=}CH_2]^+$	8.3
	$[\eta^5Cp(CO)_2(PEt_3)W{=}CH_2]^+$	9.0
III	$[\eta^5Cp((diphos)Fe{=}CH_2]^+$	10.4
	$[\eta^5Cp(NO)(PPh_3)Re{=}CH_2]^+$	>15.0

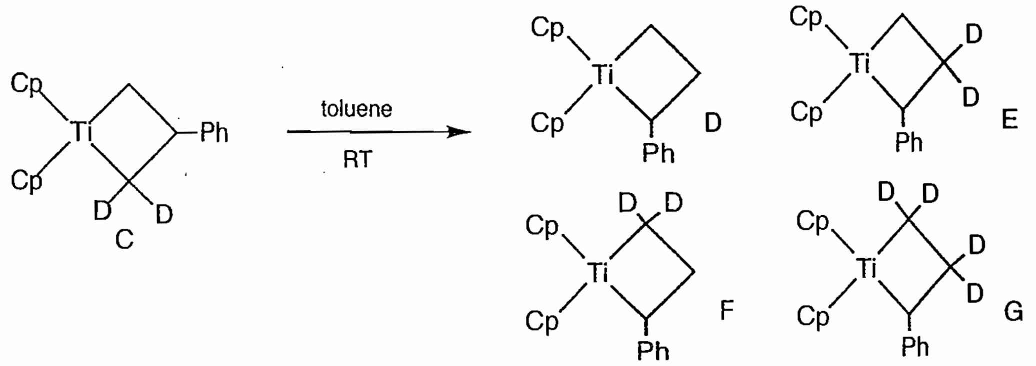
(*J. Organometal. Chem.*, 1980, Vol. 193, C23; *J. Am. Chem. Soc.*, 1979, Vol. 101, 5440; *Organometallics*, 1982, Vol. 1, 760)

6.18. Write the structures of the intermediates and the steps involved in the following isomerisation reactions (*Organometallics*, 1985, Vol. 4, 199).

(a)



(b)



Supplementary reading

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ALKYL, ARYL AND LIGANDS WITH HIGHER HAPTICITY

CHAPTER

7

7.1 σ BONDED ALKYL GROUPS AS LIGANDS

In general, alkyl ligands are very strong anionic σ-donors and are second only to hydrides in donor strength. They have practically no π-acceptor capability. Increasing the substitution on the alkyl carbon (replacing hydrogens with other alkyl groups) usually increases the donor strength, but steric factors can often weaken the metal–alkyl bond (for example, although t-butyl groups are good σ-donors, they are sterically hindered as well). However, the presence of perfluorinated groups such as CF_3 and C_6F_5 dramatically reduces the donor ability of the alkyl (aryl) group. Metal alkyls are also highly reactive towards molecular oxygen, water, and a variety of other ligands and reagents. They play a very important and active role (similar to the hydrides) in homogeneous catalysis.

7.1.1 Synthesis of Metal–Alkyl Compounds

The most common way of preparing metal alkyls is by the transmetallation reaction, that is, by reacting a transition metal halide with an alkali or main group metal alkyl which is typically far more ionic and reactive.[1–4]

$$CH_3Br + 2\,Li \longrightarrow CH_3Li + LiBr \tag{7.1}$$

$$CH_3Li + WCl_6 \longrightarrow WMe_6 + LiCl \tag{7.2}$$

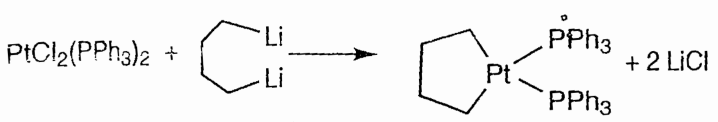
Other reactive alkyl reagents are RMgX (Grignard), R_2Zn, R_2Hg, R_2Cu, and AlR_3.

$$4\,Al + 6\,MeCl \longrightarrow Al_2Cl_2Me_4 + Al_2Cl_4Me_2 \tag{7.3}$$

$$3\,Al_2Cl_2Me_4 + 6\,Na \longrightarrow 2\,Al_2Me_6 + 2\,Al + 6\,NaCl \tag{7.4}$$

$$GaCl_3 + 3Me_3Al \longrightarrow Me_3Ga + 3Me_2AlCl \tag{7.5}$$

$$Zr\,Cl_4 + 4\,PhCH_2MgCl \longrightarrow Zr(CH_2Ph)_4 + 4\,MgCl_2 \tag{7.6}$$



(7.7)

$$ZnCl_2 + 2\,RLi \longrightarrow R_2Zn + 2\,LiCl \qquad (7.8)$$

$$C_2H_5I + Zn(Cu) \longrightarrow C_2H_5ZnI \xrightarrow[\Delta]{} Et_2Zn + ZnI_2 \qquad (7.9)$$

$$NbCl_5 + Me_2Zn \longrightarrow Me_2NbCl_3 + ZnCl_2 \qquad (7.10)$$

$$RI + Hg \xrightarrow[\text{sunlight}]{} RHgI \qquad (7.11)$$

$$HgCl_2 + RLi \longrightarrow RHgCl \xrightarrow{RLi} R_2Hg \qquad (7.12)$$

Another common way of obtaining metal–alkyl complexes is to react a moderately electron-rich metal centre with an alkyl halide (RCl, RBr or RI) by a process called an oxidative addition (discussed in Chapter 8).

$$ML_n + RBr \longrightarrow RML_nBr \qquad (7.13)$$

7.1.2 β-hydride Elimination

One of the most common 'side' reactions of the metal alkyls is called the β-hydride elimination reaction. It is the chief decomposition pathway of transition metal alkyl complexes and the reaction is much more rapid for the *d* block than for the main group alkyls. This reaction can occur whenever (i) the β-carbon of the alkyl group bears a hydrogen atom, (ii) the M–C–C–H unit attains a roughly coplanar conformation which brings the β-hydrogen close to the metal and (iii) there is a vacant site on the metal that is *cis* to the alkyl group. It is believed to be a concerted reaction, that is, the C–H bond breaking, and the M–C and M–H bond making occur at the same time (Fig. 7.1).[5]

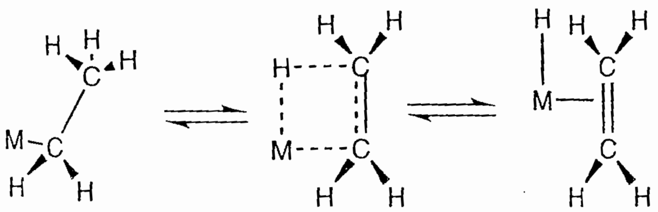
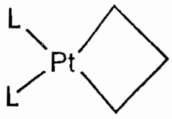
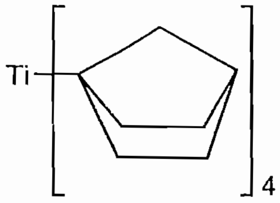


Fig. 7.1 β-hydrogen transfer

In order to design stable metal alkyl complexes, the possibility of occurrence of a β-hydride elimination reaction must be blocked. This can happen when (i) the alkyl has no β-hydrogen (as in $PhCH_2$, Me_3CCH_2, Me_3SiCH_2), (ii) the β-hydrogen is unable to approach the metal or the elimination will result in an unstable alkene (for example, CrL_4; L = bu^t or 1-norbornyl), (iii) the M–C–C–H unit cannot become syn-coplanar and (iv) the metal has firmly bound ligands which will not dissociate to generate a vacant site [for example, $Cp(CO)_2FeCH_2CH_3$, $Cp(CO)_3MoCH_2CH_3$, $EtCo(dmgH)_2Py$] or has an unusually high coordination number (7, 8...).

Examples for point (iii) are as follows.[6]





The main driving force for the β-hydride elimination reaction is the formation of a stronger M–H bond (almost always stronger than M–alkyl) and the generation of an alkene ligand that reduces the unsaturation of the metal complex. However, the reverse reaction can also occur and is called a migratory insertion. This is very important in transition metal reactions and catalysis, as we will see in later sections.

7.1.3 σ bonded η^1-aryl ligands

σ bonded η^1-aryls, similar to the alkyls, are relatively strong anionic ligands. Since they cannot easily eliminate a β-hydrogen, aryl complexes are relatively more stable compared to alkyls having β-hydrogen atoms. However, transition metal aryl complexes can be quite air-sensitive and reactive. Aryls do have the potential for both σ-donation and π-backbonding through the filled aryl π orbitals and empty π* antibonding orbitals respectively. This can provide additional stability to a metal complex, depending on whether the metal needs additional electron density from the ligand or wants to release excess electron density onto the ligand. Aryl ligands in the η^6-mode are more stable and will be discussed later in this chapter.

7.2 CYCLIC AND ACYCLIC POLYENYL π BONDED LIGANDS

7.2.1 Cyclopentadienyl (Cp^-)

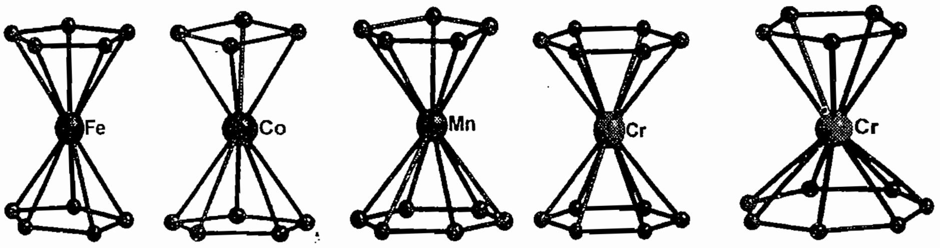
Cyclopentadienyl (Cp^-) is perhaps the most important of all the polyenyl ligands as it is firmly bound to the metal and is generally inert to nucleophilic reagents. This means, it can be used as a stabilising ligand for many complexes. It generally coordinates in the η^5-mode. It can adopt the η^1- as well, but the η^3-coordination mode is rare (Fig. 7.2). In general, three categories of mononuclear cyclopentadienyl complexes of transition metals are known; Cp_2M (metallocenes or sandwich compounds), Cp_2ML_x (bent metallocenes, $x = 1–3$; L = unidentate ligand like H, Cl, CO) and $CpML_y$ (half sandwich or piano stool, $y = 1–4$; unidentate ligand). The relative tendency of η^5 to slip into the η^1- or η^3-mode is rare but there are examples of 18e η^5-Cp piano stool type complexes undergoing substitution reactions by an associative mechanism indicating the presence of a η^3-Cp intermediate. Two structurally characterised examples of compounds having η^3-Cp coordination are (η^5-Cp)(η^3Cp)W$(CO)_2$ (18e) and (η^5-Cp)(η^3Cp)V(bipy) (17e).[7, 8] η^1-Cp complexes are more common; a well known example is $(\eta^5\text{-Cp})_2(\eta^1\text{-Cp})_2$Ti.

η^5-Cp complexes of diamagnetic metals usually show a singlet in the ^{1}H-NMR spectrum in the range of δ 3.5–5.5 appropriate for an aromatic group. For η^1-Cp, the α-hydrogens

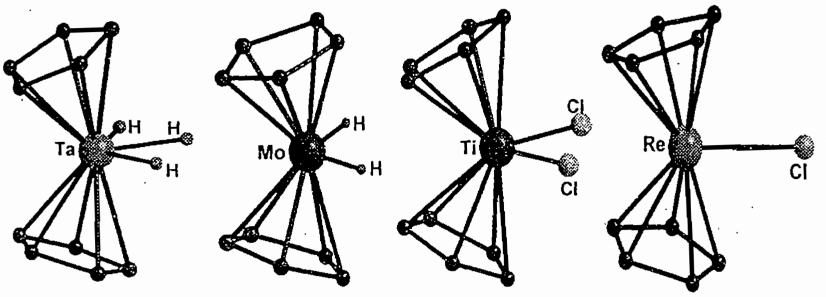
Metal sandwich compounds

Metal sandwich compounds form an integral part of organometallic chemistry and have attracted considerable interest in recent years due to their unique properties and exceptional applications. Metallocenes form a subclass of metal sandwich compounds. The name 'metallocene' has been derived from ferrocene, the first sandwich compound prepared in 1951. Thus 'metallo-' stands for the transition metal, and 'cene' indicates similarity to benzene. According to the definition by IUPAC, metallocenes are organometallic coordination compounds in which one atom of a transition metal such as iron, ruthenium or osmium is bonded to and only to the face of two cyclopentadienyl [η^5-(C_5H_5)] ligands which lie in parallel planes.[9]

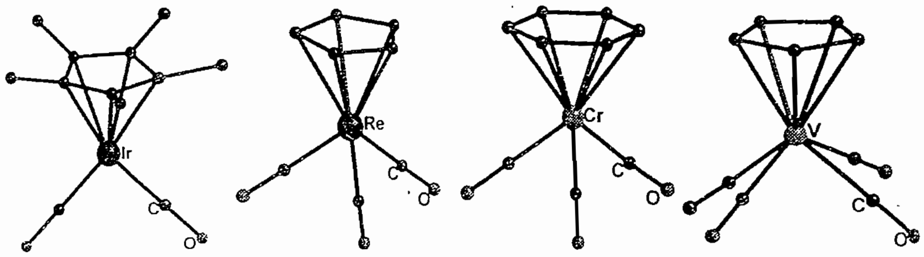
Metal sandwich compounds are now known with a range of metal ions and planar unsaturated and conjugated carbocyclic rings oriented in parallel planes with ring sizes varying from three to eight. Most of these obey the 18 electron rule and some of them such as ferrocene and $CpCoC_4H_4$ are highly stable to air and moisture. The molecular structures of some structurally-characterised 18 electron sandwich compounds are given below.[10–14]



In typical metallocene compounds, Cp_2M, the two carbocyclic rings are parallel. However, there are several sandwich compounds where the rings are tilted at angles ranging from 130.8–152.2° with respect to the metal centre. Examples of such bent sandwich compounds are Cp_2TaH_3, Cp_2MoH_2, Cp_2TiCl_2 and Cp_2ReCl in which the steric requirements of additional ligands prevent the formation of parallel Cp rings. Molecular structures of these bent sandwich compounds are shown below.[15–18]



Half-sandwich compounds have only one hapto ligand and the other ligands are mostly carbonyl, nitrosyl or phosphine groups (having halogens tends to result in halogen bridged dimers). Many half-sandwich compounds are excellent precursors to organometallic clusters and are by themselves excellent catalysts as well. Crystal structures of some carbonyl based half sandwich compounds are shown below.[19–22]



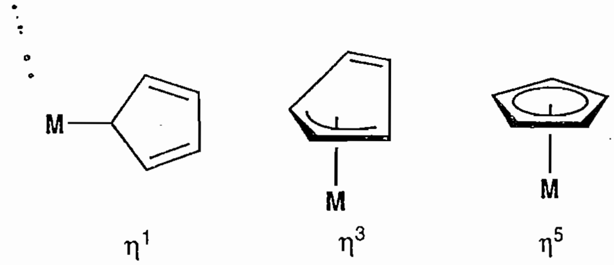


Fig. 7.2 Modes of cyclopentadienyl bonding

appear at around 3.5 ppm and the β-hydrogens in the range of 5.0–7.0 ppm. Neutral cyclopentadiene (C_5H_6) is a weak acid with a pK_a of around 15 and can be deprotonated with a strong base or with alkali metals to generate the anionic Cp^-.

7.2.2 Synthesis of Cp Based Sandwich Compounds

The synthesis of a Cp-metal complex is generally carried out by the reaction of a metal salt or a metal complex with a metallated cyclopentadienyl reagent or in some cases directly with freshly prepared cyclopentadiene obtained by cracking its dimer.[23,24]

$$M + 2\,C_5H_6 \longrightarrow Cp_2M + H_2 \quad M = Mg, Fe \tag{7.14}$$

$$FeCl_2 + 2\,C_5H_6 + 2\,Et_2NH \longrightarrow Cp_2Fe + 2\,[Et_2NH_2]Cl \tag{7.15}$$

$$RuCl_3(H_2O)_n + 3C_5H_6 + 3/2\,Zn \longrightarrow Cp_2Ru + C_5H_8 + 3/2\,Zn^{2+} \tag{7.16}$$

$$Et_3PCuOBu^t + C_5H_6 \longrightarrow CpCuPEt_3 + t\text{-}BuOH \tag{7.17}$$

A few metals such as Li, Na and K at room temperature, and Mg and Fe at high temperature, also give sandwich compounds with Cp^-. Although highly poisonous, CpTl is one of the well-utilised Cp precursors due to (i) the ease of preparation (from thallium sulphate) and (ii) high air and moisture stability as it can be prepared in water as well. Although it has poor solubility in organic solvents, CpTl when shaken with $FeCl_2$ in THF yields ferrocene, Cp_2Fe, in 87% yield along with TlCl.[25,26]

$$2\,C_5H_6 + 2\,KOH + Tl_2SO_4 \xrightarrow{H_2O} 2\,CpTl + K_2SO_4 + H_2O \tag{7.18}$$

$$CpTl + Mn(CO)_5Cl \longrightarrow CpMn(CO)_3 + TlCl + 2\,CO \tag{7.19}$$

Ferrocene can be prepared by simpler methods starting from iron.[27]

$$Fe + 2\,(R_3NH)Cl \longrightarrow FeCl_2 + 2\,R_3N + H_2 \tag{7.20}$$

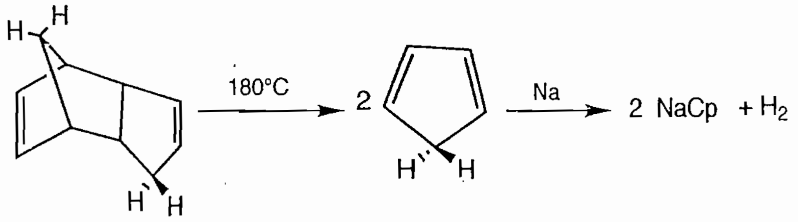
$$FeCl_2 + 2\,C_5H_6 + 2\,R_3N \longrightarrow Cp_2Fe + 2(R_3NH)Cl \tag{7.21}$$

The industrial preparation of ferrocene is in fact carried out electrochemically using a diethoxy iron (II) intermediate as shown.[28]

$$\text{Fe} + 2\,\text{C}_2\text{H}_5\text{OH} \xrightarrow{120\text{ A, }13\text{ V}} [\text{Fe(OC}_2\text{H}_5)_2] + \text{H}_2 \qquad (7.22)$$

$$[\text{Fe(OC}_2\text{H}_5)_2] + 2\text{C}_5\text{H}_6 \xrightarrow{60°\text{C}} \text{Cp}_2\text{Fe} + 2\,\text{C}_2\text{H}_5\text{OH} \qquad (7.23)$$

For the general synthesis of metallocenes, NaCp is the most favoured reagent. It is prepared by cracking dicyclopentadiene and reacting it immediately with sodium metal.[29-31]



(7.24)

$$\text{MCl}_2 + 2\ \text{NaCp} \longrightarrow \text{Cp}_2\text{M}\ [\text{M} = \text{V, Cr, Mn, Fe, Co}] \qquad (7.25)$$

Solvent: THF, DME, liquid NH_3

$$\text{Ni(acac)}_2 + 2\text{C}_p\text{MgBr} \longrightarrow \text{Cp}_2\text{Ni} + 2\ \text{acacMgBr} \qquad (7.26)$$

$$\text{CrCl}_3 + 3\,\text{NaCp} \longrightarrow \text{Cp}_2\text{Cr} + 1/2\ \text{C}_{10}\text{H}_{10} + 3\,\text{NaCl} \qquad (7.27)$$

$$\text{TaCl}_5 \xrightarrow{\text{NaCp}} (\eta^5\text{-Cp})_2\text{TaCl}_3 \qquad (7.28)$$

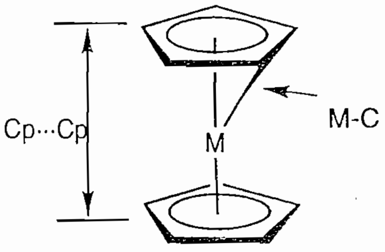
$$\text{MoCl}_5 + \text{NaCp} \xrightarrow{\text{NaBH}_4} (\eta^5\text{-Cp})_2\text{MoH}_2 \qquad (7.29)$$

$$\text{NaCp} + \text{TiCl}_4 \longrightarrow \text{Cp}_2\text{TiCl}_2 \xrightarrow{\text{Na/Hg}} \text{Cp}_2\text{Ti} \qquad (7.30)$$

7.2.3 Structure and Properties of MCp_2 Complexes

Trends in the bond distances of selected MCp_2 complexes are given in Table 7.1. The changes in the neutral Fe, Co and Ni metallocenes are a direct result of going from 18e (Fe) to 19e (Co)

Table 7.1 Bond distances M–C, C–C and Cp...Cp of selected MCp_2 compounds



	Distances (Å)		
Compound	Cp···Cp	M–C	C–C
$FeCp_2$	3.29	2.03	1.42
$[Fe\,Cp_2]^+$	3.40	2.07	1.40
$Co\,Cp_2$	3.44	2.10	1.41
$[Co\,Cp_2]^+$	3.24	2.03	1.42
$Ni\,Cp_2$	3.63	2.19	1.41
VCp_2	3.84	2.27	1.42
$CrCp_2$	3.58	2.15	1.40

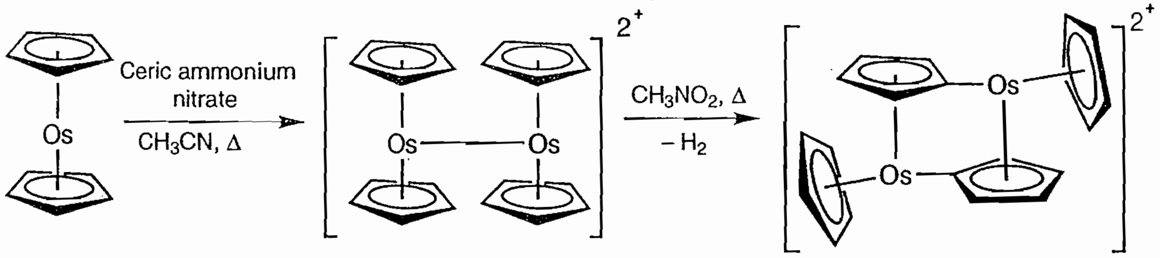
to 20e (Ni)[10, 32] counts. The extra electrons in the Co and Ni complexes go into the M–Cp antibonding orbitals, which are delocalised and progressively weaken the M-Cp bonding, leading to an increase in bond distances. This is in spite of the fact that the covalent radius of the metal decreases as one goes from Fe to Ni. Physical properties of some of the MCp_2 compounds are given in Table 7.2.

Table 7.2 Melting point, colour and selected properties of MCp_2 compounds[33–38]

Complex	mp (°C)	Colour	Miscellaneous properties
$Ti(C_5H_5)_2$	200	Green	The structure shows a bimetallic compound with two M–H bridges and a fulvalene bridging ligand
$V(C_5H_5)_2$	167	Purple	Compound is very air sensitive and paramagnetic
$Cr(C_5H_5)_2$	173	Scarlet	Compound is very air sensitive
$Mn(C_5H_5)_2$	173	Brown	Compound is air sensitive and easily hydrolysed. Interesting high to low spin interconversion observed
$Fe(C_5H_5)_2$	173	Orange	Highly stable. It can be oxidised to blue-green $[Fe(C_5H_5)_2]^+$ which in turn is a good oxidising agent
$Ru(C_5H_5)_2$	199–200	Pale yellow	Stable compound with eclipsed structure; chemistry similar to ferrocene; used as a photoinitiator in polymerisation reactions
$Os(C_5H_5)_2$	229–230	Snow white	Stable; undergoes oxidation with ceric ammonium nitrate in CH_3CN to give $[Os_2Cp_4]^{2+}$
$Co(C_5H_5)_2$	174	Purple-black	Compound is air-sensitive, paramagnetic and is a 19e complex; easily oxidised to the air stable 18e yellow complex $[Co(C_5H_5)_2]^+$
$Ni(C_5H_5)_2$	173	Green	Compound is a 20e complex; undergoes slow oxidation in air to the labile, orange cation $[Ni(C_5H_5)_2]^+$
$Mo(C_5H_5)_2$	-	Black	Compound is diamagnetic and air sensitive
$Nb(C_5H_5)_2$	-	Yellow	Monomer is stable only below -50°C; above this temperature, it is a dimer with η^1-, η^5-C_5H_4 bridges and terminal hydrides

The actual structures of many MCp_2 complexes – especially of those which do not have 18 electrons and belong to the second and the third rows of the periodic table – are quite interesting and have unusual properties. Unlike ferrocene, oxidation of the 18e compound Cp_2Os with ceric ammonium nitrate in hot acetonitrile does not produce a simple cationic monomer. Instead it results in dimerisation producing a bimetallic complex that has an Os–Os bond (3.038 Å) (Scheme 7.1).[39]

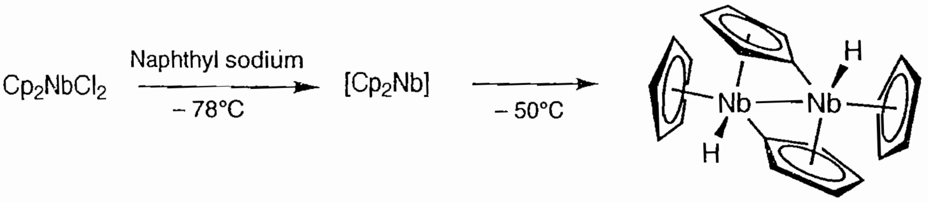
This compound upon warming in nitromethane, results in the loss of H_2 and the formation of another dimer without Os–Os bonds, but having osmium bonded to Cp rings both in the η^5 and η^1 modes. The simple neutral bis-Cp complexes of the early



Scheme 7.1 Oxidation of osmocene

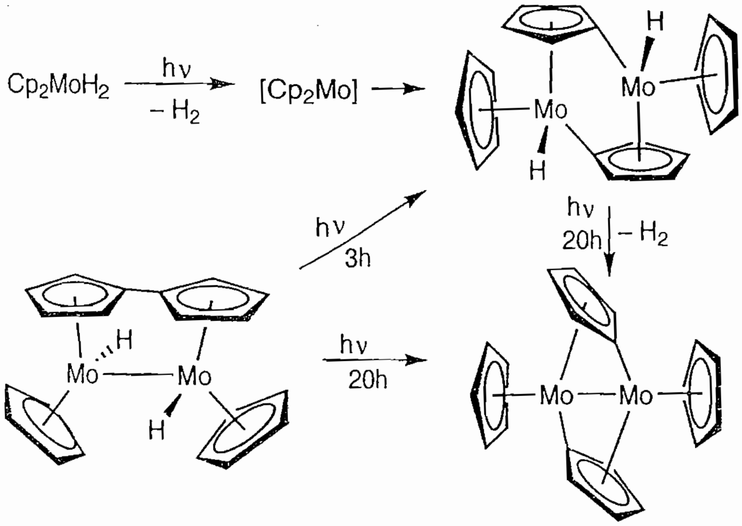
transition metals are quite different because they are in low +2 oxidation states and quite unsaturated.

Cp_2Nb for example, is a 15e complex with a highly reactive Nb with a d^3 configuration. It is highly unstable and exists in the monomeric form only below –78°C. Above –50°C, the molecule dimerises to give an unusual structure. Two molecules of niobocene react with one another to produce the structure shown (Eq. 7.31). Note that two of the Cp rings are dianionic forming both a traditional anionic η^5- π-type donor to one metal, while bridging and acting as an anionic 1e σ-donor to the other metal centre.[40]



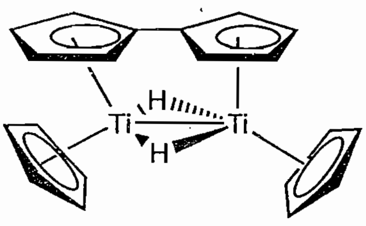
(7.31)

The Cp_2Mo and Cp_2W complexes might appear to have a 16e count, but they are also quite reactive and also self react with one another to produce several isomeric bimetallic complexes as shown in Eq. 7.32. The driving force for the structural variation as one can see, is to gain 18e around the metal centre.[41]

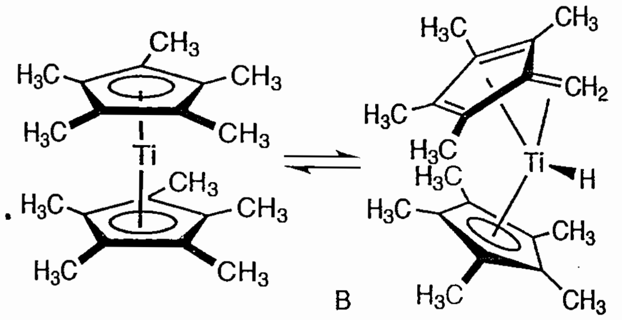


(7.32)

Cp_2Ti is a 14e complex with a highly reactive d^2 electronic configuration. Two molecules of titanocene also react with one another to produce a bimetallic complex that may well look just like the niobium complex discussed above. But, it undergoes a further reaction (perhaps due to steric crowding) leading to the coupling of two σ bound Cps to produce C–C bound bis-Cp and the complex (A) shown below. The more sterically crowded Cp* complex does a hydride abstraction and the reaction stops at this stage, also shown below (B). Both A and B are 16e species similar to Cp_2TiCl_2.[42]



A

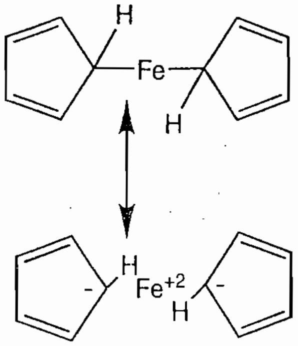


B

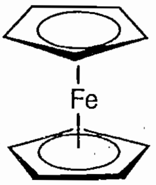
These dimerisation reactions occur by C–H bond activation (oxidative addition) which will be discussed in detail in Chapter 8.

7.2.4 Ferrocene: The First Metal-Sandwich Compound

Ferrocene was discovered accidentally by T J Kealy and P L Pauson in 1951. The structure was determined a few years later by G Wilkinson and E O Fisher. The astounding diversity of the chemistry demonstrated by this compound is unique in organometallic chemistry.[43–45]



A



B

Kealy and Pauson obtained this new thermally stable orange compound when they attempted to prepare dihydrofulvalene by the oxidation of a cyclopentadienyl Grignard reagent.

$$2C_5H_5MgBr + FeCl_3 \longrightarrow (C_5H_5)_2Fe$$

They proposed a resonance structure having a Fe–cyclopentadienyl σ bond with a canonical ionic formula (A). Almost at the sme time, Miller, Tebboth and Tremaine prepared a compound from a reaction of reduced iron with cyclopentadiene which they named as dicyclopentadienyliron. At this time, the British chemist R B Woodward and the German chemist E O Fischer questioned the claim of Pauson about the exact nature of the iron–carbon bond in bis(cyclopentadienyl)iron.[46]

Wilkinson knew that such a stable organometallic compound could not possibly have metal–carbon σ bonds. After remaking the iron complex as well as the ruthenium and cobalt complexes, and based on spectroscopic data, the 'sandwich' structure (B) was eventually proposed. Woodward coined the name 'ferrocene,' after 'benzene' because of the aromatic nature of the complex. Consequently, similar compounds with other transition metals were called 'metallocenes'.[46]

General properties of ferrocene

Ferrocene, also known as dicyclopentadienyl iron, has the primary chemical formula $C_{10}H_{10}Fe$. The cyclopentadienyl ligands (C_5H_5) bond with the iron in the center of the complex, resulting in the now familiar sandwich structure of ferrocene. The name metallocene was given because the cyclopentadienyl rings react and behave much like normal benzene rings, thus 'metallo' stands for the transition metal, and 'cene' is derived from 'benzene'.

Ferrocene is the most stable of all the metallocenes and has a boiling point of 249°C, a melting point of 173–174°C, and does not decompose below 400°C. The compound also sublimes readily at temperatures over 100°C, which makes purifying the product quite an easy task. Solubility of ferrocene is less than 0.1 mg/mL in water, 100 mg/mL in DMSO, less than 1 mg/mL in 95% ethanol and 10–50 mg/mL in acetone at 20°C. At room temperature, ferrocene is an orange crystalline solid with an odour much like camphor.[47, 48]

Ferrocene has an eclipsed configuration in the gas phase and is nearly eclipsed (with a rotational angle of 9° between the two rings) in the solid state. The barrier to rotation between the two rings is only 4±1 kJ/mol and this allows the rings to have free rotation. All the C–C bonds are of the same length and the iron is equidistant from all the Cp ring carbons. Neutron diffraction has also shown that the hydrogen atoms on the Cp rings are tilted slightly towards the iron center in ferrocene, presumably because this shift permits a better overlap of the Fe orbitals with the π orbitals of the Cp rings. The heavier analogues ruthenocene and osmocene also have a structure similar to ferrocene. Decamethylferrocene $(C_5Me_5)_2Fe$, a derivative of ferrocene, has a staggered conformation with the methyl groups tilted away from the Fe atom. Considering the great difference in the size of the hydride group on ferrocene (-H) vs the methyl group in decamethylferrocene, the methyl groups tend to repel one another and tilt away from the Fe centre because of steric hindrance. Similarly, decabenzyl ferrocene also has the staggered configuration. Many other metallocenes like cobaltocene Cp_2Co, and manganocene Cp_2Mn, have staggered configurations in the solid state.

General applications of ferrocene

Ferrocene is primarily used as a catalyst. In the industrial world, the catalytic properties, combined with high solubility in less polar organic solvents make ferrocene a perfect fuel additive (see Section 1.3.2). Ferrocene is also a lubricant at higher temperatures, thereby it serves to cut down on mechanical friction where normal lubricants cannot. For engines, this translates into a higher efficiency which leads to higher engine speed and power levels.

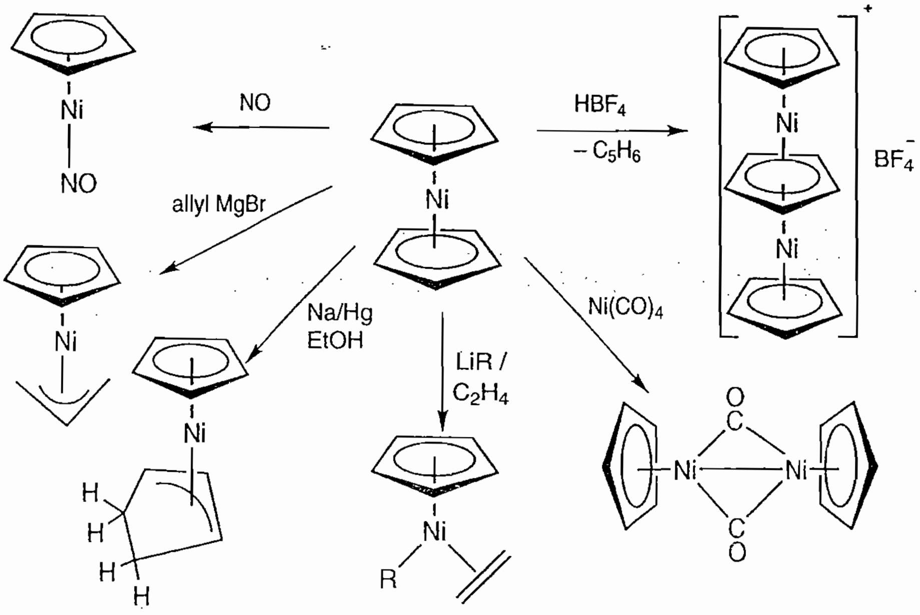
Besides its use as a combustion catalyst, ferrocene has many other useful applications. Some derivatives of ferrocene can inhibit the degradation of polyethylene by light, thus making ferrocene useful in some polymerisation techniques. By acting as a protective agent, ferrocene can improve the thermal stability of not only polyethylene, but polypropylene, polyester fibers, plastics and rubber as well. Later, we will explore in detail how ferrocene derivatives are used in polymerisation. Other uses of ferrocene are:

- as an ultraviolet absorber,
- as an electron beam sensitiser,
- as a coating for missiles and satellites, and
- as a standard in some electrochemical systems like cyclic voltammetry.

Ferrocene also finds application as a group that can be incorporated onto existing drug molecules to improve their activity (for example, *ferrocifen* and *ferroquin*). An important medical application is its use as an electrode mediator in blood glucose level monitors (see Chapter 20 for more details).

7.2.5 Reactions of Metal-Sandwich Compounds

Many of the reactions involving ferrocene revolve around the Cp ligands. These rings are very important for organic chemists since they behave very much like benzene rings and other aromatic hydrocarbons. In some cases, ferrocene reacts faster than arenes; for example, the Friedel–Crafts acylation reaction is 10^6 times faster in ferrocene than in benzene.



Scheme 7.2 Selected reactions of nickelocene, Cp_2Ni

Furthermore, the formation of a single isomer, 1,1′-diacetyl ferrocene, suggests free rotation between the two Cp rings. Since ferrocene is prone to one electron oxidation to $[Cp_2Fe]^+$, many electrophilic substitutions like nitration and halogenation cannot be performed. Therefore, groups like nitro and chloro cannot be directly introduced on ferrocene. Chapter 18 discusses the chemistry centred around the cyclopentadienyl rings of ferrocene in detail.

The chemistry of other metallocenes differs from that of ferrocene. Some of the well known reactions of nickelocene are given in Scheme 7.2.[49, 50]

7.2.6 Bent Sandwich Compounds

Bent sandwich compounds of the type Cp_2ML_x (x = 1–3; unidentate ligands) are important as some of them behave as catalysts for olefin polymerisation. The general methods of syntheses are given below. [51, 52]

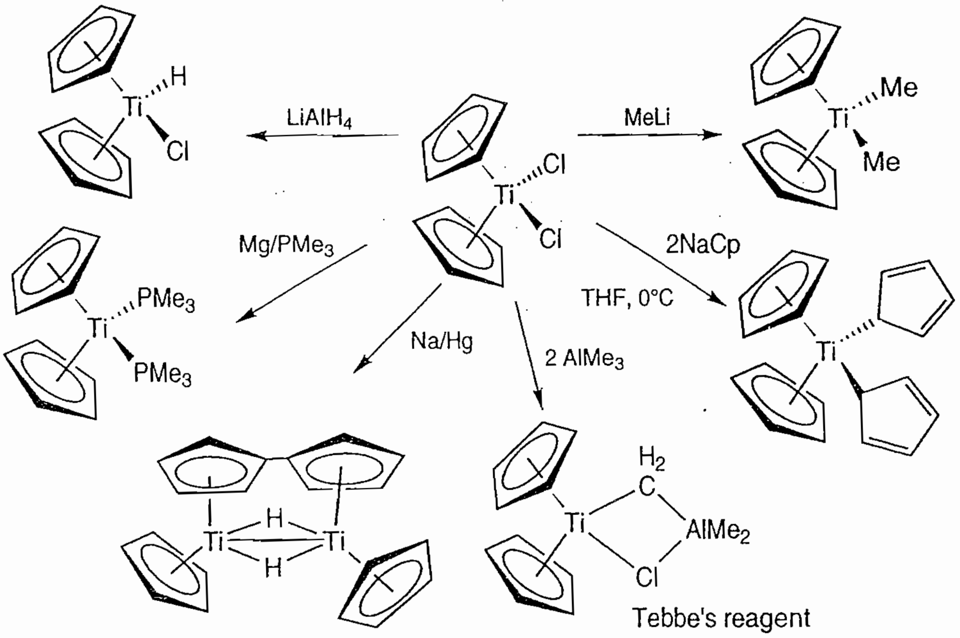
$$TiCl_4 + 2\,NaCp \xrightarrow[25°C]{THF} Cp_2TiCl_2 + 2\,NaCl \qquad (7.33)$$

$$TiCl_4 + Cp_2TiCl_2 \xrightarrow[130°C]{xylene} 2\,CpTiCl_3 \qquad (7.34)$$

$$VCl_3 + CpTi \longrightarrow 2\ Cp_2VCl \qquad (7.35)$$

$$Cp_2MoH_2 + 2\,CHCl_3 \longrightarrow Cp_2MoCl_2 + 2\,CH_2Cl_2 \qquad (7.36)$$

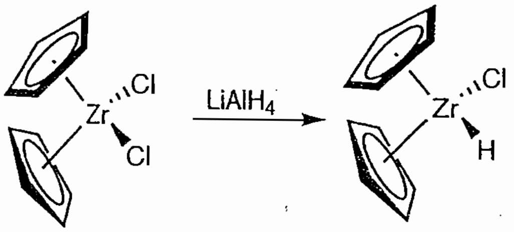
Some of the reactions of titanocene dichloride, a well known bent sandwich compound are given below.



Scheme 7.3 Selected reactions of titanocene dichloride

7.2.7 Schwartz's Reagent and Hydrozirconation

Schwartz's reagent is prepared from Cp_2ZrCl_2 by reduction with $LiAlH_4$.[53]



(7.37)

Hydrozirconation is an important reaction and involves the insertion of a terminal or internal olefin into a Zr–H bond. This, after a series of β-H eliminations and olefin insertion gives a terminal alkyl substituted compound (Fig. 7.3). The olefin rapidly isomerises to the terminal alkyl form. For example 1-hexene, *cis*-3-hexene and *trans*-3-hexene all give the same primary alkyl substituted product. The alkyl zirconocene derivatives are excellent precursors for a host of organic molecules.

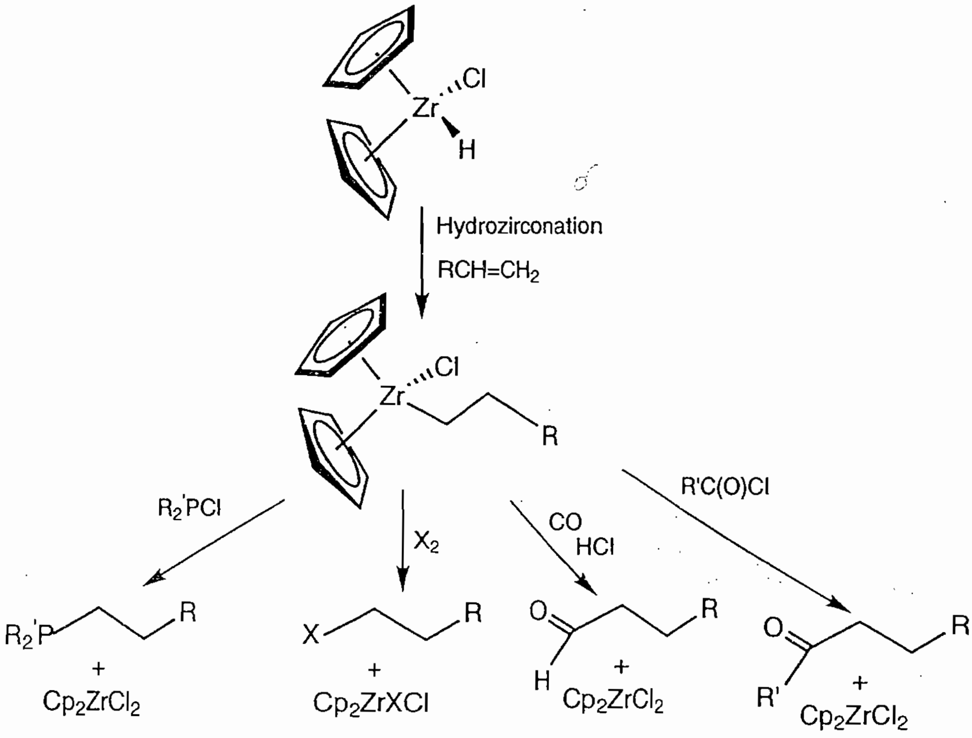


Fig. 7.3 Uses of Schwartz's reagent in hydrozirconation

7.2.8 Chemistry of Cp*

The low solubility of many Cp substituted organometallic compounds as well as the need for a sterically bulky η^5 ligand with a significantly better donor capability led to the synthesis and use of pentamethylcyclopentadienyl as a ligand $(C_5Me_5)^-$ or Cp*. Cp* has the following advantages in comparison to Cp.[54]

(i) Cp* is a stronger π donor and weaker π acceptor ligand compared to Cp.

(ii) Steric shielding of the sandwiched metal ion is increased providing an increased kinetic stability for otherwise reactive molecules.

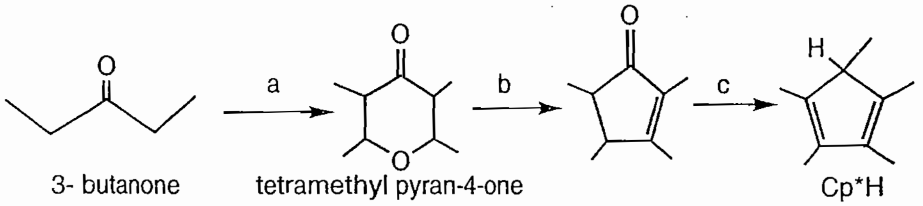
(iii) The methyl groups provide increased solubility for the Cp* based metal complex in nonpolar organic solvents which helps in growing crystals (structural studies are vital in understanding bonding and geometry of organometallic compounds).

(iv) Thermal stability of the complex increases.

(v) Dimerisation and oligomerisation of the molecule is reduced significantly.

(vi) Since there are no aryl–H bonds, prototropic rearrangements involving C–H activation and agostic interactions (interaction between alkyl/aryl hydrogens belonging to a ligand and metal ion in some complexes) are minimised. However, hydride elimination from the CH_3 by the metal can occur.

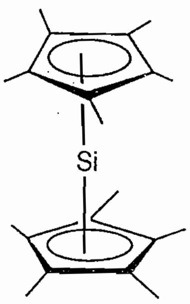
Preparation of Cp*H is carried out according to Eq. 7.38.[55]

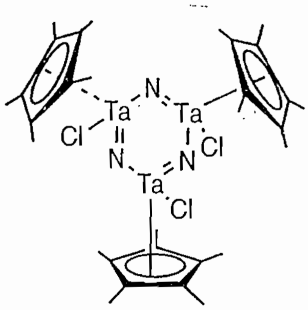


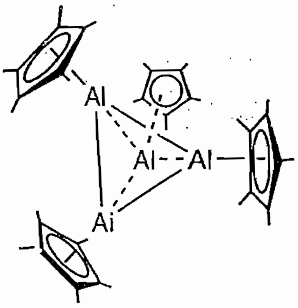
(7.38)

a: CH_3CHO / KOH / MeOH   b: p-$CH_3C_6H_4$-SO_3H or $HCOOH/H_2SO_4$ c: MeMgI / H^+ or MeLi / HCl

There are many examples of molecules which can be prepared in the stable form and are structurally characterised only by using Cp* and not by Cp. The silicon (II) sandwich compound, the tetrahedral aluminium (I) cluster as well as a Ta–N inorganic heterocycle shown below were isolated in stable forms by using Cp* as ligand.[56–58]

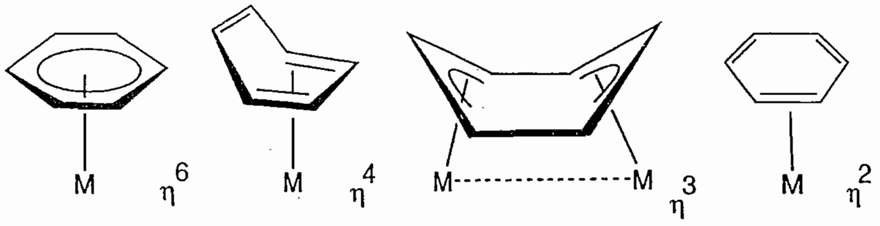






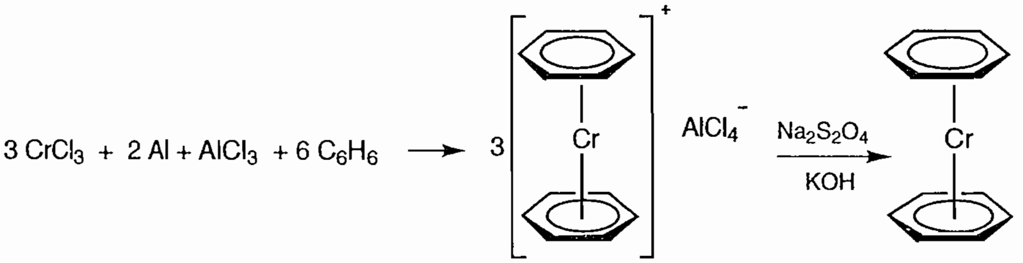
7.2.9 Chemistry of Arene Sandwich Compounds

Arenes (benzene being the simplest member of this family) are neutral 6e donors, which typically coordinate in the η^6 fashion, although they can adopt lower coordination modes (η^4, η^3 and η^2) as well. Examples of compounds with these hapticities are $(\eta^6\text{-}C_6H_6)_2Cr$, $(\eta^5\text{-}C_p{*})Ir(\eta^4\text{-}C_6H_6)$, $\mu(\eta^3{:}\ \eta^3\text{-}C_6H_6)RhIr(\eta^5\text{-}C_p)_2$ and $[Os(NH_3)_5(\eta^2\text{-}C_6H_6)]^{4+}$. Piano stool type compounds with one η^6 coordinated arene are also known.



Synthesis and reactions

Bisbenzene chromium is the classic example of an arene sandwich compound which was prepared in 1919 in small amounts without knowing its true identity. It was later prepared in a systematic manner in 1955 by Fischer and Hafner (Eq. 7.39). Limitations of this method include low yield and difficulty in isolating the organometallic product. The arene must be inert towards the very reactive $AlCl_3$. Alkylated arenes get isomerised by $AlCl_3$. Arenes having substituents with lone pairs (such as haloarenes, anilines, phenols) are also unsuitable since they can bind to the $AlCl_3$ and inhibit the reaction. Metal vapour synthesis in which the metal vapour is mixed with ligand vapours and the product is allowed to condense, also yields arene sandwich compounds but the method requires a sophisticated metal vapouriser.[59]

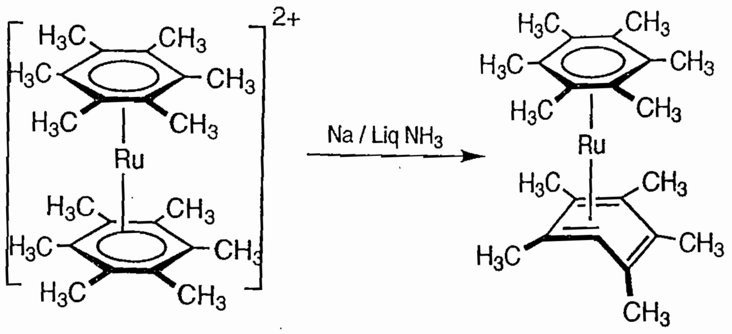


(7.39)

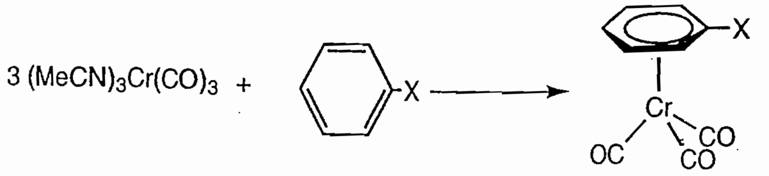
An interesting aspect of metal–arene complexes is that the π-backdonation plays a relatively important role in the bonding and in its chemistry. Arenes often do not coordinate very strongly to metals, but they do tend to favour metals in low oxidation states and often generate surprisingly stable complexes. $Cr(C_6H_6)_2$, for example, is kinetically inert to most substitution reactions, not only due to its 18e configuration, but also due to the mix of σ bonding and π-backbonding.

An interesting example of the significance of the 18 electron configuration in deciding the hapticity is seen in the reactions of $[Ru(C_6Me_6)_2]^{2+}$. This 18e complex can be reduced to the neutral $Ru(C_6Me_6)_2$, a 20e complex.[60] The structure of $Ru(C_6Me_6)_2$ reveals that one of the arene rings has lost its aromaticity and is strongly folded to give a 4 electron η^4-coordination geometry. Thus, the correct formulation of this compound is 18 electron, $Ru[\eta^4\text{-}(C_6Me_6)\eta^6\text{-}(C_6Me_6)]$ (Eq. 7.40). Such effects are more common among second and third row metal complexes where metal–ligand bonding interactions are stronger and going above 18 electrons significantly affects the stability.

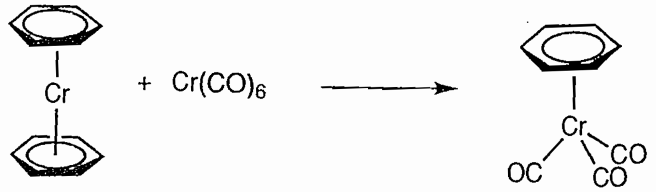
Arene half sandwich compounds show chemistry which resembles, to some extent, that of ferrocene. The chromium compound has been well studied and it can be prepared by the methods shown. Due to umpolung, the reactivity of the aryl group bound in the η^6-mode to $Cr(CO)_3$ changes dramatically. The reactivity of chlorobenzene bound to $Cr(CO)_3$ is comparable to that of *p*-nitrochlorobenzene.[61]



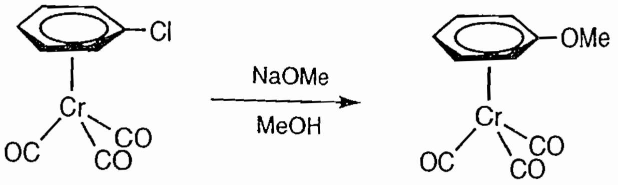
(7.40)



(7.41)



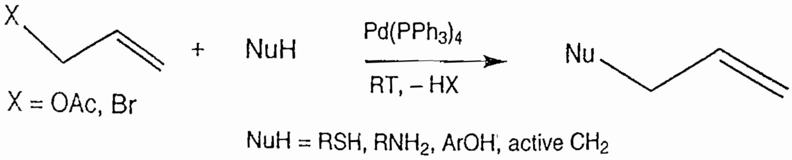
(7.42)



(7.43)

7.2.10 Allyl Groups as Ligands

The allyl group can bind to a metal in two ways: η^1-allyl is σ bonded to the metal with a free C=C whereas η^3-allyl has all the three carbon atoms at the same bonding distance to the metal. The coordinated allyl group can switch between these two bonding modes when the metal undergoes substitution reactions. The coordinated allyl group is also an active ligand susceptible to nucleophilic attack which makes them very valuable in organic synthesis and is the basis for their use in the catalytic reactions. Barry M Trost and Jiro Tsuji have fine-tuned the reaction – well known as the Tsuji–Trost reaction – which has excellent synthetic utility. The reaction goes via a η^3-allyl palladium complex as intermediate with the nucleophile attacking the terminal carbon of the coordinated allyl group.[62]

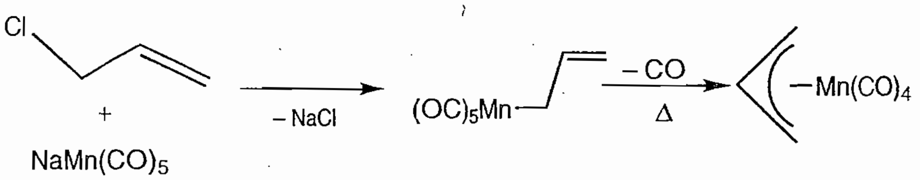


(7.44)

Both internal and external attacks on the coordinated η^3-allyl have been reported; the mode of attack depends on the complex and the nucleophile involved. In general, the allyl groups with cationic character are attacked at the terminal position and the attack occurs in a *trans* manner, that is, from the face opposite to the metal, and forms a neutral η^2-olefinic complex. The nature of the attack of a nucleophile on the coordinated allyl moiety in 18e cationic complexes is discussed under Davies–Green–Mingos rules (see Section 7.3).

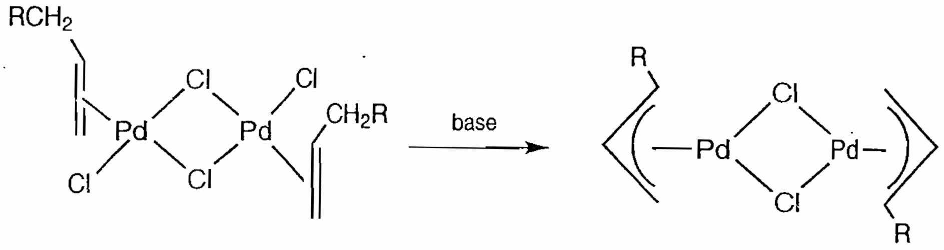
Synthesis of allyl complexes[63]

From allylic halides



(7.45)

From alkenes



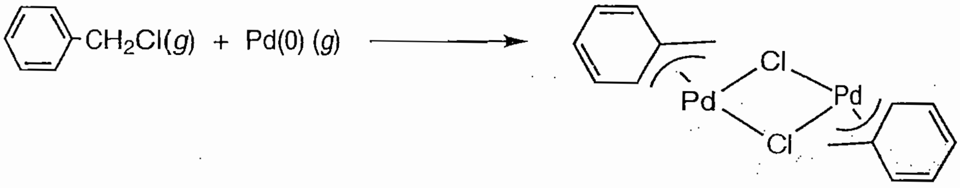
(7.46)

Using Grignard reagents

$$\mathrm{NiBr_2} + 2\ \mathrm{C_3H_5MgBr} \longrightarrow \mathrm{Ni}(\eta^3\text{-}\mathrm{C_3H_5})_2 + 2\ \mathrm{MgBr_2} \qquad (7.47)$$

$$\mathrm{ZrCl_4} + 4\ \mathrm{C_3H_5MgBr} \longrightarrow \mathrm{Zr}(\eta^3\text{-}\mathrm{C_3H_5})_4 + 4\ \mathrm{MgClBr} \qquad (7.48)$$

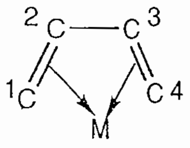
By vapour phase condensation[64]



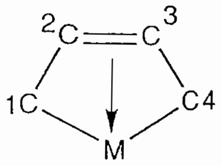
(7.49)

7.2.11 1,3-Butadiene Complexes

Butadiene usually acts as a 4e donor in its *cisoid* conformation. Two extreme representations of bonding can be written.[65]

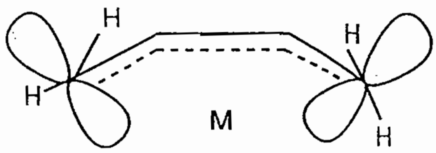


I

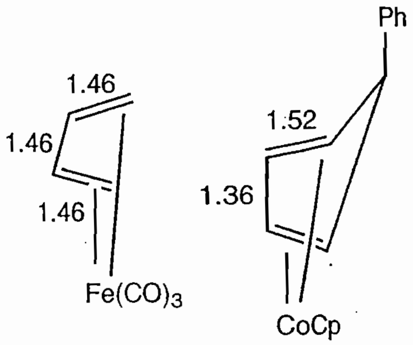


II

In the type I complexes, two more or less independent monoolefin metal interactions take place whereas in the type II complexes, two σ bonds to C1 and C4 and one π bond to C2–C3 exist. In many complexes, the C2–C3 distance is slightly shorter (–0.02 Å) than the two other C–C distances, and the substituents at C1 and C4 are twisted ~ 20–30° out of the plane of the ligand so that the corresponding *p*-orbitals can overlap better with the metal. The free butadiene is planar and the C2–C3 distance is shorter by ~ 0.12 Å.



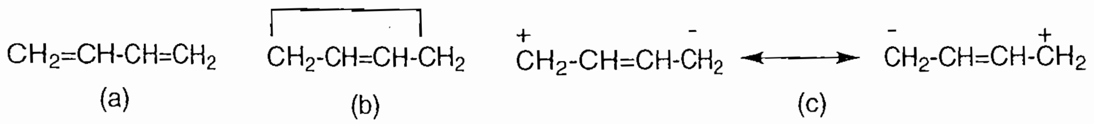
The degree to which the individual structure approaches either of these two extremes can be judged by the C–C bond lengths in the 1,3-butadiene moiety. A S–L–S (short–long–short) is indicative of I and L–S–L (long–short–long) refers to II. The actual variation generally seems to span between all bonds being equal (C1–C2, C2–C3, C3–C4) to the L–S–L form. Generally, the S–L–S form is not observed with precision.



The MO diagram of 1,3-butadiene shows that both – the depletion of electron density in the Ψ_2 molecular orbital by a σ donation to the metal and the population of Ψ_3 by back donation from the metal – have the effect of lengthening the C1–C2 and shortening the C2–C3. This is because the Ψ_2 is C1–C2 bonding and C2–C3 antibonding, and Ψ_3 is C1–C2 antibonding and C2–C3 bonding in character. This is quite a general picture since bonding to a metal usually depletes the ligand HOMO and fills the LUMO and is the main reason that binding has such a profound effect on the chemical character of the ligand (Fig. 7.4).[66, 67]

Interestingly, the structure of the bound ligand is often similar to that of the first excited state of the free ligand. This is because, in order to reach the first excited state, an electron has to be promoted from the HOMO to the LUMO, thus partially depleting the former and filling the latter. This statement can be further understood from the following description.

In order to obtain a qualitative picture of the MO diagram of 1,3-butadiene (especially the π MO), assume that the molecule is generated from two ethylene molecules. So, a linear combination of π and π* orbitals in two ethylene molecules is done. Though butadiene is not a linear molecule, it is assumed to be linear in this treatment. In the ground state the resonance structures are as shown below.



$$CH_2{=}CH{-}CH{=}CH_2 \qquad CH_2{-}CH{=}CH{-}CH_2 \qquad \overset{+}{C}H_2{-}CH{=}CH{-}\overset{-}{C}H_2 \longleftrightarrow \overset{-}{C}H_2{-}CH{=}CH{-}\overset{+}{C}H_2$$

(a) (b) (c)

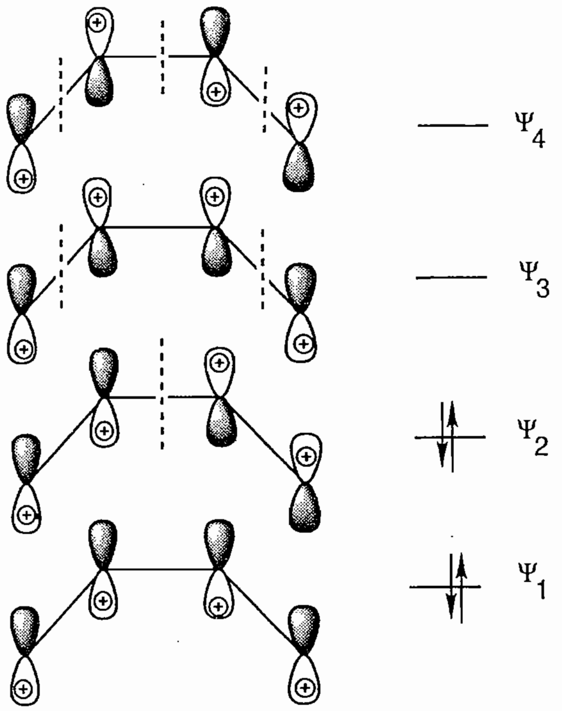


Fig. 7.4 Molecular orbitals of nonbonded 1,3-butadiene

Structures (b) and (c) involve a double bond between C2 and C3; in (b) a long bond exists between C1 and C4 and in (c) formal charges exist on C1 and C4. The resonance structures show some double bond character between C2–C3 though small, since (b) and (c) contribute less in the ground state as compared to (a).

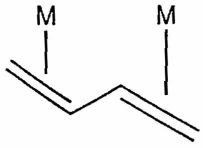
A qualitative explanation of the MO diagram shows that, in the ground state the MOs are occupied in such a way that the bond order and bond lengths vary as shown below.

Table 7.3 Bond order and bond lengths of 1,3-butadiene based on Hückel calculations

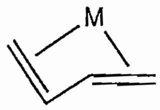
	Bond order (bond length in parentheses)		
	C1/C2	C2/C3	C3/C4
Ground state	1.89 (1.36 Å)	1.45 (1.45 Å)	1.89 (1.36 Å)
First excited state	1.45 (1.45 Å)	1.67 (1.39 Å)	1.45 (1.45 Å)

In the first excited state, one electron is transferred from the HOMO (bonding) to the LUMO (antibonding). This affects the bond order and bond length and results in the weakening of the C1–C2, C3–C4 and strengthening the C2–C3 bond. This is similar to what has been observed in the 1,3-butadiene–metal complex.

The bonding of butadiene in the *transoid* form is quite rare. But it has been observed in $Os_3(CO)_{10}(C_4H_6)$ in which the diene is η^2-bound to each of the two different Os centers. The diene is bound to a single Zr in $Cp_2Zr(C_4H_6)$.



$Os_3(CO)_{10}(C_4H_6)$

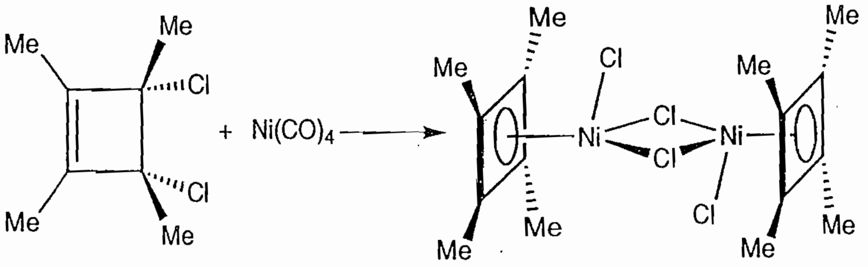


$Cp_2Zr(C_4H_6)$

When butadiene competes with CO for metal electron density, the back bonding into the antibonding orbitals of the butadiene moiety will be less. On the other hand, if it competes with Cp (a weaker π acid ligand), the back bonding into the butadiene will be considerably more. These facts will help in making structural predictions. For example, the L–S–L form will be less pronounced in (butadiene)$M(CO)_3$ than in (butadiene)M(Cp).

7.2.12 Cyclobutadiene Complexes

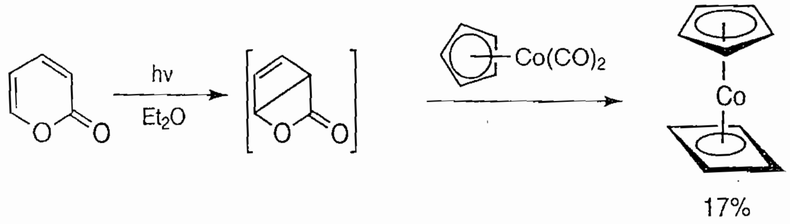
Cyclic conjugated π systems are aromatic if the number of π electrons equals $4n + 2$ (where n = an integer). Cyclobutadiene is antiaromatic since it has four π electrons. The antiaromaticity combined with the ring strain makes this simple molecule too unstable to exist as a free organic compound. A triumph of the early days of organometallic chemistry was the successful synthesis of a stable metal-coordinated cyclobutadiene molecule, $(\eta^4\text{-}C_4H_4)Ni_2(\mu\text{-}Cl)_2Cl_2$ by Criegee in 1959.[68]



(7.50)

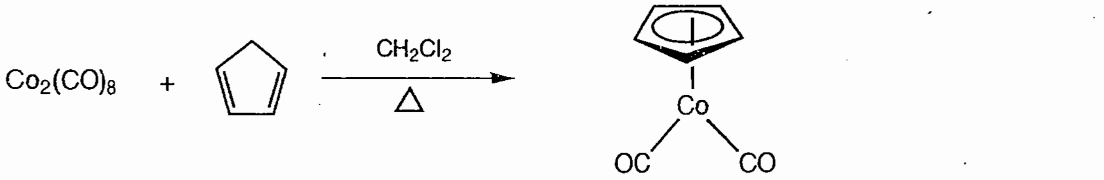
A more simple route was discovered shortly after this which involved the cyclodimerisation of diphenylacetylene by $Fe(CO)_5$ yielding $(Ph_4C_4)\ Fe(CO)_3$.[69] The high stability of a cyclobutadiene coordinated metal complex arises from the mixing of four π electrons of the cyclobutadiene with one of the filled metal *d* orbitals of the right symmetry. The high energy of the HOMO of nonbonding cyclobutadiene allows it to interact extremely well with the metal orbitals that are of approximately the same energy.

[(η^5-cyclopentadienyl)(η^4-cyclobutadiene)cobalt] is the best known example of mixed sandwich complexes in which the Cp ring is coordinated in the η^5-mode and the Cb (cyclobutadiene) ring is coordinated in the η^4-mode.[70]



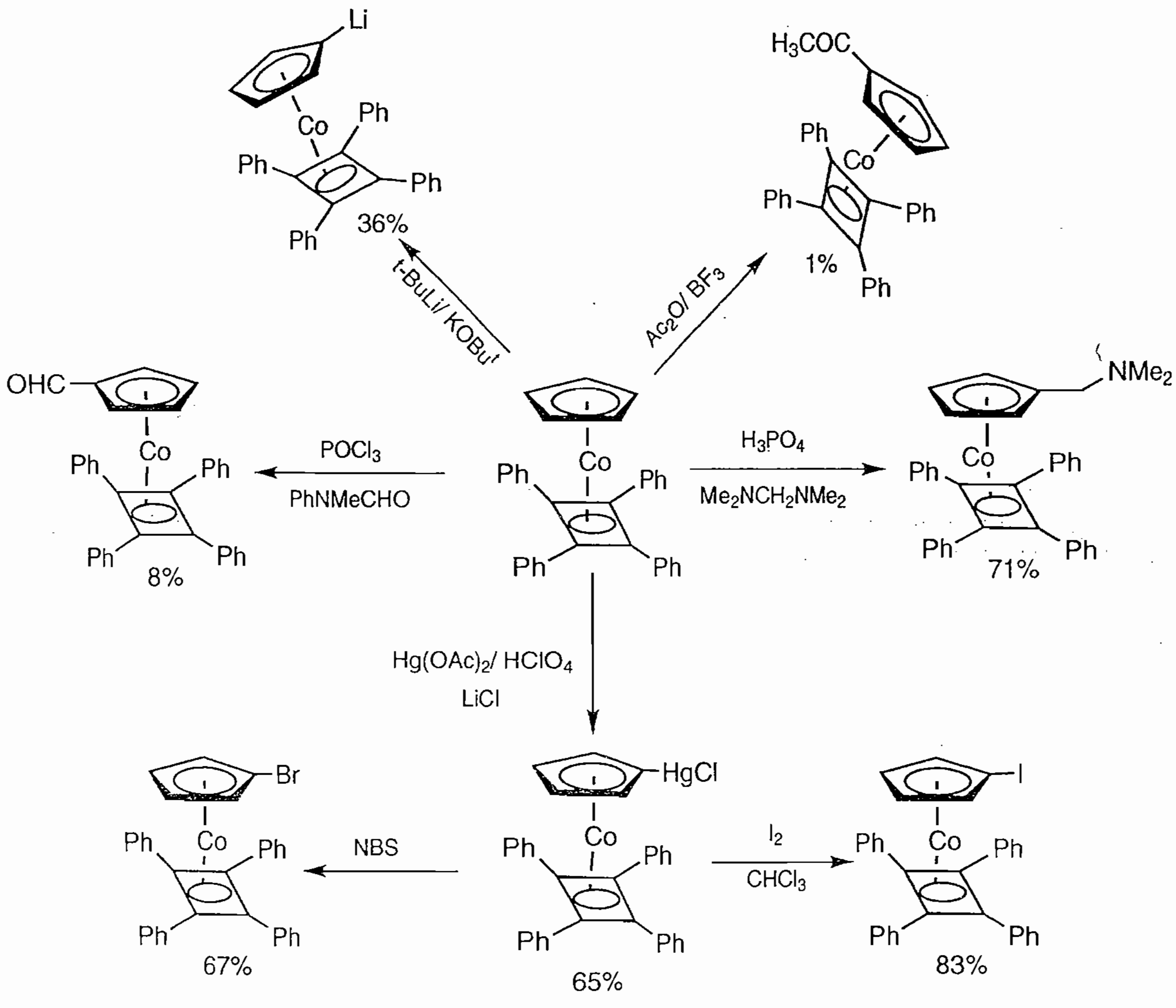
(7.51)

This compound and its analogues have turned out to be potential competitors to ferrocene in many aspects. However, unlike ferrocene, the chemistry centered around $(\eta^5\text{-Cp})Co(\eta^4\text{-}C_4H_4)$ has not developed much as it has so far been obtained only in poor yields and complex reactions are required to prepare it (Eq. 7.51). Although this sandwich compound is known with a variety of substituents on the cyclobutadiene ring, one with a tetraphenyl cyclobutadiene ring has been found to be the most stable among these, and this is prepared relatively easily and is the one whose chemistry has been explored in detail.[71, 72]

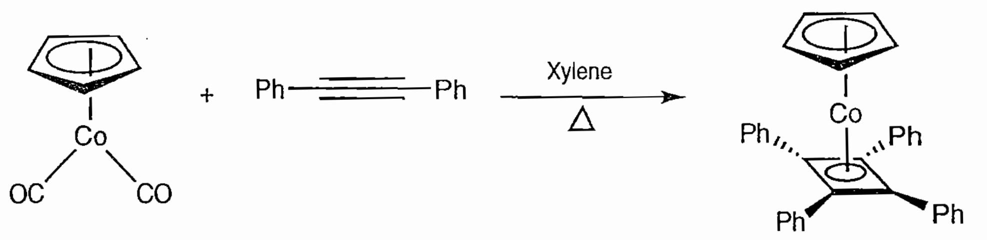


(7.52)

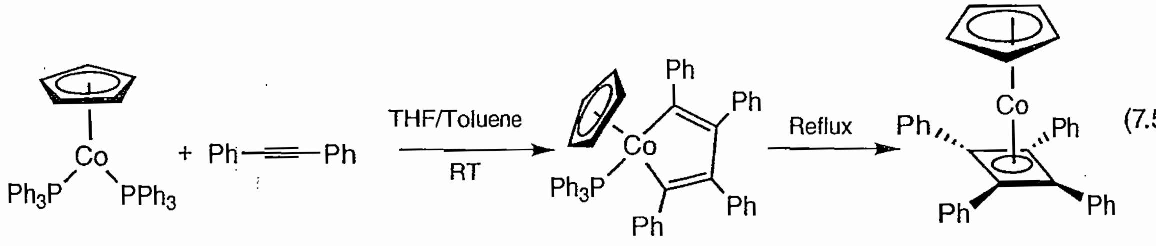
Some of the known substitution reactions of $(\eta^5\text{-Cp})Co(\eta^4\text{-}C_4Ph_4)$ are given in Scheme 7.4. Unlike ferrocene, electrophilic substitution reactions on the Cp ring have been comparatively difficult on this sandwich compound.[73, 74]



Scheme 7.4 Electrophilic substitution reactions on $(\eta^5\text{-Cp})Co(\eta^4\text{-}C_4Ph_4)$



(7.53)



(7.54)

The most useful derivatives of (η^5-Cp)Co(η^4-C_4Ph_4) and its cyclobutadiene linked dimer are the chiral cobalt oxazoline palladacycles (Fig. 7.5) prepared from their carboxylic esters. These palladacycles, which are extremely efficient catalysts in promoting the Overman–Claisen rearrangement of trichloroacetimidates, provide a simple and elegant route to chiral allylic amines, which are not otherwise easily accessible.[75–77]

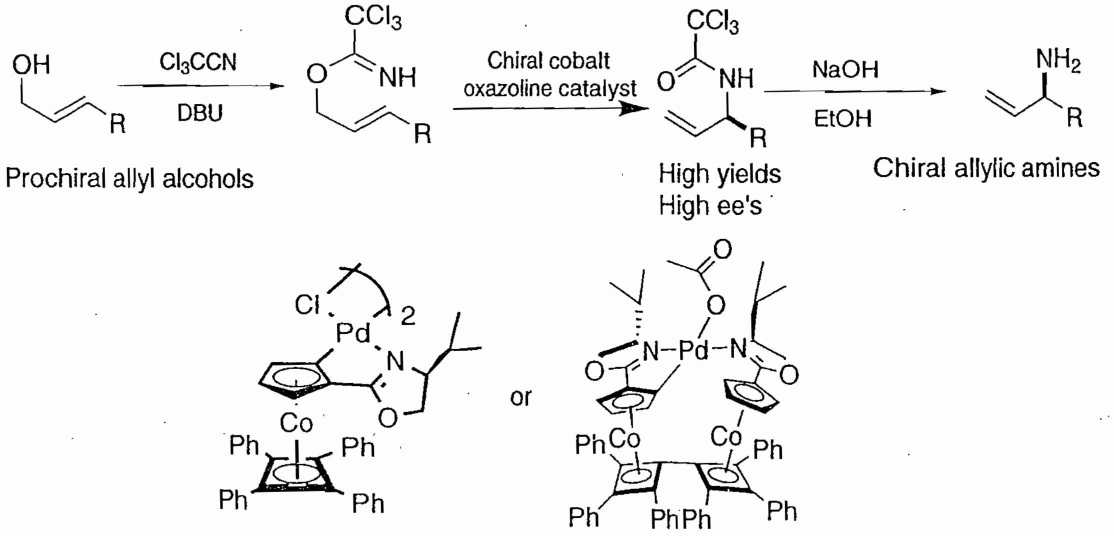
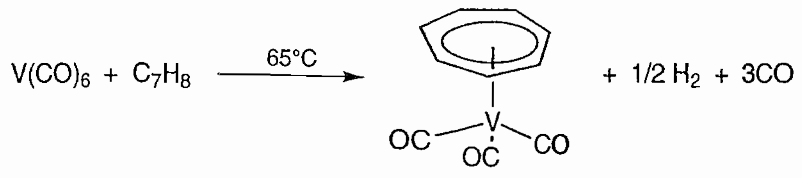


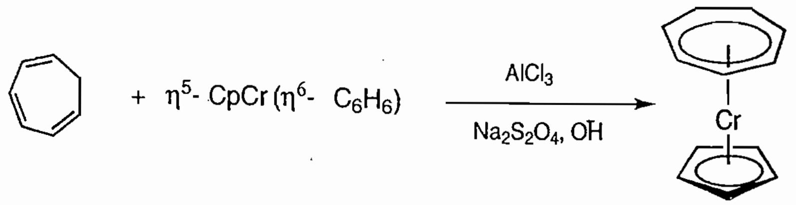
Fig. 7.5 Overman–Claisen rearrangement catalysed by chiral monomeric and dimeric cobalt oxazoline palladacycles

7.2.13 Cycloheptatriene and Cyclooctatetraene as Ligands

η^7-C_7H_7 metal complexes are mostly of the mixed ligand type or half sandwich type. The ligand is generally regarded as a coordinated tropylium cation and is classified in the oxidation state count method as a six electron ligand. It also occasionally acts as a η^3- or a η^5-ligand. A few examples are given in Eqs 7.55 and 7.56.[78]

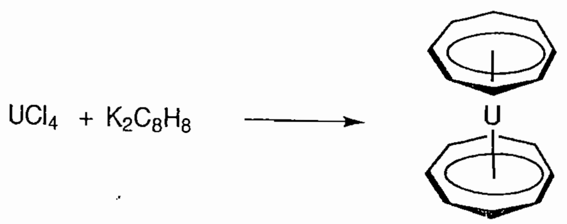


(7.55)

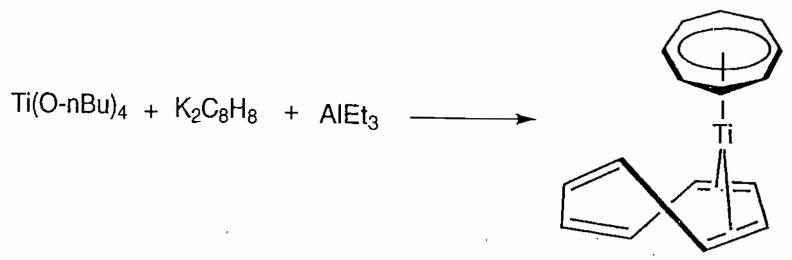


(7.56)

Cyclooctatetraene (COT) readily reacts with potassium metal to form the salt K_2COT, which contains the dianion $C_8H_8^{2-}$. The dianion is planar in shape and is aromatic with a Hückel electron count of 10 π electrons. COT forms complexes with transition metals such as Ti, Zr and Hf where the ring can be planar or puckered. The examples where it forms sandwich compounds with both the COT units planar are observed in lanthanides and actinides including Ce and U; with uranocene $U(COT)_2$, being one of the best known examples.[79, 80]



(7.57)



(7.58)

7.3 Davies–Green–Mingos (DGM) Rules

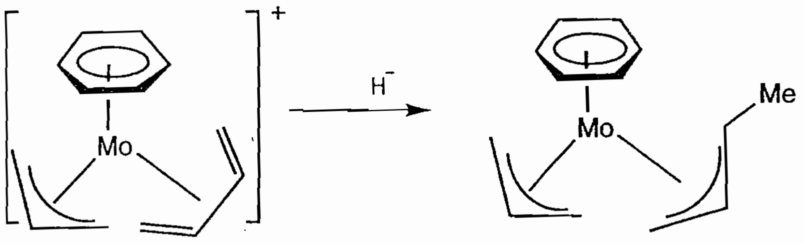
In 1978, Davies, Green and Mingos proposed three general rules – based on theoretical considerations – which allow predictions regarding the direction of kinetically controlled nucleophilic attack at 18 electron cationic complexes having unsaturated hydrocarbon ligands.[81] Application of these rules requires the ligands to be classified as even or odd, and as closed or open classes. The rules say that:

(i) Nucleophilic attack occurs preferentially at even coordinated polyenes.

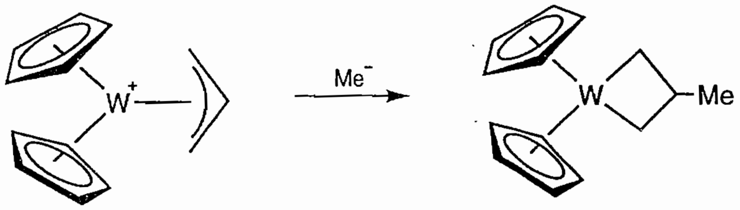
(ii) Nucleophilic addition to open coordinated polyenes is preferred over closed polyene ligands.

(iii) In the case of even open polyenes, nucleophilic attack always occurs at the terminal carbon atom. For odd open polyenyls, attack at the terminal carbon occurs only if L_nM^+ is a relatively stronger electron withdrawing fragment.

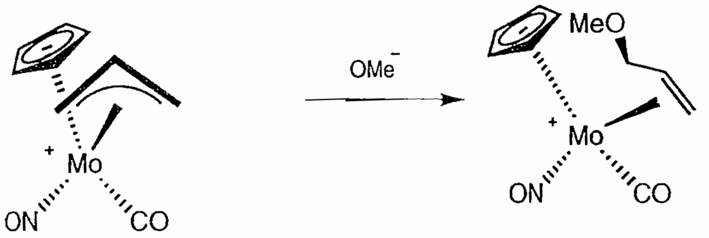
The following examples illustrate all the rules.



(7.59)



(7.60)

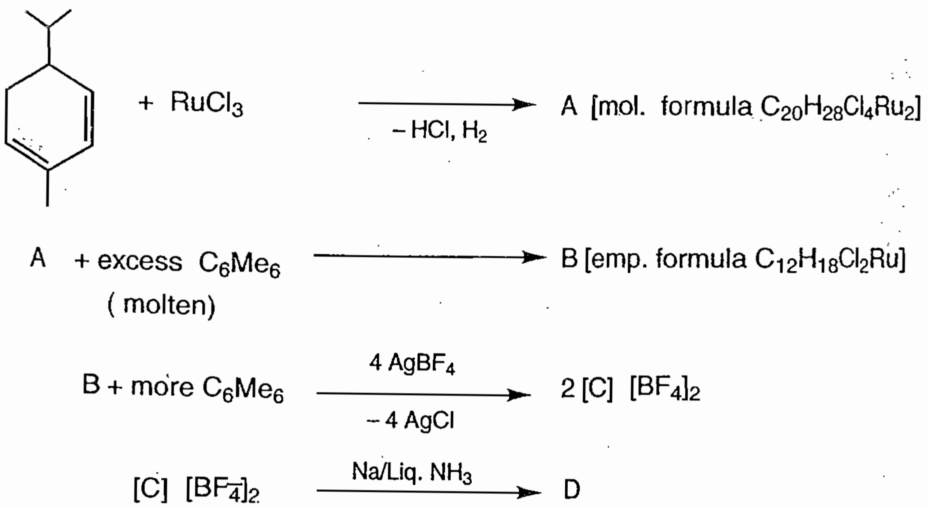


(7.61)

Problems and Exercises

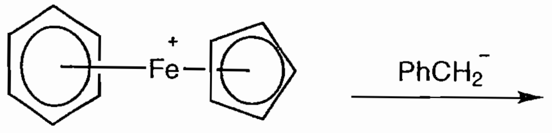
7.1. Heating $[(\eta^5\text{-Cp})Fe(CO)_3]^+$ with NaH gives compound A with a molecular formula $FeC_7H_6O_2$, along with the evolution of a colourless gas. Compound A reacts rapidly at room temperature to liberate another colourless gas, and forms a solid compound B, which has the empirical formula $FeC_7H_5O_2$. Compound B shows two strong infrared bands, one near 1850 and the other near 2000 cm^{-1}. Treatment of B with I_2 generates another solid compound C with a molecular formula $FeC_7H_5O_2I$. The reaction of NaCp with C gives a solid compound D having a formula $FeC_{12}H_{10}O_2$. On heating, D liberates a colourless gas, leaving an orange solid E with a formula $FeC_{10}H_{10}$. Compounds A to E obey the 18 electron rule and all of them have at least one Cp ring in the η^5 mode. Propose structures for compounds A to E.

7.2. Considering the following reaction schemes, draw the structures of A–D. The compounds C and D are monomeric and do not contain chlorine and D is a neutral molecule (hint: The compounds A–D obey the 18 electron rule and they all have at least one η^6-coordinated ligand on ruthenium).

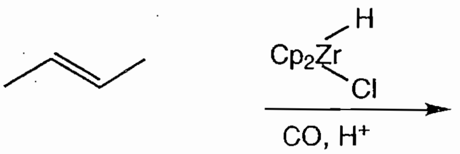


7.3. Predict the products in the following reactions.

(a)



(b)



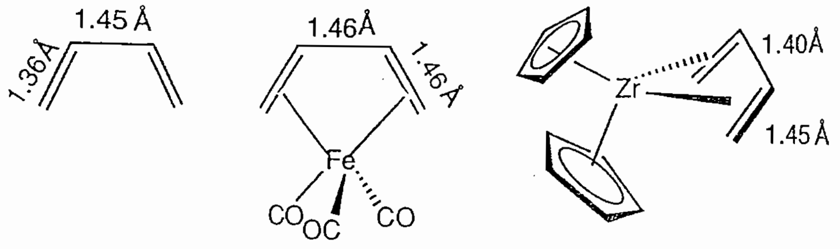
7.4. $Cr(CO)_6$ can be prepared by the reaction of $CrCl_3$, Al and CO in benzene medium with $AlCl_3$ as catalyst (300 bar and 140°C). Another ionic organometallic compound also gets formed in small quantities in this reaction. Suggest its structure.

7.5. Which among the following beryllium alkyl compounds is/are stable?

(a) $BeMe_2$ (b) $Be(Et)_2$ (c) $Be(Bu^t)_2$ (d) $Be(CH_2Bu^t)_2$

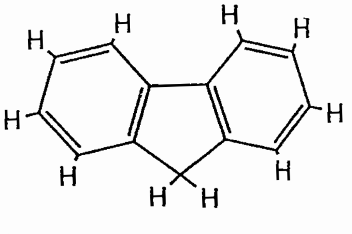
7.6. The reaction of MCl_4 (M is a second row transition metal) with two moles of NaCp resulted in a neutral 16e compound A. Compound A on reduction with $LiAlH_4$ gave a compound B with the molecular formula $C_{10}H_{11}ClM$. The reaction of B with $CH_3CH{=}CH_2$ resulted in C with the empirical formula $C_{13}H_{17}ClM$. Compound C on reaction with CO, followed by HCl gave the aldehyde $CH_3CH_2CH_2CHO$ along with the formation of A again. Identify the species A to C.

7.7. Consider the binding of 1,3-butadiene to Fe and Zr and explain the bond length data.

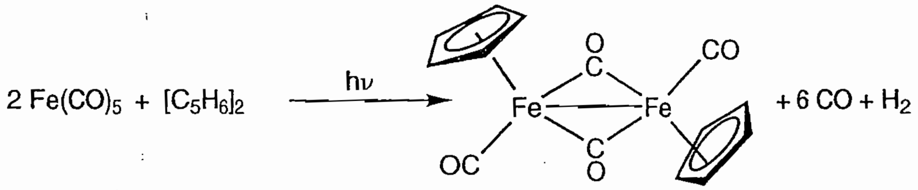


7.8. Fluorene, a polycyclic organic compound, forms an ionic organometallic compound with a CpFe fragment and obeys the 18e rule. It has the molecular formula $[(C_5H_5)Fe(C_{13}H_{10})]^+[PF_6]^-$ (A). Treatment of A with a base results in another 18e organometallic complex B with the formula $[(C_5H_5)Fe(C_{13}H_9)]$. Draw reasonable structures of complexes A and B.

Fluorene



7.9. The reaction of $Fe(CO)_5$ with cyclopentadiene dimer proceeds according to the overall equation given below.



The reaction involves two intermediates A and B and both obey the 18 electron rule. While A (mol. formula $C_8H_6O_3Fe$) is formed in the first step with the evolution of CO, B is generated from A with the release of another molecule of CO and H_2 under UV irradiation in the final step. The proton NMR of A indicates 3 sets of peaks in the ratio (1:1:1) while that of B indicates 2 sets of peaks in the ratio (1:5). Draw the structures of A and B.

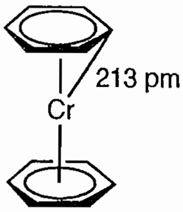
7.10. The reaction of two moles of CpNa with MCl_2 gave an unstable compound A with the molecular formula $C_{10}H_{10}M$ (M is a first row TM). Reacting A with excess of a hydrocarbon gas B along with metallic potassium, gave a relatively stable compound C with the empirical formula $C_9H_{13}M$ along with a potassium compound as side product. Reaction of C with excess diphenylacetylene gave a highly stable compound D with the molecular formula $C_{33}H_{25}M$ along with the evolution of gas B. Spectral studies indicate that the phenyl groups present on D are all under an identical environment. Write the structures of compounds A to D.

7.11. UV irradiation of $(\eta^5\text{-Cp})(\eta^2\text{-}C_2H_4)_2Rh$ in the presence of benzene results in the release of ethylene gas and the formation of an unusual bimetallic product. This product has a M–M single bond and both metal centres obey the 18e rule. It shows 3 resonances in proton NMR with relative intensities of 5:2:1 and has the empirical formula RhC_8H_8. Predict its structure.

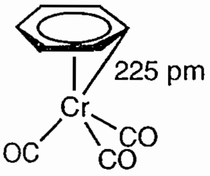
7.12. The structure for (cycloheptatriene)$Fe_2(CO)_6$ can have two possibilities with different hapticities and metal–metal bond multiplicities (cycloheptatriene = C_7H_8). The molecule obeys the 18e rule, has only terminal carbonyl ligands and has a mirror plane of symmetry. Draw the two possible structures.

7.13. When η^3-allyl-Ru(NO)$(PPh_3)_2$ reacts with CO, a new 18e compound with the formula allyl-Ru(NO)$(PPh_3)_2$(CO) is produced. Draw two possible structures of the new compound showing the bonding modes of the ligands. For each compound, indicate the *d* electron count around the metal centre.

7.14. Based on the following data, comment on the reactivity order of the following compounds towards electrophilic substitution reaction into the η^6-arene ring and justify your answer.



I



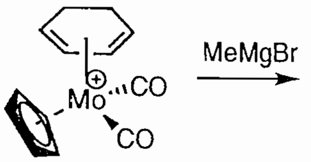
II

7.15. $NiCp_2$ readily reacts with a weak acid HF to yield $[NiCp(\eta^4\text{-}C_5H_6)]^+$. On the other hand, ferrocene reacts with a strong acid and the protonation occurs at Fe to produce $[Fe(Cp)_2H]^+$. Why does the protonation occur at different sites in these complexes? Which reaction is more facile? Give a plausible reason.

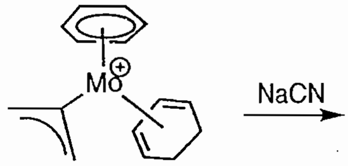
7.16. Nickel carbonyl reacts with cyclopentadiene (C_5H_6) to produce a stable red, diamagnetic compound of formula $NiC_{10}H_{12}$. The ^1H NMR spectrum of this compound at RT shows four different types of hydrogen; integration gives relative areas of 5:4:2:1, with the most intense peak in the aromatic region. Suggest a structure for $NiC_{10}H_{12}$ that is consistent with this NMR spectrum.

7.17. Write the products in the following reactions.

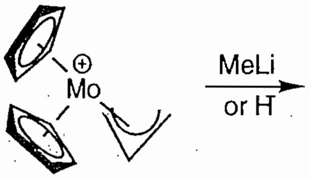
(a)



(b)



(c)



Supplementary reading

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CHAPTER

8

UNIQUE REACTIONS IN ORGANOMETALLIC CHEMISTRY

8.1 OXIDATIVE ADDITION AND OXIDATIVE COUPLING

Neutral or anionic nucleophiles can generally add on to coordinatively unsaturated molecules with or without the transition metal. These are simple addition reactions and indicate the Lewis acidic nature of the metal/central atom.

$$PF_5 + F^- \rightleftharpoons PF_6^- \tag{8.1}$$

$$TiCl_4 + 2\,POCl_3 \rightleftharpoons TiCl_4(OPCl_3)_2 \tag{8.2}$$

When addition of a ligand is accompanied by oxidation of the metal, it is called an oxidative addition reaction and is generally represented as

$$\underset{d^n}{L_nM} + XY \longrightarrow \underset{d^{n-2}}{L_n(X)(Y)M} \tag{8.3}$$

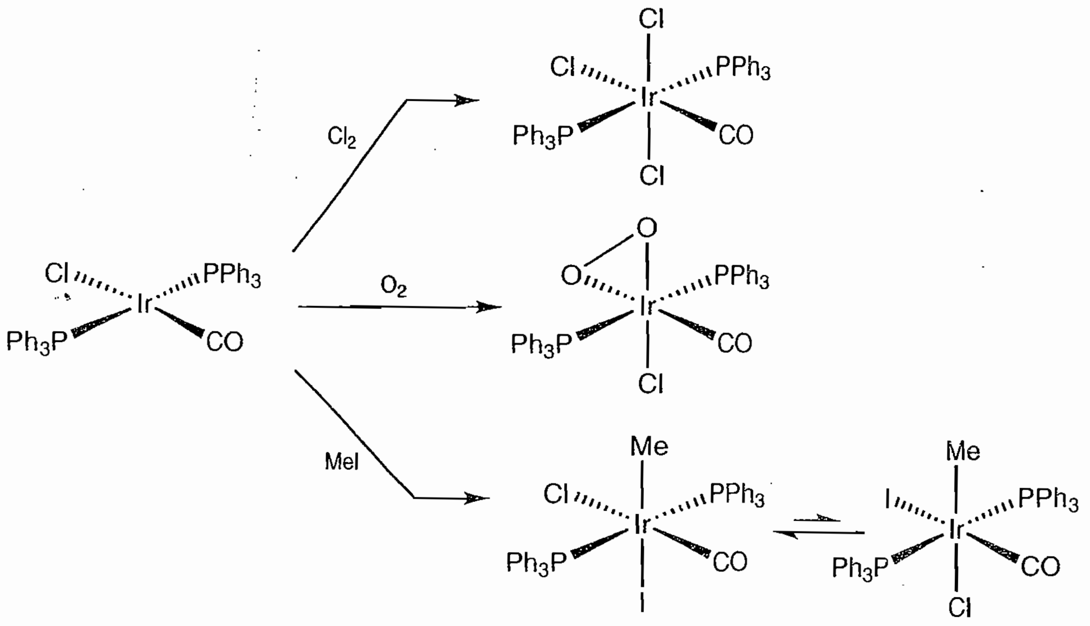
In this reaction, the formal oxidation state of the metal increases by two units. The transfer of two electrons from the metal to the incoming ligand breaks a bond in that ligand and forms two new anionic ligands. Hence, the coordination number of the metal also increases by two units.

For an oxidative addition to proceed, we must have:

- nonbonding electron density on the metal,
- two vacant coordination sites on the reacting complex (L_nM), that is, the complex must be coordinatively unsaturated, and
- a metal with stable oxidation states separated by two units; the higher oxidation state must be energetically accessible and stable.

For example, oxidative addition from Ir(I) to Ir(III) is common but an oxidative addition from Fe(III) to Fe(V), while possible, is unlikely to occur. The tendency of the complexes to undergo oxidative addition is governed by the electron density on the metal centre, that is, the ease with which metals can be oxidised. Such reactions are most common in transition metal complexes (mostly square planar) with the metal in d^8 and d^{10} electronic configurations, notably Fe^0, Ru^0, Os^0, Rh^I, Ir^I, Pd^{II}, Pt^{II}, Ni^0 Pd^0 and Pt^0. An especially well-studied system is the square planar *trans*-$IrCl(CO)(PPh_3)_2$, well known as the Vaska's complex. Thus on adding Cl_2, a four coordinate d^8, 16 electron complex is converted to a six coordinate d^6, 18 electron product. The oxidation state of Ir increases from I to III. Consistent with this change, the stretching frequency of the CO increases from 1967 to 2075 cm^{-1}. The Cl–Cl bond is broken and two Ir–Cl bonds are formed.[1, 2]

Depending on the nature of the adding group (polar, nonpolar) as well as the type of mechanism involved (concerted, S_N2, free radical and ionic) one can get either *cis* addition products, a mixture of *cis* and *trans* addition products or in few cases *trans* addition products.

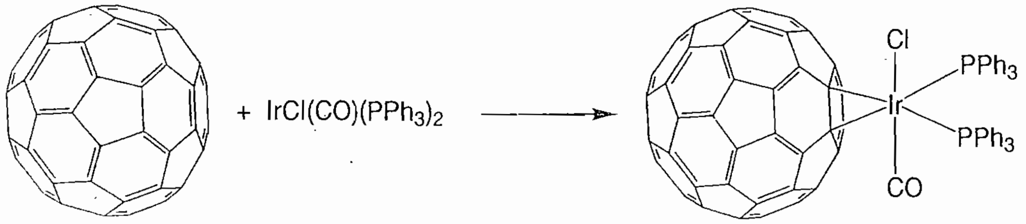


(8.4)

Three major classes of compounds undergo oxidative addition reaction:

(i) nonpolar and low polarity compounds (H-H, H-SiR_3, RH, ArH, RSH, X_2),
(ii) polar compounds (R-X, H-X, Ar-X, RCOX, $CHCl_3$, ROTs, RSO_2X), and
(iii) ligands with π systems (O_2, alkenes, alkynes).

Most of the nonpolar compounds such as H_2 or Cl_2 will add in the *cis* manner but steric requirements of the existing substituents (for example, a bulky group like PPh_3) can force it to rearrange to a *trans* configuration. In the same manner, ionic and S_N2 type mechanisms operating on polar molecules like MeI will form the kinetic controlled *trans* product which may convert to the *cis* product under thermodynamic conditions. However, unsaturated compounds like O_2 or an alkyne will form a metallacycle; for example, in the reaction with molecular oxygen, Ir(I) is oxidised to Ir(III) and a three membered ring with single bonds is formed. Both C_{60} and C_{70} have also been found to undergo oxidative addition reactions with Vaska's complex (Eq. 8.5).[3]



(8.5)

Several trends in the oxidative addition reaction have been noticed.

- The tendency of oxidative addition increases as one moves down in a group in the periodic table; for example, $\mathrm{Ir^{1+}}$ is easier to oxidise than $\mathrm{Rh^{1+}}$ which in turn is easier to oxidise than $\mathrm{Co^{1+}}$.
- A low initial oxidation state is more favourable for oxidative addition to occur; for example, when all other factors are equal, $\mathrm{Fe^{0}}$ is easier to oxidise than $\mathrm{Co^{I}}$ and this is easier to oxidise than $\mathrm{Ni^{2+}}$. Fe(0), Co(I) and Ni(II) are isoelectronic metals. The presence of electron-rich donor ligands around the metal increases the rate of oxidative addition reaction. In comparing two or more metal complexes to find the most reactive one towards a particular substrate for oxidative addition, the metal centre having the strongest donor ligands, the fewest π acceptor ligands and the highest negative charge is picked.
- The possibility of oxidative addition of A–B to a metal M, depends on the relative strengths of the A–B, M–A and M–B bonds. For example, oxidative addition of an alkane is much less common than oxidative addition of an alkyl halide. In an alkane, the C–H bond is fairly strong compared to the M–H and M–R (R = alkyl) bonds. For isostructural complexes, the following trends are observed for oxidative addition.

Fe(0)	Co(I)	Ni(II)
Ru(0)	Rh(I)	Pd(II)
Os(0)	Ir(I)	Pt(II)

↓ *increase in tendency for oxidative addition*

← *increase in tendency for oxidative addition*

- Complexes with 18 electrons cannot undergo oxidative addition without the expulsion of a ligand.[4]

$$\mathrm{Ru(CO)_4(PMe_3)} + \mathrm{MeI} \longrightarrow \mathrm{Ru(CH_3)(I)(CO)_3(PMe_3)} + \mathrm{CO}$$

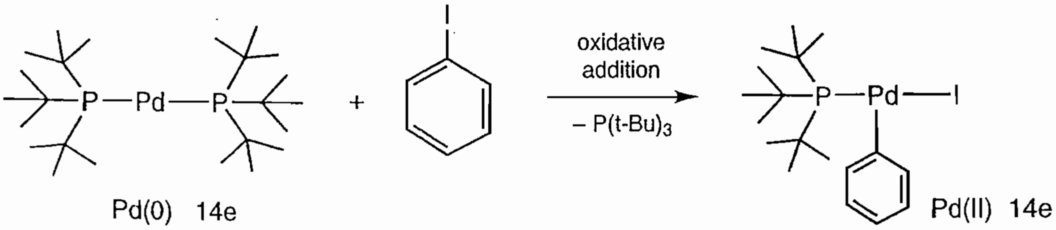
Please note:

- Oxidative addition reactions cannot occur on metal centres that are already in their highest oxidation state. For example, $\mathrm{Ta^{5+}}$ cannot undergo oxidative addition to give $\mathrm{Ta^{7+}}$. In these cases, a σ bond metathesis reaction is a likely alternative.
- Complexes with d^0 metals do not undergo oxidative addition reactions.

Therefore, the number of electrons in the starting and the final metal complexes are always counted to check out the overall electron count, the oxidation state of the metal and the number of d electrons.

8.1.1 Oxidative addition involving C–X bonds

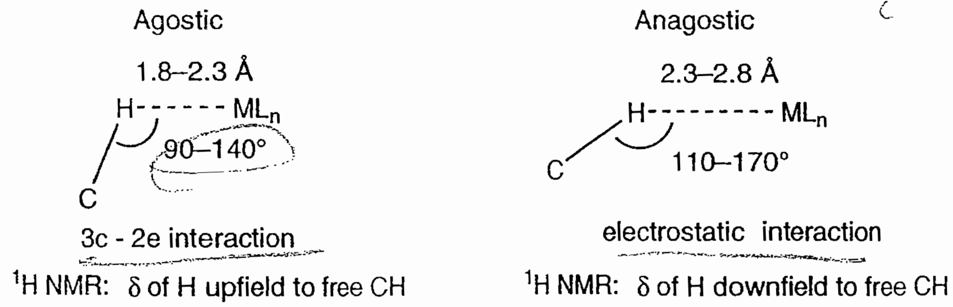
Oxidative addition of polar (R–X) substrates is most visible in the catalytic cycles of palladium catalysed cross coupling reactions of aryl halides with a variety of aryl/alkyl functionalities (for example, boronic acids—Suzuki coupling, Chapter 16) for which Suzuki, Negishi and Heck received the Nobel Prize in 2010. The first step in the mechanism of these cross coupling reactions has been proposed as the oxidative addition of the aryl halide on a Pd(0) metal centre. Several studies indicated that sterically demanding phosphine ligands have the ability to stabilise low coordination palladium complexes which, owing to their low electron count, are very reactive. If these ligands are electron donating as well, then they will help to generate an electron-rich metal complex which can undergo faster oxidative addition reactions. Such ligands (for example, $(t\text{-}Bu)_3P$ or S Phos, Section 16.5) were used by Fu, Buchwald and others to carry out palladium catalysed cross coupling reactions of aryl chlorides which does not happen when common phosphines such as PPh_3 are used.[5] A monoligated sterically hindered and electron rich phosphine complex of palladium such as $Pd[P(t\text{-}Bu)_3]$ was proposed as the active catalyst for these reactions. Evidence for this was provided by carrying out a reaction of Ph–X with $Pd[P(t\text{-}Bu)_3]_2$, isolating and structurally characterising the oxidatively added product which was a T-shaped 14 electron complex (Eq. 8.6).[6]



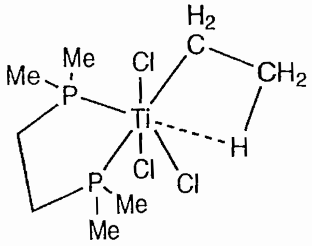
(8.6)

8.1.2 Prelude to Cyclometallation: Agostic and Anagostic interactions

From the mid-1960s it was observed that certain transition metal complexes exhibited a close proximity of CH bonds of their coordinated ligands to the metal atoms. Maurice Brookhart and Malcom Green in 1983 coined the word *agostic* to describe such weak bonding interactions between hydrogen atoms of aliphatic or aromatic CH bonds with metal centers in organometallic and coordination compounds.[7] The word agostic, originally from Greek, means 'to hold on to oneself'. Agostic interactions play a pivotal role in many organometallic reaction mechanisms especially those involving C–H activation and cyclometallation. These interactions which are mostly intramolecular, can be of the type α, β, γ, δ and so on depending upon the connectivity of the carbon atom from the metal centre whose C–H bond takes part in the interaction. Among these, β agostic interactions are the most commonly observed and structurally proved. Reservations have been raised about the appropriateness of the term α agostic interaction with a suggestion that α agostic geometry is a better term to describe the interaction.[8] While agostic interactions were defined as possessing 3-centre 2-electron bonds, many similar interactions were observed which were mostly electrostatic interactions especially in the case of square planar electron-rich d^8 metal complexes. These interactions which were clearly not 3-centre 2-electron bonds were named *anagostic* interactions by Lippard in 1990.[9] In 2007, Brookhart, Green and Parkin after considering a large number of C–H···M interactions, redefined agostic and anagostic interactions as shown overleaf by illustrating the major structural and spectral differences between them.[10]

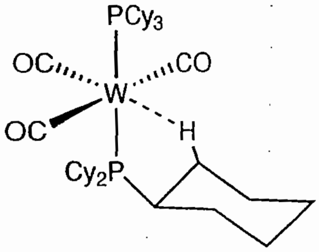


Another unique feature of agostic interactions has been identified as the reduction in the $^1J_{C-H}$ coupling constant of the interacting C–H bond. For alkyl groups having β-agostic interactions, reduction in the $MC_\alpha C_\beta$ angle to values below 90° has also been observed. As stated by Brookhart and Green, 'the minimal requirement is that the metal centre should have an empty orbital to receive the two electrons of the C–H bond'. Expected upfield ^{1}H NMR shifts of alkyl hydrogen atoms involved in agostic interactions are sometimes not experimentally observed due to fluxionality of the molecule. The following examples illustrate agostic interactions.[11,12] The titanium–ethyl complex has been tailor made to explore agostic interactions. Agostic interactions do play a significant role in many mechanisms of homogeneous catalysis especially those of alkene polymerisation catalysts.



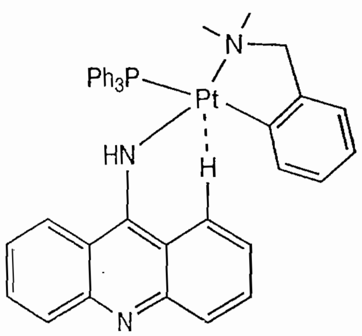
β agostic

	Ti	W
M—H	2.06 Å	2.27 Å
$\angle$MHC	90.4°	127.6°
^{1}H NMR: CH	fluxional	
$\angle MC_\alpha C_\beta$	84.6°	

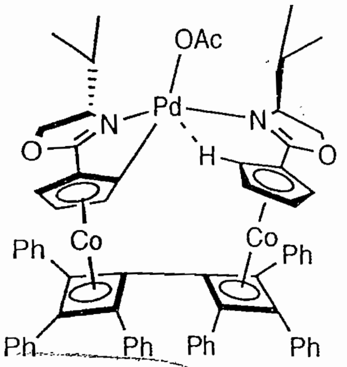


γ agostic

Many examples of anagostic interactions were reported after its difference from agostic interactions were defined in 2007 and numerous reports of C–H···M interactions, classifed earlier as agostic are currently being looked into once again. The following examples illustrate anagostic interactions.[13,14]



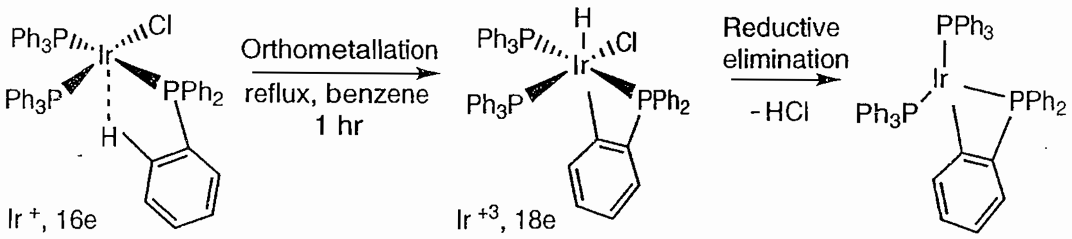
	Pt	Pd
M—H	2.54 Å	2.66 Å
$\angle$MHC	143°	125.9°
^{1}H NMR: δ CH	10.97	8.61
Δδ	2.64	3.44



Agostic and anagostic interactions are best analysed by X-ray crystallography and to some extent by neutron diffraction data. It has been shown that C–H and M–H bond distances are 5% to 20% longer in these metal complexes than expected for isolated metal hydrides and hydrocarbons. Unlike agostic interactions, the anagostic interactions are mostly electrostatic interactions. Some authors try to differentiate anagostic interactions from standard C–H···M hydrogen bonds by defining the latter as typical 3-centre 4-electron bonds with more linearity.[15] However, this differentiation is still sketchy and for all practical purposes, one may treat anagostic and hydrogen bond interactions as similar. This is supported by the fact that both show downfield ^{1}H-NMR shifts of the hydrogen atoms involved in the interaction.[16]

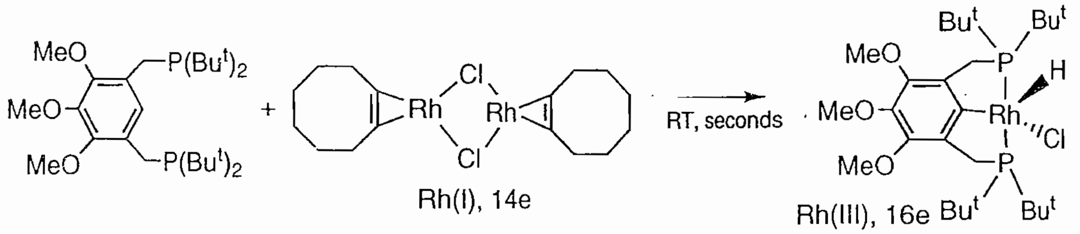
8.1.3 Oxidative addition involving C–H bonds and cyclometallation

Oxidative addition involving C–H bonds is also termed as C–H bond activation and often involves agostic or anagostic/hydrogen bond type of weak M···H interactions prior to the oxidative addition step. These reactions which are unique to organometallic chemistry have an enormous potential in catalytic conversion of relatively unreactive non-polar hydrocarbon compounds such as methane, benzene and hexane to useful functionalised organic compounds.[17, 18] These reactions can happen intermolecularly or intramolecularly and the latter is more frequently encountered. As the intramolecular reaction results in the formation of a cyclic product with the transfer of the hydride to the metal, it is also called cyclometallation. Often, the product of the cyclometallation step (having a hydride group) undergoes a reductive elimination with the loss of the hydride as a stable side product (Scheme 8.1).



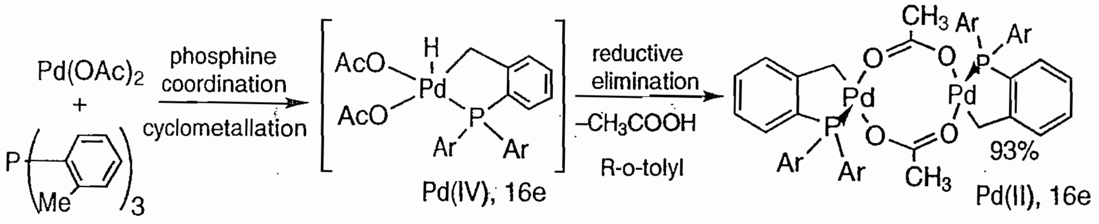
Scheme 8.1 Orthometallation involving PPh_3 group of the complex $IrCl(PPh_3)_3$

The cyclometallation can occur from aromatic (sp^2) or aliphatic (sp^3) hybridised carbon atoms from a coordinated ligand such as phosphine or aromatic nitrogen-based heterocycles such as pyridines. The following example shows the formation a pincer type of cyclometallated complex by the activation of an aromatic C–H bond of a biphosphine.[19]



(8.7)

One of the most well studied examples of cyclometallated compounds are palladacycles which are readily formed from oxidative addition reactions of nitrogen, phosphorus and sulphur containing ligands with palladium salts, especially palladium acetate. Palladacycles have proven applications as catalysts in chiral and non-chiral organic synthesis.[20] The following example shows the synthesis of one of the early examples of palladacycles resulting from an aliphatic C–H activation which has excellent catalytic activity in Heck olefination of aryl halides.[21] The possible steps involved are phosphine coordination and cyclometallation followed by reductive elimination of acetic acid along with dimerisation.



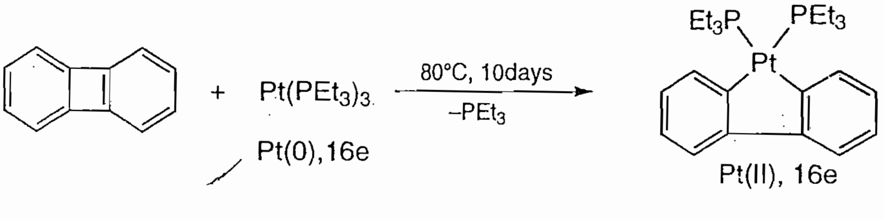
(8.8)

8.1.4 Orthometallation

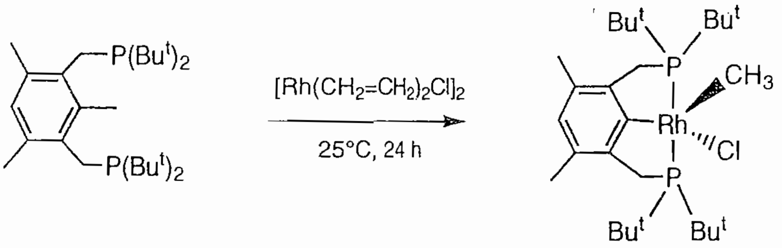
Orthometallation is the most common type of cyclometallation reaction. In this, the *ortho* hydrogen of an aryl group in compounds such as aryl phosphines or phosphates, azobenzene and other nitrogen donors is often transferred to the metal. The orthometallation is preceded by an agostic or anagostic interaction between the metal and the hydrogen atom *ortho* to the phosphorus-bound carbon (Scheme 8.1).[22]

8.1.5 Oxidative addition involving C–C bonds

This reaction, also a form of C-C bond activation, is relatively rare compared to oxidative addition on C–H bonds and is often encountered in reactions involving strained cyclic compounds. For example, biphenylene undergoes oxidative addition of the C–C bond with $Pt(PEt_3)_3$ resulting in a thermodynamically more stable five-membered metallacycle.[23] C–C bond activations are also observed in the formation of some pincer complexes.[24]



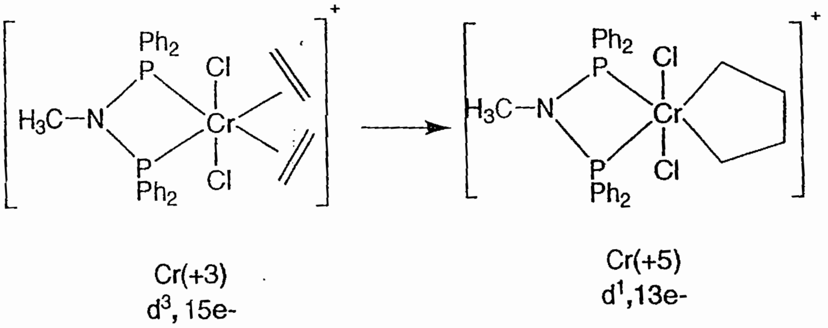
(8.9)



(8.10)

8.1.6 Oxidative addition of ligands with π systems (Oxidative Coupling)

In the given reaction (Eq. 8.11), the Cr in the product has two new anionic alkyl ligands forming a metallacyclopentane ring system. This is also an oxidative addition reaction but in forming a new bond between two ethylene molecules (and losing the original double bonds), we have coupled the two ligands together. There is a special term for this type of reaction called oxidative coupling. The metal is being oxidised to create two new anionic ligands, but the original two neutral ligands also form a new bond between them, instead of fragmenting to make two new independent anionic ligands. The driving force for this reaction is the formation of a new C–C σ-bond and the creation of two new strongly donating anionic ligands that can donate better to the metal even though one has technically lowered the electron count.[25]



(8.11)

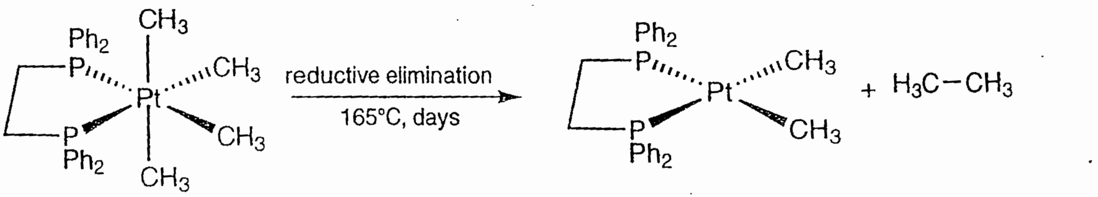
Such reactions are found quite often with alkynes. They also form the major steps in the cyclotrimerisation of acetylenes using nickel and cobalt catalysts with metallacyclopentadiene and metallacycloheptatriene as intermediates (see section 5.5).

8.2 REDUCTIVE ELIMINATION

Reductive elimination is almost exactly the reverse of oxidative addition and it decreases both the coordination number as well as the oxidation state of the metal by two units.

The key requirement for reductive elimination to occur is that the eliminating groups must be adjacent (*cis*) to each other. Other factors that facilitate an easy reductive elimination are,

- a high formal positive charge on the metal,
- the presence of bulky groups on the metal, and
- an electronically stable organic product.



(8.12)

Other observations related to reductive elimination are:

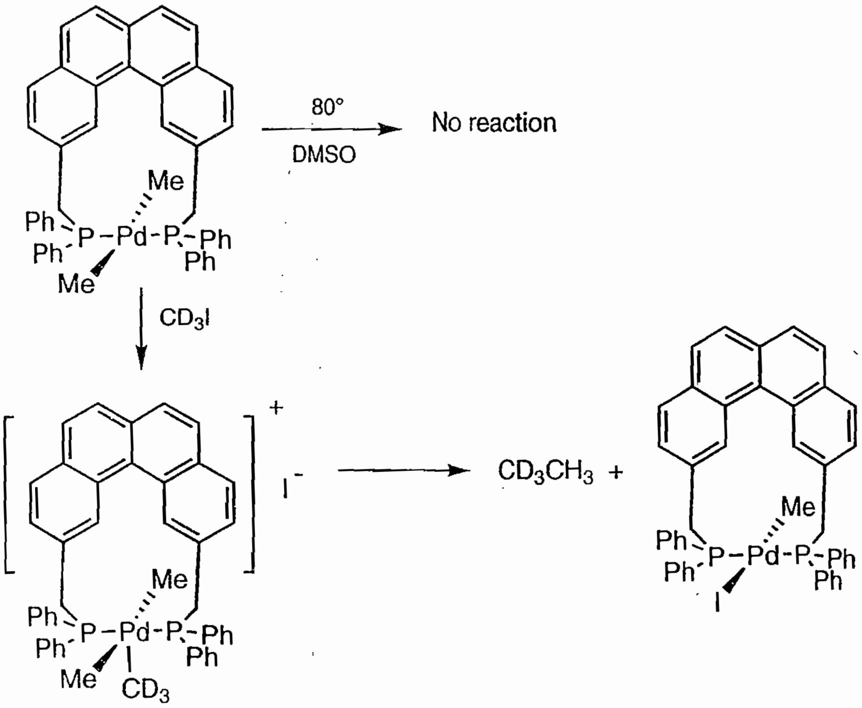
(i) The rate of reductive elimination follows the trend H–C > H–H > C–C. This is slightly different from the change in free energies.

(ii) The low valent ML_n complex formed after reductive elimination must be stable.

(iii) π-accepting ligands on the metal generally accelerate reductive elimination.

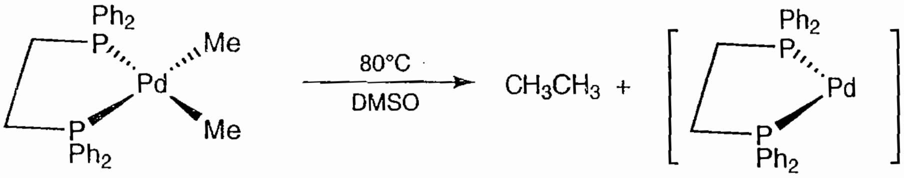
8.2.1 Mononuclear Systems

The significance of having two eliminating groups in the *cis* disposition, for reductive elimination to occur, can be inferred from the following examples.[26]



(8.13)

(8.14)



(8.15)

Reductive elimination reactions are intramolecular and this can be seen from the following example (Eq. 8.14) where no cross product is formed when the reaction is carried out with a mixture of deuteriated and non-deuteriated cyclohexane complexes.[27a]

$$\begin{matrix}[Cp^*Ir(PMe_3)(C_6H_{11})H]\\ +\\ [Cp^*Ir(PMe_3)(C_6D_{11})D]\end{matrix} \xrightarrow[\text{solvent}]{\text{heat}} [Cp^*Ir(PMe_3)solv] + C_6H_{12} + C_6D_{12} \qquad (8.16)$$

As oxidative addition and reductive elimination are microscopic reverse reactions of each other, the position of the equilibrium depends on the thermodynamics of the process. For example, many metal complexes will oxidatively add on MeI, but only few will reductively eliminate MeI. Similarly, oxidative addition of RCH_2–H is less common while reductive elimination of alkanes from $M(H)CH_2R$ is very often observed. These points are well illustrated from the thermochemical studies specific to iridium(I) complexes (Table 8.1). Notably, oxidative addition with CH_3I and H–H is feasible as per this analysis while it is thermodynamically unfavourable with CH_3–H and CH_3–CH_3. This is indeed so because only CH_3I and H–H oxidative addition is known with Vaska's complex.

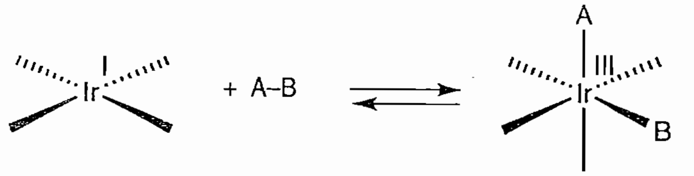
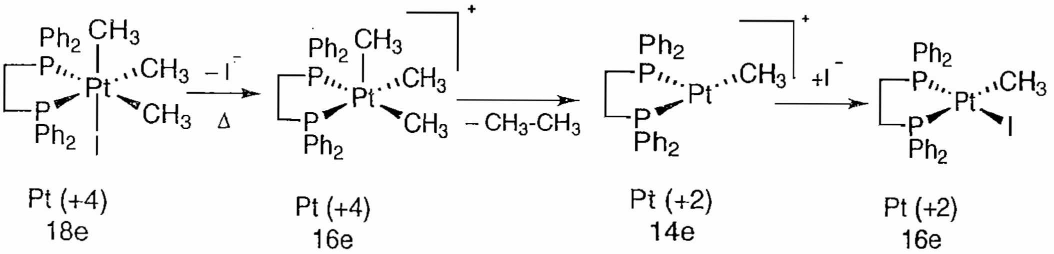

(8.17)

Table 8.1 Thermochemical data and bond dissociation energies of iridium complexes [27b,c]

A–B	Bond dissociation energy of A–B (kcal/mol)	Bond dissociation energy of Ir–A (kcal/mol)	Bond dissociation energy of Ir–B (kcal/mol)	ΔH (kcal/mol)	ΔG (kcal/mol)
H–H	104	Ir–H : 60	Ir–H : 60	–16	–6
CH_3–H	104	Ir–CH_3 : 46	Ir–H : 60	–2	+8
CH_3–CH_3	88	Ir–CH_3 : 46	Ir–CH_3 : 46	–4	+6
CH_3–I	56	Ir–CH_3 : 46	Ir–I: 45	–35	–25

Since an *electron rich* metal favours oxidative addition, the reverse is true for reductive elimination. As the latter involves pushing a pair of electrons back onto the metal centre from two anionic ligands which are usually more electronegative than the metal centre, it is best if the metal centre is *electron deficient*. This can be accomplished by having electron withdrawing ligands like CO, cationic charge(s), and/or coordination unsaturation (sub-18 electron counts). The following examples highlight the role of coordination unsaturation and the cationic nature of the complex in the reductive elimination reactions.

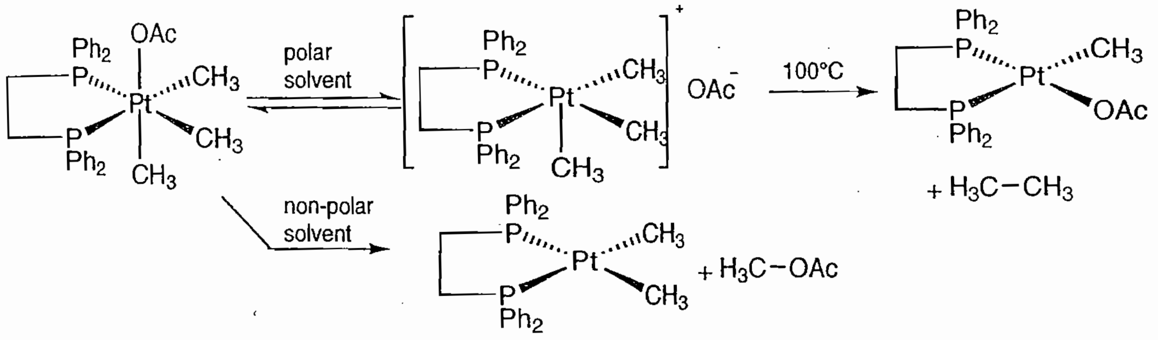
Generally, reductive elimination of two *cisoidal* groups from saturated 18e complexes occurs without difficulty. However, it has been shown that the rates of such reactions can be promoted by a ligand dissociation which generates an unsaturated and more electron deficient metal centre. In the following reaction, the reductive elimination of ethane from the cation, formed by the iodide dissociation, occurs much more rapidly compared to the direct elimination from the initial 18e complex.[28]



(8.18)

Oxidation, therefore, can be used to induce reductive elimination when the reaction would not occur otherwise. The classical case of $Et_2Fe(bipy)_2$ which involves oxidation has been discussed later in this chapter (Section 8.3.5).

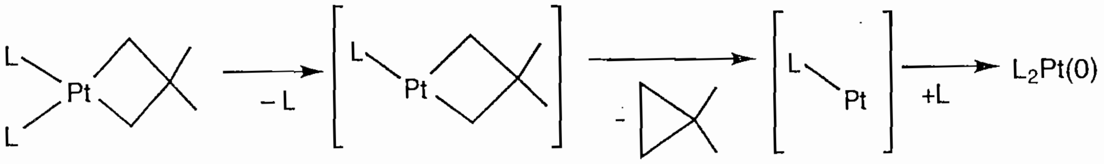
The solvent plays an important role in the following reaction and leads to different elimination products because prior ligand dissociation occurs in polar solvents and forms a coordinatively unsaturated intermediate which then forms the final product (Scheme 8.2).[29]



Scheme 8.2 Effect of solvents on reductive elimination reactions

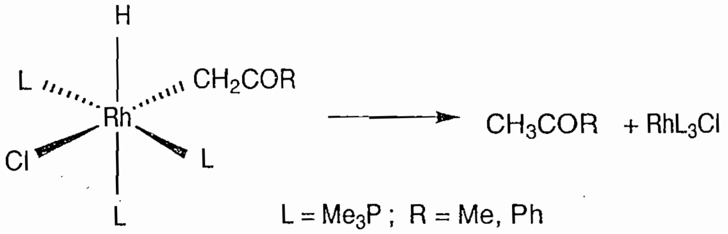
There are many more examples where ligand dissociation is essential before elimination. In the following reaction, the dissociation of one phosphine ligand prior to reductive elimination of 1, 1-dimethylcyclopropane is mandatory.

Some reactions which form a C–H bond also require prior dissociation of the ligand. For example, in Eq. 8.20, reductive elimination occurs by a dissociative mechanism. The loss of PMe_3 prior to this step is the rate determining step and this has been confirmed by kinetics studies.[30]



(8.19)

$L = (^iPr)_3P, Cy_3P$



(8.20)

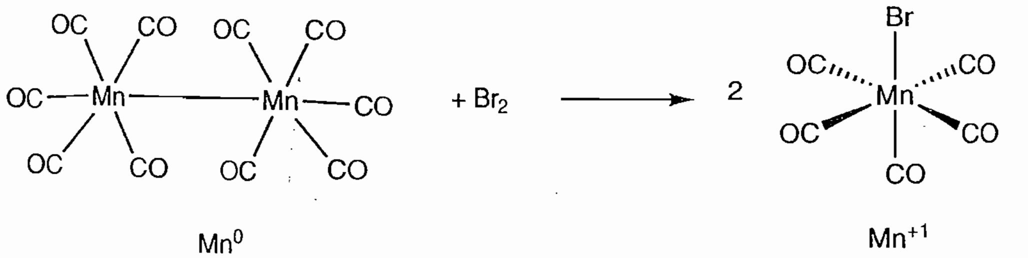
$L = Me_3P$; R = Me, Ph

Though coordinative unsaturation is a general feature of reductive elimination reactions, it may so happen that other factors may dominate in some reactions. For example, some reductive elimination reactions that form C–H bonds are so facile that they do not require prior dissociation of any ligand. The elimination of methane from *cis*-$PtL_2(H)CH_3$ and the elimination of dihydrogen from *cis*-$(Me_3P)_2PtH_2$ occur without prior phosphine dissociation.

Considerable effort has been devoted by theoreticians to understand the entire phenomenon. It is generally agreed that the reductive elimination of *cis* ligands from 4-coordinate d^8 square planar complexes is possible, but the reaction in the corresponding 3 and 5 coordinate complexes is easier. Some unusual facile reductive elimination such as those forming C–H bonds can occur in planar complexes without prior ligand dissociation, as mentioned above. Similarly, although reductive elimination of *cis* ligands from an octahedral complex is possible, it is much easier after the dissociation of a ligand leads to a 5-coordinate species.

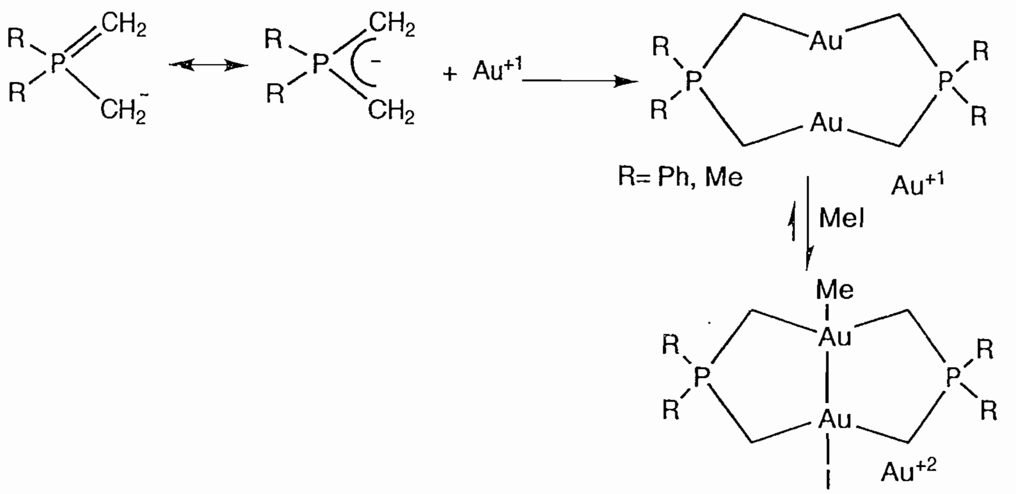
8.2.2 Binuclear Systems

Complexes with two (or more) adjacent metal atoms can also participate in oxidative addition and reductive elimination reactions. This often involves both metal centres and each metal changes its oxidation state by only ±1, instead of ±2 as is the case with complexes possessing single metal centres.



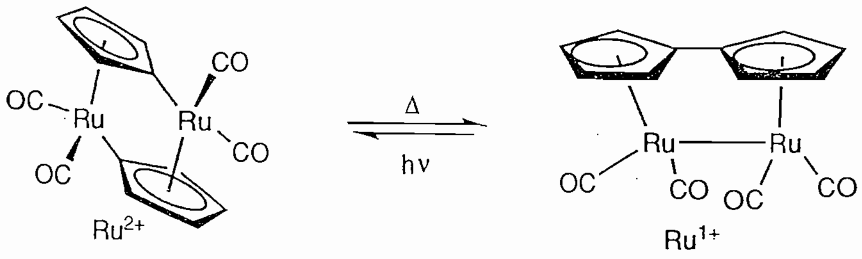
(8.21)

The following reaction shows an oxidative addition on a dinuclear complex in which two metal centres are not joined by a M–M bond (*Organometallics*, 1984, Vol. 3, 821).[31]



(8.22)

The following reaction can be considered as a reductive elimination occurring on two metal centres which are not joined by a metal–metal bond.[32]

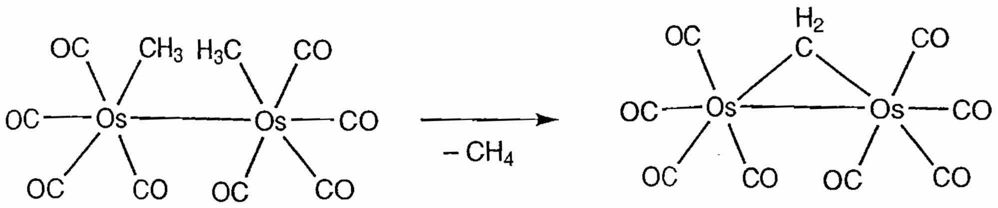


(8.23)

The reductive elimination of two organic ligands from a pair of metals already joined by a bond is comparatively uncommon (Eq. 8.24). It has been pointed out that the reaction is symmetry forbidden, similar to the elimination of dihydrogen from ethane to form ethylene (*Organometallics*, 1984, Vol. 3, 370). Alternative pathways may become dominant in such cases (Eq. 8.25).[33]

$$\overset{R}{M}-\overset{R}{M} \longrightarrow M\equiv M + R-R$$

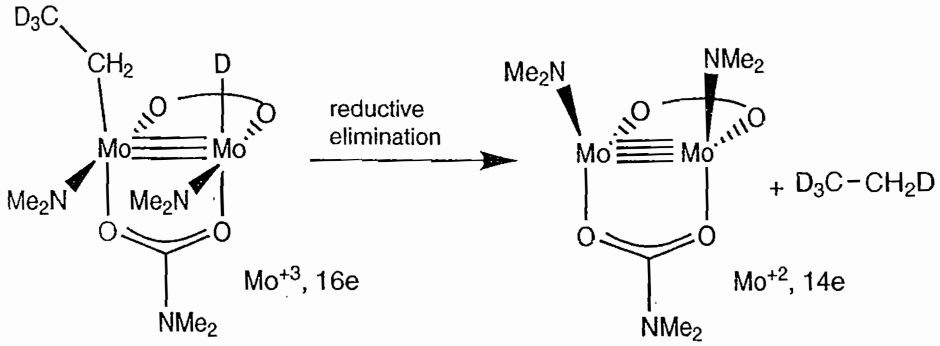
(8.24)



(8.25)

There is some evidence that reductive elimination of R–R is possible especially in metal–metal multiple bonded compounds with leaving groups on adjacent metal units.

The elimination of two organic ligands from two metals not already joined by a bond is much more common than eliminations as in Eq. 8.24. At least one of the ligands eliminated is usually hydrogen.

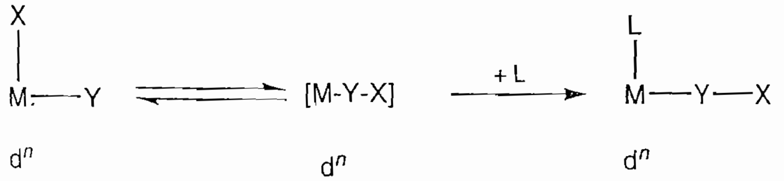


(8.26)

8.3 MIGRATORY INSERTION REACTIONS

Oxidative addition and substitution reactions allow us to assemble 1e or 2e ligands on the metal. With insertion and its reverse reaction, de-insertion or extrusion, these ligands can be combined and transformed within the coordination sphere of the metal. The ligands can then be expelled to obtain the organic products.

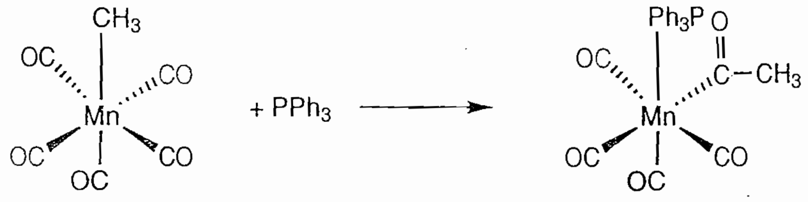
Insertion broadly describes a reaction in which any atom or group is inserted between two other atoms initially bound together. Another ligand L usually occupies the vacant site that is created by the insertion. The incoming ligand L, may be any Lewis base, including the solvent.[34]



$$\underset{d^n}{\overset{X}{M}-Y} \rightleftharpoons \underset{d^n}{[M\text{-}Y\text{-}X]} \xrightarrow{+L} \underset{d^n}{\overset{L}{M}-Y-X}$$

(8.27)

Y = CO, C=C, –C≡C–, arene; X = H, R, Ar, –COR



(8.28)

These *intramolecular* reactions are often referred to as 'migratory insertions' to distinguish them from the *intermolecular* attack of a nucleophile X: on the coordinated ligand M–Y. This is discussed in detail, later in this chapter.

$$\mathrm{M{-}Y} + \overset{\bullet\bullet}{\mathrm{X}} \longrightarrow \mathrm{M{-}Y{-}X}$$

The general features of migratory insertions are specified below.

- A vacant coordination site is generated during a migratory insertion occurring in the forward direction. A trapping ligand is often needed to coordinate to the vacant site in order to stop the reverse reaction from taking place and to regain the initial electron count.
- The groups undergoing migratory insertion must be *cisoidal* to one another. When the *cis* sites are blocked (for example, in tetradentate macrocycles), both the forward as well as the reverse reactions are inhibited.
- There is no change in the formal oxidation state of the metal (unless the inserting group is alkylidene or alkylidyne).
- Migratory insertions are usually favoured on more electron deficient metal centres.
- Between two alkyl groups, the one which is more electron rich makes the better nucleophile for migrating to the electron deficient CO (n-alkyl$^-$ > $PhCH_2^-$).
- Migratory insertion can be brought about by ligands other than CO. Ligands which are better donors are ideal for displacing the alkyl group for migratory insertion (for example, PMe_3 > PPh_3).
- When the migratory ligand 'X' is chiral, the reaction usually proceeds with retention of configuration at that chiral carbon. Racemisation occurs in a few cases because of free radical mechanism.
- Insertions are reversible, but in practice only one direction is observed.
- Cases where X migrates on to Y and where Y inserts into the M–X bond are known.
- The position of equilibrium of the reaction depends upon the strength of the M–X, M–Y and M–(YX) bonds.
- One electron oxidation of the starting complex, X–M–Y, often speeds up the reaction; a Lewis acid can often promote the rate of reaction.

8.3.1 Lewis Acid Acceleration

Experiments by several scientists have clearly established the role of Lewis acids in accelerating the alkyl–carbonyl migratory insertion reactions. This effect is probably related to the ease with which Lewis acids bind with the basic oxygen of the acyl group. It is envisaged that the acceleration occurs because the Lewis acid lowers the activation energy of the reaction by this coordination. An interesting example is the carbonyl insertion in $MeMn(CO)_5$ which occurs with a rate enhancement of 10^8 in the presence of strong Lewis acids such as $AlCl_3$ and $AlBr_3$. Here, one halide on Al fills the vacant coordination site in the acyl complex and the Lewis acid initiates the reaction by coordination to the carbonyl oxygen (*J. Am. Chem. Soc.*, 1979, Vol. 101, 5864).[35, 36]

(8.29)

8.3.2 Redox Acceleration

Rate acceleration as a result of oxidation of the starting alkyl carbonyl complex in migratory insertion has been well studied. The forward rate constant of the equilibrium in the reaction (Eq. 8.30) increases by at least 10^{11} units with 1e oxidation of the metal from Fe(+2) to Fe(+3). A stoichiometric amount of the oxidant converts the reactant to $[(MeCO)CpFe(L)(CH_3CN)]^+$ which is then converted to the product (Eq. 8.30).

$$(Me)Fe(Cp)(CO)(L) + CH_3CN \underset{L = CO,\ PPh_3}{\overset{K_{eq}}{\rightleftharpoons}} (MeCO)Fe(Cp)(CH_3CN)(L) \qquad (8.30)$$

Similarly, the following reaction is catalysed by only a small amount of the oxidising agent; for example, enormous rate enhancement occurs by the addition of a few mole percent of the oxidising agents such as silver ions or ferrocenium ions.[37]

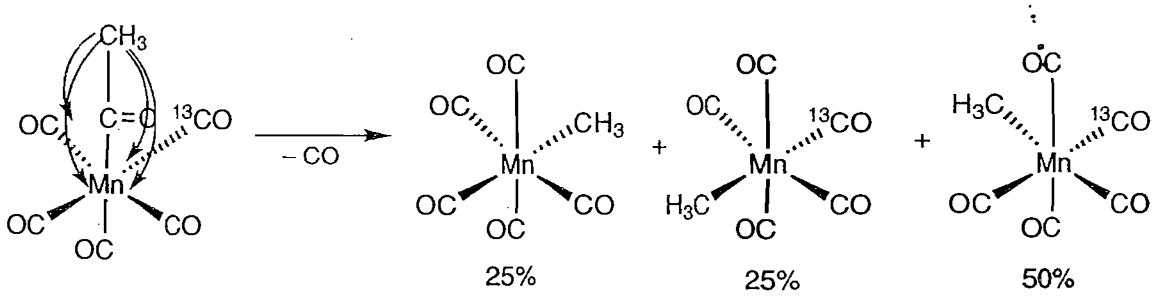
$$MeFe(Cp)(CO)(PPh_3) + CO \xrightarrow[\text{or } Cp_2Fe^+]{Ag^+} (MeCO)Fe(Cp)(CO)(PPh_3) \qquad (8.31)$$

8.3.3 Migration Versus Insertion

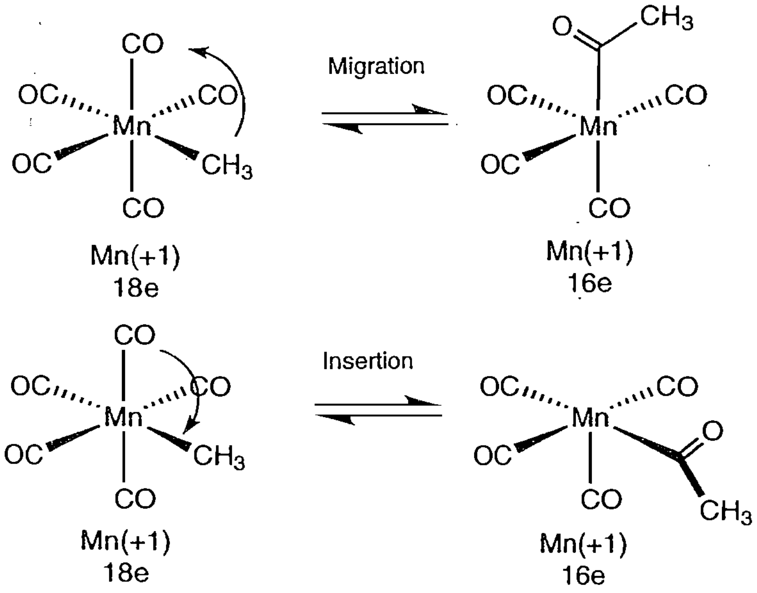
There are two different ways to visualise a migratory insertion. A migration occurs when the anionic ligand moves and performs a nucleophillic-like *intramolecular* attack on the electrophillic neutral ligand. An insertion occurs when the neutral ligand moves and gets inserted into the bond between the metal and the anionic ligand. Both of these pathways are illustrated in Scheme 8.3.

Most systems studied have been shown to undergo migrations and not insertions. The reaction of labelled ^{13}CO and $CH_3Mn(CO)_5$ yields *cis*-$(CH_3CO)Mn(^{13}CO)(CO)_4$ as the sole product. This indicates that the CO molecule that takes part in migratory insertion is not derived from the external (gaseous) ^{13}CO, but from the CO that was already coordinated to Mn. It was also seen that no ^{13}CO was present at the *trans* position of the CH_3CO group which indicates that the CO ligands in the product do not scramble to give a statistical distribution. Additional mechanistic evidence for migration versus insertion was obtained by studying the reverse reaction, that is, decarbonylation of *cis*-$(CH_3CO)Mn(^{13}CO)(CO)_4$. As the mechanisms of the opposing reactions must be the reverse of each other according to the principle of microscopic reversibility, the reverse of CO insertion favours the formation of the products shown in Eq. 8.32.[38]

The CO of the acetyl group has the choice of four *cis* positions into which it may shift by displacing the CO that is already present. One of these sites is occupied by ^{13}CO. Thus it is



(8.32)



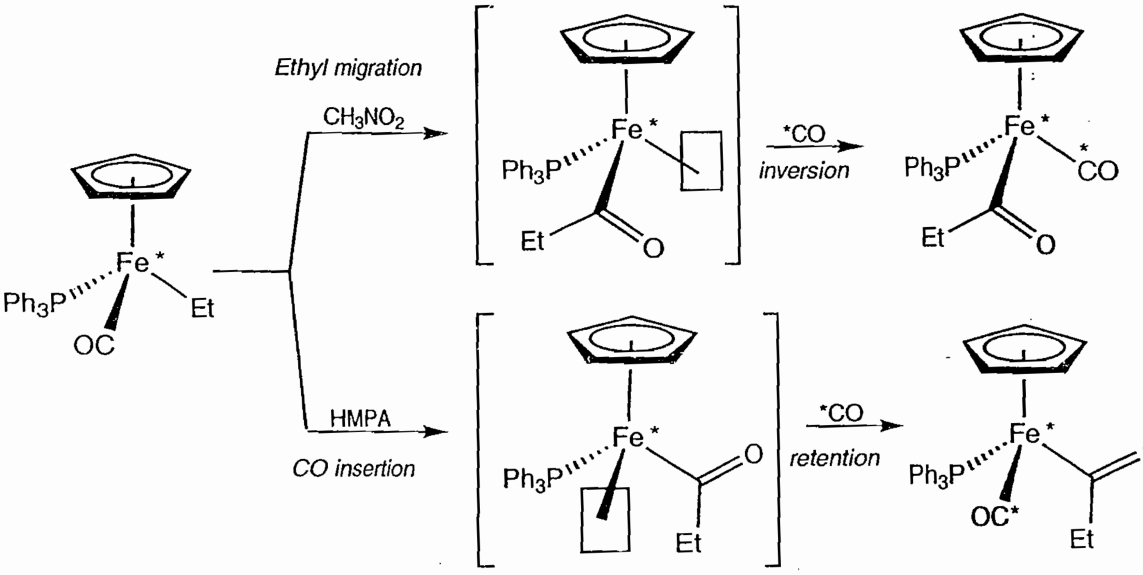
Scheme 8.3 Migration versus insertion

expected that 25% of the product would have no ^{13}CO while 75% would have ^{13}CO *cis* to the methyl. However, the results obtained experimentally were different. 25% of the product had no ^{13}CO, 25% had ^{13}CO *trans* to the methyl and 50% had ^{13}CO *cis* to the methyl. A methyl migration is consistent with these experimental results. As it migrates, the methyl group can displace the ^{13}CO to give a product containing no ^{13}CO (25%); it may displace either of the two CO ligands adjacent to the tagged CO to give the product with CH_3 *cis* to ^{13}CO (50%), or it may displace the CO *trans* to ^{13}CO to give the *trans* product (25%). Thus, when the term CO insertion is used, it often means alkyl migration.

An 'Indian bus' analogy

All the seats in a crowded bus (each seat can accommodate two people) are fully occupied. One of the seats has a mother and child sitting side by side. You enter the bus and would like to occupy a seat. Seeing your woeful look, the child climbs on to the mother's lap and you occupy the seat vacated by the child. This is *migration.* (Note that the mother will not allow you to take the child on your lap and sit next to her and also the only seat available is the one which was vacated by the child.) If the child is an adamant one and refuses to vacate the seat, the mother will be accommodative and move over to the child's seat taking the child in her lap creating a vacant seat which you occupy. This is *insertion.* In Indian buses and migratory insertion reactions, what occurs most often is migration!

The pseduotetrahedral iron complex given in Scheme 8.4 is an interesting system where both alkyl migration and insertion, are very similar in energy and the solvent favours one reaction or the other. In general, one does not bother about the exact pathway and the term *'migratory insertion'* is used to indicate that either directional pathway is fine. The driving force for carbonyl insertion lies in its thermodynamics; an M–C bond is broken and a C–C bond is formed. In addition, a bond is formed between the metal and the incoming L. The major driving force for this reaction seems to be (i) the lesser amount of energy required to break an M–C bond and (ii) the greater amount of energy released when the C–C and M–CO or M–PR_3 bonds are formed. These reactions are enthalpy driven and although the reaction is entropy prohibited (CO is captured and 2 moles of reactants give 1 mole of product) the large enthalpy term is dominant. The enthalpy change for the formation of $(CH_3CO)Mn(CO)_5$ has been calculated as -54 ± 8 kJ/mol. All insertions are not thermodynamically favoured; a reaction of $Mn(CO)_5H$ with CO does not proceed to give $Mn(CO)_5$ (COH) (enthalpy change +20 kJ/mol).[39, 40]

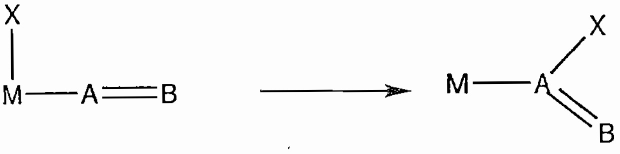


Scheme 8.4 Effect of solvent in deciding migration versus insertion

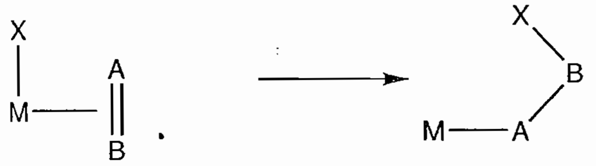
Two different types of insertions can be envisaged for unsaturated ligands like CO and alkenes (Eqs 8.33 and 8.34):

- 1,1-insertion is the type in which the metal and the migrated ligand end up bound to the same atom of the unsaturated ligand, and
- 1,2-insertion is the type in which metal and the migrated ligands end up on adjacent atoms of the unsaturated ligand.

The type of insertion observed in any given case depends on the nature of the 2 electron inserting ligand. For example, CO gives only 1,1-insertion, that is, both M and X end up bound to the carbon atom of CO, while ethylene gives only 1,2-insertion in which M and X end up on adjacent atoms. In general, η^1 ligands tend to favour 1,1-insertion while η^2 ligands tend to favour 1,2-insertion (SO_2 is one of the rare examples of a ligand which can undergo both 1,1- and 1,2- insertion reactions).



1, 1 - migratory insertion (8.33)

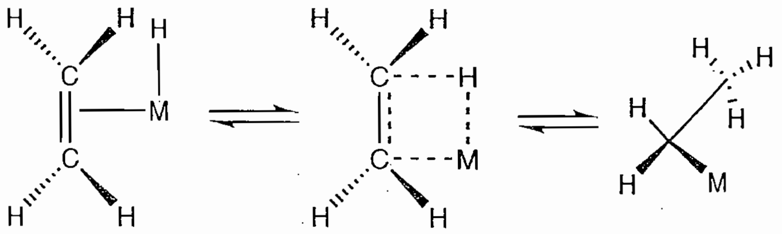


1, 2 - migratory insertion (8.34)

8.3.4 Insertion of Alkenes

The migratory insertion of an alkene into the M–H or M–R bond is one of the important steps in many multistep stoichiometric and catalytic reactions. But migratory insertion of this kind is rarely observed directly. The alkyl–carbonyl migratory insertions, as discussed above, are promoted by Lewis acids and 1e oxidations, but such effects have not been well studied in olefin insertions.

The *intramolecular* insertion of a hydride to the coordinated olefin is an obligatory step in many important reactions like olefin hydrogenation and hydroformylation. A general representation of hydride–olefin insertions is given below.



(8.35)

It is important to keep the following points in mind.

- The hydride is transferred to the β carbon of the alkene to form the metal alkyl complex. The hydride, the metal and the alkene must become coplanar during the reaction, that is, the addition is *cis* and has a four centered transition state as shown in Eq. 8.35.
- The stereochemistry at both carbons is retained since it is *syn* addition.

CO insertion occurs in M–R bonds but not in M–H bonds; alkene insertion on the other hand, is very facile in M–H bonds but it is not so common in an M–R bond. Considering the C–H and C–C bond strengths and the overall thermodynamics of the reaction, it seems that alkyl–olefin migratory insertion may have a larger thermodynamic driving force than hydride–olefin migratory insertion. However, the kinetic barrier to olefin–hydride insertion is much smaller than that for olefin–alkyl insertion. As a consequence, there are a few stable complexes that have the hydride and olefin *cis* to each other, but there are many stable complexes with the alkyl and olefin *cis* to each other. For example, the hydride complex (Fig. 8.1) undergoes rapid intramolecular olefin insertion (this has been proved by isotopic labelling) whereas its methyl or phenyl analogue is stable and does not undergo insertion.[41]

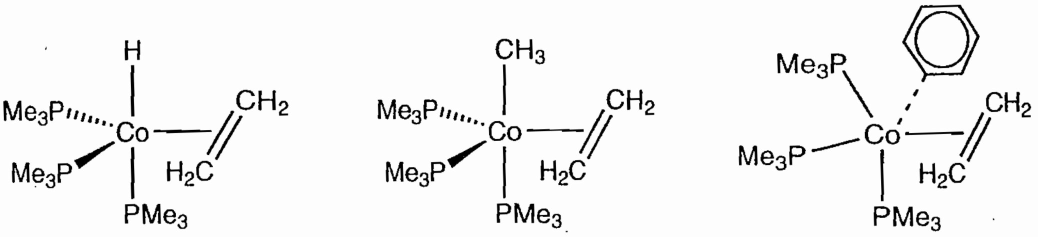


Fig. 8.1 Alkene insertion in M–H bonds

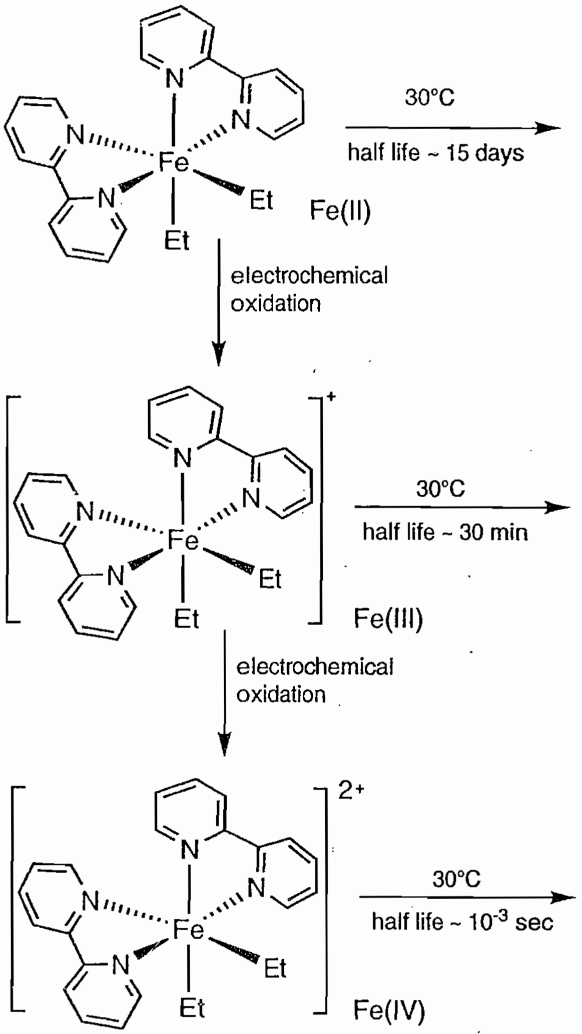
- β-Hydrogen elimination is the reverse of alkene insertion and it represents the chief decomposition pathway of transition metal alkyl complexes (see Chapter 7). Since the forward as well as the backward reactions are quite facile, complexes which contain both the olefin and the hydride (*cis* disposition) are quite rare.
- For many alkenes, the insertion and β-hydride elimination reactions can be considered to be in equilibrium. The position of the equilibrium is decided by the overall thermodynamics of the particular system and it depends strongly on the nature of the alkene. For simple alkenes, the equilibrium lies towards the left (since β-hydrogen elimination is equally important) but for alkenes with electron withdrawing groups like C_2F_4, the alkyl group is particularly stable and the equilibrium lies entirely to the right.

8.3.5 β-Hydrogen Elimination Versus Reductive Elimination

In some metal alkyl complexes, there exists the possibility of both β-hydrogen elimination and/or reductive elimination upon thermal degradation. It is observed that stable organometallic complexes can be made to undergo reductive elimination upon oxidation of the metal. The following example illustrates this point. While β-elimination is the major reaction product of decomposition for the Fe(II) complex, reductive elimination products dominate in the higher oxidation states of the same complex (Eqs 8.36–8.38).[42]

The formation of butene and butane during the thermal degradation of dibutylplatinum complex can be explained based on several cycles of migratory insertions and β-hydrogen eliminations (Scheme 8.5).[43]

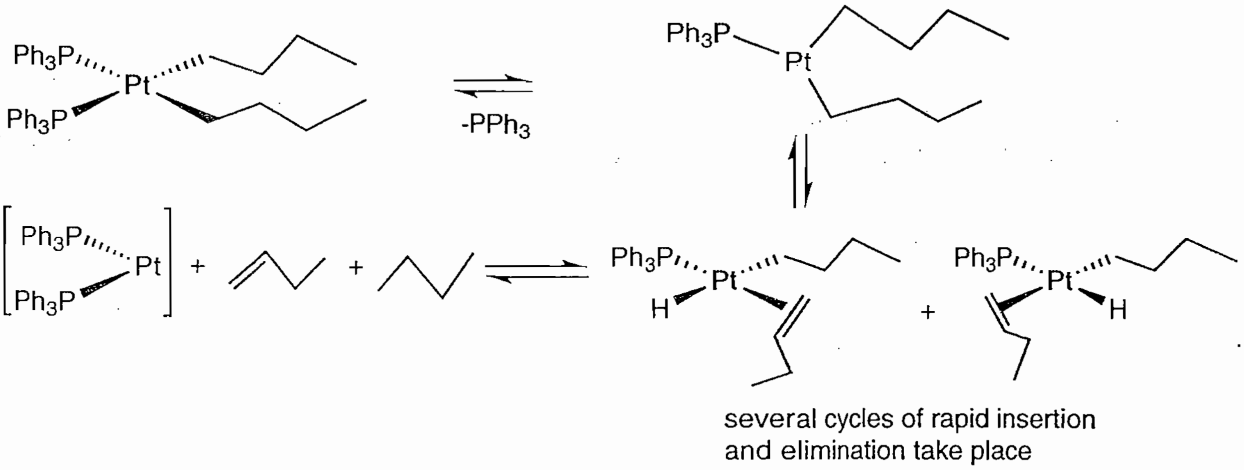
The transfer of a double bond to the end of an alkyl chain, a unique property of Schwartz's reagent is also explained by a series of migratory insertions followed by β-hydrogen eliminations (Scheme 8.6).[44, 45]



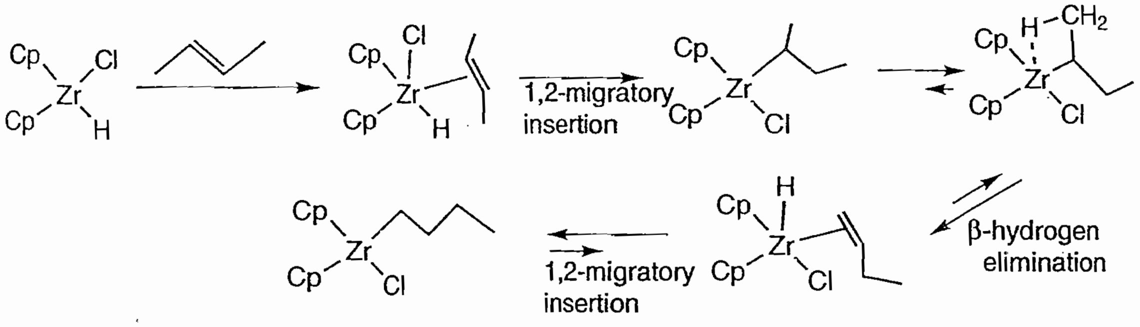
C_2H_6 (major) + C_2H_4 (minor) (8.36)
β-Elimination product

C_2H_6 and C_4H_{10} (major) + C_2H_4 (minor) (8.37)

C_4H_{10} (major) and C_2H_6 (traces) (8.38)
Reductive elimination product



Scheme 8.5 The formation of butene and butane from dibutylplatinum complex



Scheme 8.6 Mechanism of alkene isomerisation using the Schwartz's reagent

Problems and Exercises

8.1. Classify the following reactions as oxidative addition, reductive elimination, migratory insertion, β-elimination, ligand coordination change or simple addition.

(a) $[RhI_3(CO)_2CH_3]^- \rightarrow \{RhI_3(CO)(solvent)[C(O)CH_3]\}^-$

(b) $Co_2(CO)_8 + H_2 \rightarrow 2\,HCo(CO)_4$

(c) $Ir(PPh_2Me)_2(CO)Cl + CF_3I \rightarrow Ir(I)(CF_3)(PPh_2Me)_2(CO)Cl$

(d) $TiCl_4 + 2\,Et_3N \rightarrow TiCl_4(NEt_3)_2$

8.2. Which of the following in each pair will be more reactive towards oxidative addition of dihydrogen?

(a) $[Co(dppe)_2]^+$ or $[Ir\,(dppe)_2]^+$

(b) $Rh(PPh_3)_2Cl$ or $Rh(PPh_3)(CO)Cl$

(c) $IrCl(CO)(PPh_3)_2$ or $RhCl(CO)(PPh_3)_2$

(d) $[P(OMe)_3]_2Ir(CO)Cl$ or $(PMe_3)_2Pt(CO)_2$

8.3. (a) Which among the following compounds will not undergo oxidative addition of methyl iodide? Give reasons.

(i) $Ir(PPh_3)_2(CO)Cl$ (ii) $[RhI_2(CO)_2]^-$ (iii) η^5-$Cp_2Ti(Me)Cl$

(b) Which of the two, Ir(dppe)Cl(CO) and Ir(dmpe)Cl(CO), will react faster with methyl iodide? Justify your answer.

8.4. Against each statement, mark the appropriate type of reaction or reactions from the list (oxidative addition, reductive elimination, migratory insertion and β-H transfer).

(a) *cis* orientation of the participating ligands is a must.

(b) This reaction does not occur for d^0 metal complexes.

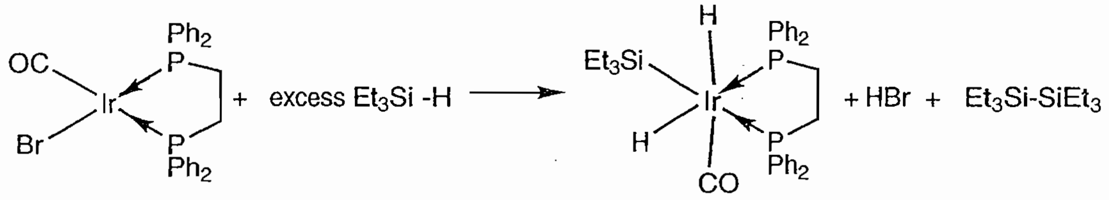
(c) This reaction is enthalpy favoured and entropy prohibited.

(d) A vacant coordination site on the metal centre is a prerequisite.

(e) The more electron rich the metal centre, the more facile is the reaction.

(f) There is an increase in the electron count of the metal complex by two units during this reaction.

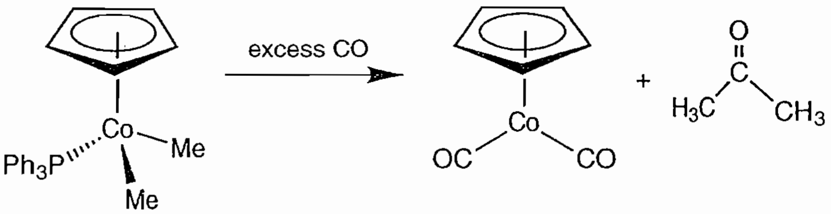
8.5. Using only the oxidative addition and reductive elimination reactions, give a suitable mechanism for the formation of each of the products in the following reaction ($Et_3Si–H$ is weakly polar). (*J. Am. Chem. Soc.*, 1985, Vol. 107, 6531)



8.6. Benzene, on heating with D_2 in the presence of the precatalyst η^5-Cp_2TaH_3, gets converted to monodeuterobenzene and finally to hexadeutero benzene. The reaction involves only oxidative additions (both $C_6H_5–H$ and D–D) and reductive eliminations. Suggest a sequence of reactions for the formation of monodeuterated benzene ($C_6H_5–D$) from benzene. (Hint: the active form of the catalyst is a 16e species.)

8.7. Wilkinsons catalyst, $RhCl(PPh_3)_3$ catalyses the reaction of trimethylsilyl hydride with ethylene to give ethyltrimethylsilane. Show the steps involved and mark the electron count and type of reaction at each step.

8.8. Consider the following reaction:



The most plausible sequence of mechanistic steps for the above reaction is

(a) (i) Loss of PPh_3 (ii) addition of CO (iii) insertion of CO (iv) addition of excess CO along with reductive elimination of acetone.

(b) (i)Addition of CO (ii) loss of PPh_3 (iii) insertion of CO (iv) addition of excess CO along with reductive elimination of acetone.

(c) (i) Addition of CO (ii) insertion of CO (iii) reductive elimination of acetone (iv) addition of CO (v) loss of PPh_3.

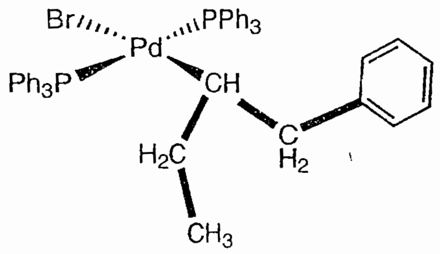
(d) (i) Loss of PPh_3 (ii) addition of CO (iii) addition of CO (iv) reductive elimination of acetone (v) addition of CO.

8.9. Write the reductive elimination product (organic part only) in each of the following. Which one is least likely to undergo reductive elimination?

(a) η^5-$Cp_2Zr(n\text{-}Bu)H$ (b) $(CO)_2I_3Rh(C(O)Me]^-$

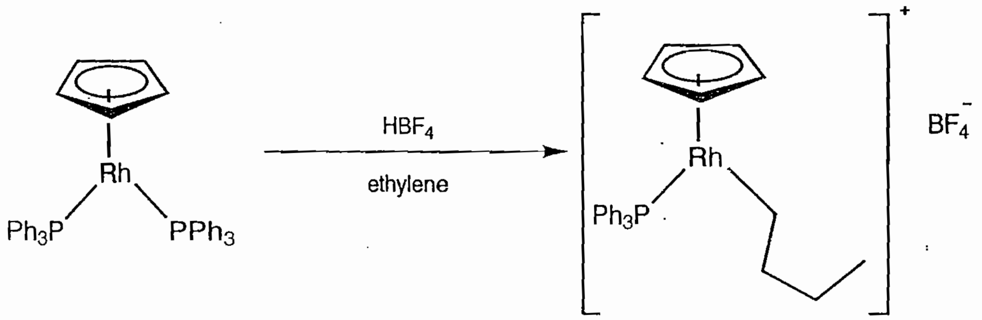
(c) $(PPh_3)_2Pd(Me)H$ (d) η^5-$Cp_2Nb(H)(\eta^2$-$C_2H_4)$

8.10. The given metal–alkyl complex is unstable and undergoes a rearrangement resulting in the formation of two different arylalkene complexes. Predict these structures.

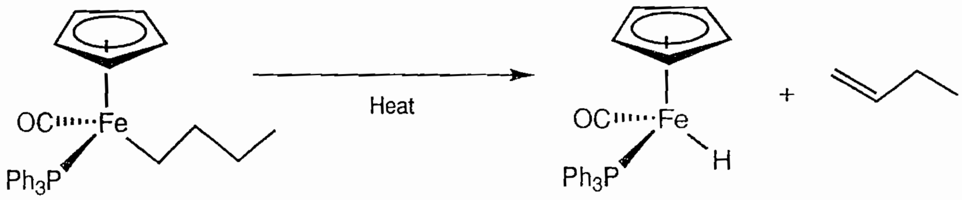


8.11. Write the mechanisms for the following reactions. Indicate the intermediates formed, reagents used and type of reaction occurring at each step.

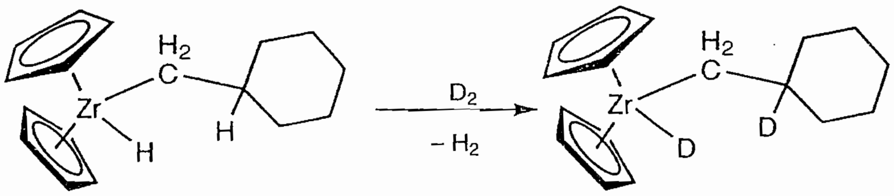
(a)



(b)



(c)



8.12. Write the products in the following reactions. Also write the electron count and the formal oxidation state of the metal in the reactant and the product.

(a) $Ir(PPh_3)_2(CO)(Cl) + CF_3I \longrightarrow$

(b) $\eta^5\text{-}CpRh(CO)_2 + CF_3CF_2I \longrightarrow$

(c) $\eta^5\text{-}Cp_2W(CH_3)(H) \xrightarrow{h\nu} \quad \xrightarrow[\Delta]{\text{benzene}}$

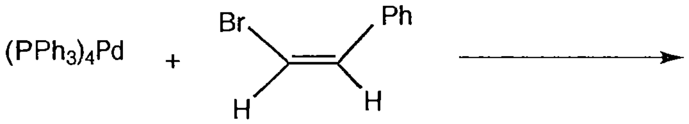
(d) $\eta^5\text{-}Cp(CO)_3Re + Br_2 \longrightarrow$

(e) $(PPh_3)_2Rh(CO)(COCH_2CH_2R) + H_2 \longrightarrow$

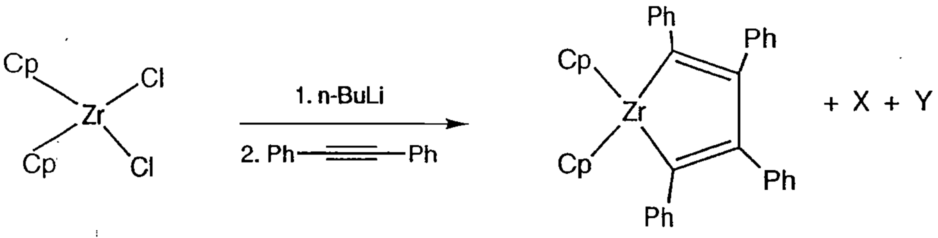
(f) $(PPh_3)_4Pd + PhBr \longrightarrow$

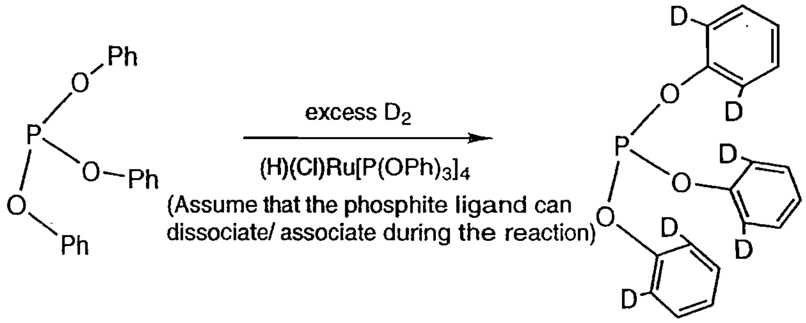
(g) $\eta^5\text{-}Cp(CO)_2Ir + CH_4 \longrightarrow$

(h) $\eta^5\text{-Cp(CO)}_2\text{RuCH}_3 + \text{Br}_2 \longrightarrow$

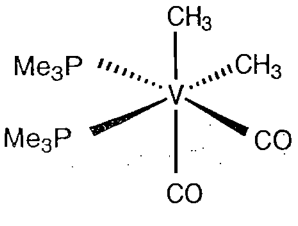
(i)


8.13. Write the mechanism for the following reactions. Indicate intermediates formed and the type of reaction occurring at each step.

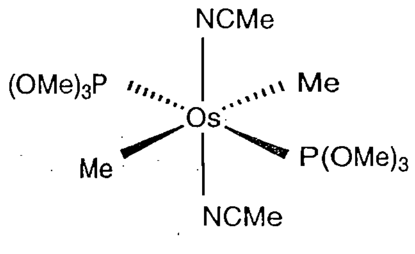




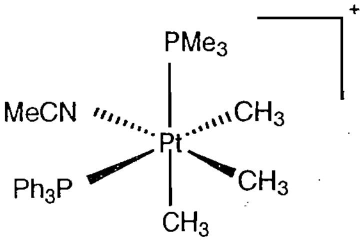
8.14. Which one of the following compounds will be most likely to undergo reductive elimination of ethane and why?



(a)

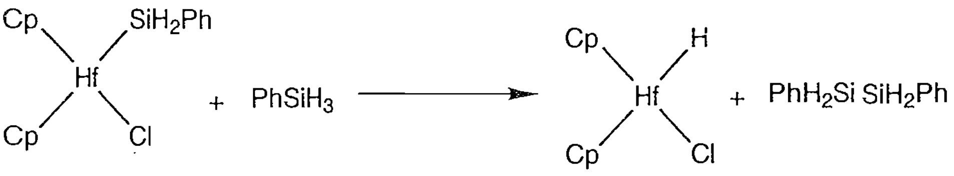


(b)



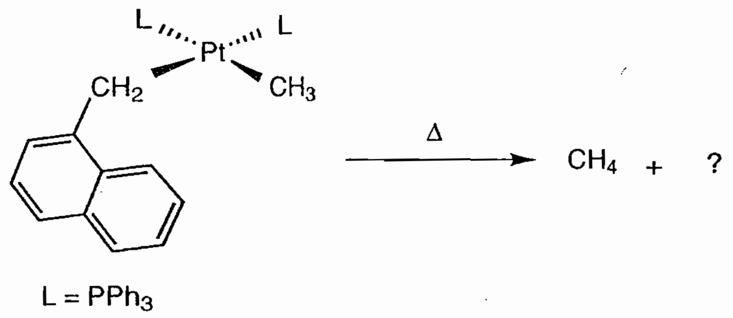
(c)

8.15. Write the possible intermediate in the following transformation.



8.16. The complex $(\text{PPh}_3)_3\text{Rh–Me}$ is cleaved by D_2 and forms methane and $(\text{PPh}_3)_2\text{RhD}[\text{PPh}_2(\text{C}_6\text{H}_4\text{D})]$. Suggest a suitable mechanism for the reaction. (*J. Organometal. Chem.*, 1969, Vol. 19, 161)

8.17. Draw the structure of the missing product in the following reaction.

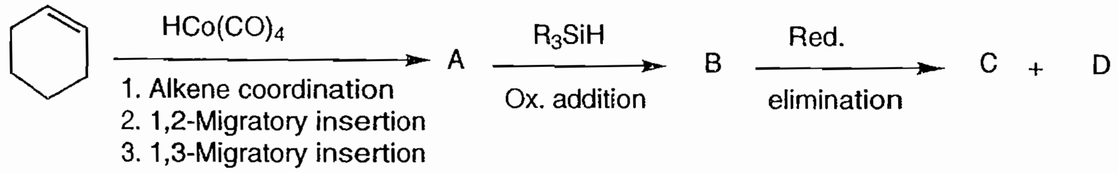


8.18. Write the catalytic cycle for cyclotrimerisation of acetylene using square planar Ni(dppe) $(C_2H_2)_2$ as the active catalyst. The reaction involves ligand additions, reductive elimination, migratory insertion and oxidative coupling (not in this order). If dppe is replaced by dmpe (dimethylphosphinoethane) will it make any difference to the reaction?

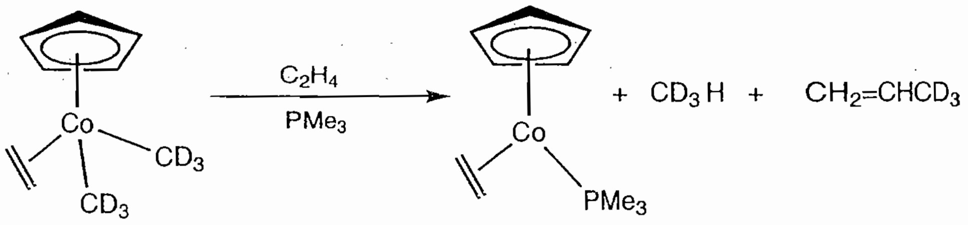
8.19. Write the products A, B and C in the following transformation.

$$\underset{cis}{\mathrm{Pt\,(Et_3P)_2\,(CH_2CMe_3)_2}} \xrightarrow[-\mathrm{L}]{\text{cyclometallation}} \mathrm{A} \xrightarrow[\text{elimination} + \mathrm{L}]{\text{reductive}} \mathrm{B + C}$$

8.20. Write the products A, B, C and D in the following transformations. (*Angew. Chem. Int. Ed.*, 1979, Vol. 18, 837)



8.21. Write the steps involved to explain the formation of products in the following reaction.

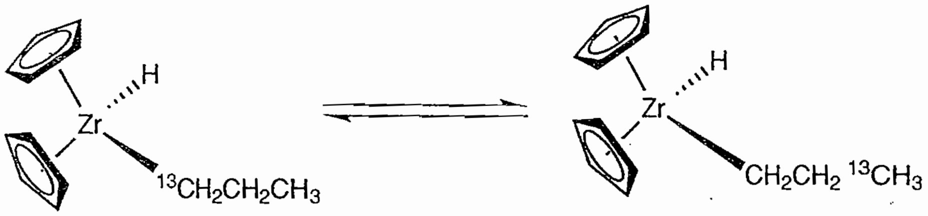


8.22. Draw the structure of A with proper stereochemistry.

(Hint: A shows a prominent band at 1964 cm^{-1} in the infrared spectrum and it can undergo reductive elimination to give a mixture of ethane and H_2.)

$$\mathrm{IrH_3(CO)(dppe)} \xrightarrow{C_2H_4} \mathrm{Ir(C_2H_4)(Et)(CO)(dppe)} \xrightarrow{H_2} \mathrm{A}$$

8.23. Write the mechanism for the following transformation.



8.24. $Os(CO)_5$ and $L_2Os(CO)_3$ (where L is a neutral monodentate non-π acid ligand), both undergo oxidative addition with molecular hydrogen. Which one should react faster and why? (*Adv. Organometal. Chem.*, 1968, Vol. 7, 53)

Supplementary reading

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LIGAND SUBSTITUTION REACTIONS AND FLUXIONALITY IN ORGANOMETALLIC COMPOUNDS

CHAPTER 9

9.1 TYPES OF LIGAND SUBSTITUTION REACTIONS

Many synthetic reactions require the substitution of one ligand by another. Reactions in which coordinated ligands are displaced by other ligands are termed *substitution reactions.* Such a reaction is often the first step and sometimes the rate determining step in many stoichiometric and catalytic reactions of organometallic complexes. In fact 'a site of coordination unsaturation' is perhaps the single most important property of a homogeneous catalyst.

A substitution reaction in organometallic chemistry is one in which an existing ligand on a metal centre is removed and its position gets occupied by another ligand. The way this occurs depends on factors such as the geometry and electron count of the metal complex, the existing ligands on the metal, and their steric and electronic properties. Substitution reactions occur by a combination of ligand addition and ligand dissociation reactions and a range of possibilities exist for such reactions. At one extreme, the departing ligand leaves and a discernible intermediate with a lower coordination number is formed and the mechanism is labelled D (for dissociation) (Fig. 9.1). At the other extreme, the incoming ligand adds to the complex and a discernible intermediate with an increased coordination number is formed and the mechanism is labelled A (for association). A continuum of possibilities stretches between these two extremes; for example, interchange I is used when the incoming ligand is presumed to assist in the reaction but no detectable intermediates appear. When the degree of assistance by the incoming ligand is small, and the reaction is primarily dissociation, it is called dissociative interchange (I_d). When the incoming ligand begins to form a bond with the central metal before the departing ligand bond is weakened appreciably, it is called associative interchange (I_a). Whether or not an organometallic complex is coordinatively saturated, is important in determining the mechanism by which it undergoes ligand substitution. The exact mechanism of ligand substitution – which may occur either by an associative or dissociative route – depends, in large part, on the electron count of the metal complex undergoing the ligand substitution.[1–3]

In 18e coordinatively saturated compounds, substitution often occurs through a dissociative pathway while in coordinatively unsaturated compounds, it often occurs through an associative pathway and sometimes by a dissociative pathway. Most of the substitutions involve 2e pathways. Radical pathways involving odd electrons are also known, but are less common.

9.1.1 Activation Entropy and Activation Volume

Kinetic studies can often provide indications regarding the nature of a reaction—associative, dissociative or interchange. Reaction kinetic studies indicate that reactions having a large negative activation entropy ($\Delta S^{\ddagger}$) and negative activation volume ($\Delta V^{\ddagger}$) are indicative of an associative mechanism while reactions having a large positive $\Delta S^{\ddagger}$ and $\Delta V^{\ddagger}$ indicate a dissociative mechanism. For the interchange mechanisms, $\Delta S^{\ddagger}$ and $\Delta V^{\ddagger}$ should be very small and close to zero. If the reaction rate is dependent on the incoming ligand, it indicates an associative mechanism while no such dependence exists for a dissociative mechanism.[4]

Figure 9.1 clearly depicts all three types of mechanisms. An Eyring plot is usually made after carrying out kinetic studies at different temperatures and from the intercept of the plot, the activation entropy ($\Delta S^{\ddagger}$) can be experimentally determined (Fig. 9.2). Knowledge of the activation volume ($\Delta V^{\ddagger}$) (the difference between the partial molar volumes of the transition state/intermediate and the sum of the partial molar volumes of the reactants at the same temperature and pressure) is important in reactions carried out under high pressure. Those reactions having a large negative $\Delta V^{\ddagger}$ are accelerated by high pressures as the volume of the intermediate/transition state will be smaller than that of the reactants. $\Delta V^{\ddagger}$ is obtained from a plot of ln$k$ versus p.

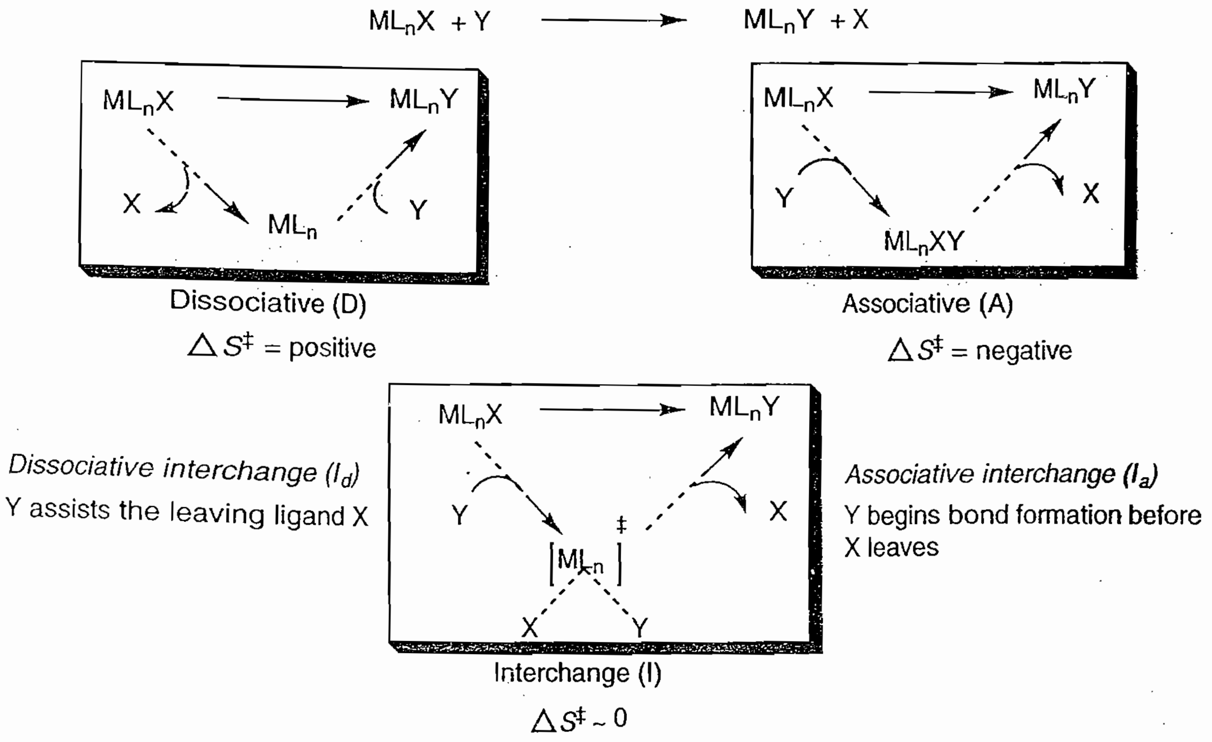
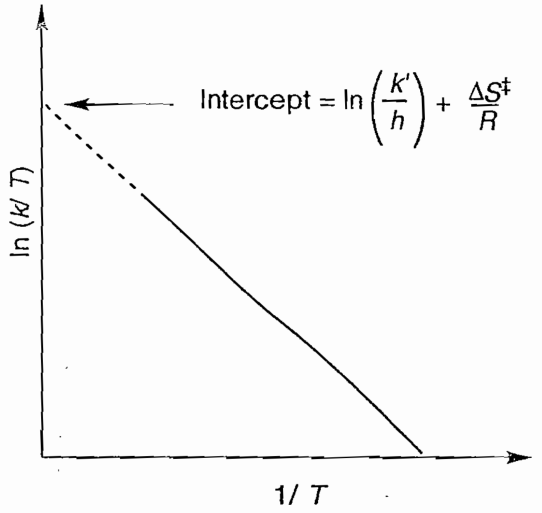


Fig. 9.1 Summary of ligand substitution reactions in organometallic complexes



$$\ln(k/T) = -\frac{\Delta H^{\ddagger}}{RT} + \ln\left(\frac{k'}{h}\right) + \frac{\Delta S^{\ddagger}}{R}$$

k = rate constant
R = molar gas constant
k' = Boltzmann constant
h = Plank's constant
$\Delta H^{\ddagger}$ = enthalpy of activation
$\Delta S^{\ddagger}$ = entropy of activation

Fig. 9.2 Eyring plot for determination of activation entropy

It is observed that 17e complexes undergo ligand substitution reactions much faster (10^3 to 10^7 times) than 18e complexes. For example, $V(CO)_6$ undergoes substitution by PPh_3 at –70°C in 90 minutes while $[V(CO)_6]^-$ does not react even with molten PPh_3. The substitution in $V(CO)_6$ is 10^{17} times faster than in $Cr(CO)_6$. While the 17e $V(CO)_6$ complex undergoes substitution by an associative mechanism, the preferred pathway for $Cr(CO)_6$ at high temperature is dissociative in nature. As a 17e species undergoes ligand substitution at higher rate than an 18e species, the latter can be oxidised to generate a substitutionally labile 17e species.[5–7]

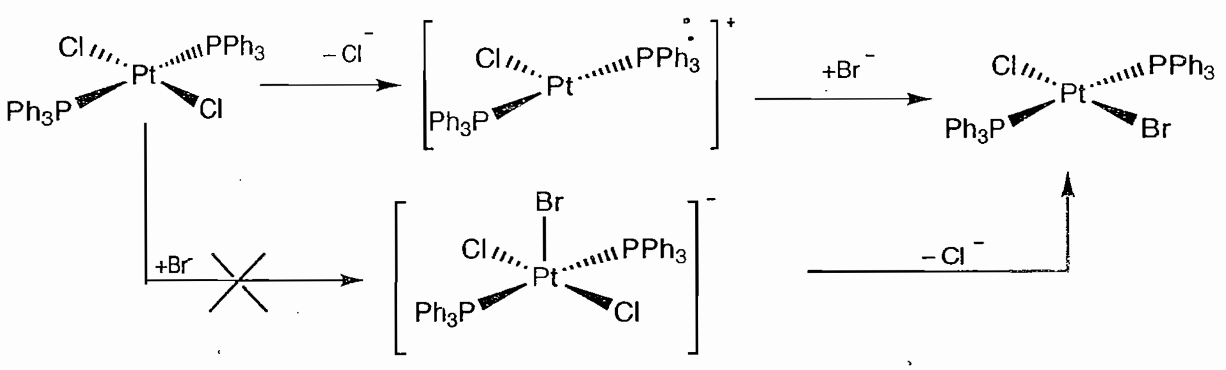
9.1.2 Factors Affecting Substitution Reactions

Steric factors

The dissociative mechanism that is observed in 18e complexes may operate in 16e complexes as well (or in very unusual cases, even in lower electron count systems) when these complexes either have sterically bulky ligands that block an open coordination site, or when they belong to the third row square planar d^8 complexes like Pt (+2), where strong electronic factors limit the coordination of an additional ligand to the empty axial site. For example, the large PCy_3 ligands sterically block access to the empty axial p_z orbital in the nickel complex *trans* $NiCl_2(PCy_3)_2$. In the Pt complex *trans* $PtCl_2(PPh_3)_2$, the coordination of the incoming ligand via the empty p_z orbital is partially blocked by the filled d_{z^2} orbital of Pt. This limits ligand association, although it can logically occur. Hence, the substitution occurs via a 3-coordinate intermediate (Scheme 9.1).[1]

As bulky ligands occupy more space around a metal centre and can block incoming ligands that are trying to access vacant coordination sites on a metal, they often dissociate to relieve the steric strain. Consider, for example, the following equilibrium reaction where the dissociation of bulky phosphites has been found to be more facile.

Dissociation of PPh_3 from many complexes such as $Ni(PPh_3)_4$, $Pd(PPh_3)_4$ and $RhCl(PPh_3)_3$ is well documented in the catalytic cycles involving these catalysts.[8] Replacing PPh_3 by PEt_3



Scheme 9.1 Substitution reactions on square planar platinum complexes

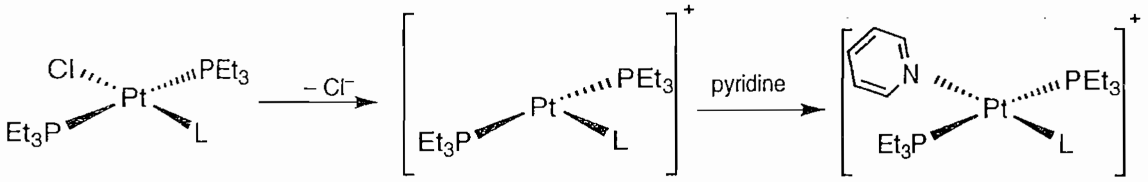
$$\mathrm{Ni(PR_3)_4} \underset{25°\mathrm{C}}{\overset{K_D}{\rightleftharpoons}} \mathrm{Ni(PR_3)_3} + \mathrm{PR_3}$$

PR_3	$P(OEt)_3$	P(O-*p*-tolyl)$_3$	P(O-*i*-Pr)$_3$	P(O-*o*-tolyl)$_3$	PPh_3
Cone angle	109°	128°	130°	141°	145°
K_D (extent of dissociation)	$< 10^{-10}$	6×10^{-10}	2.7×10^{-5}	4×10^{-2}	No data

in Wilkinson's catalyst results in an inactive catalyst as the ligand dissociation becomes very difficult due to the stronger Rh–PEt_3 bond.

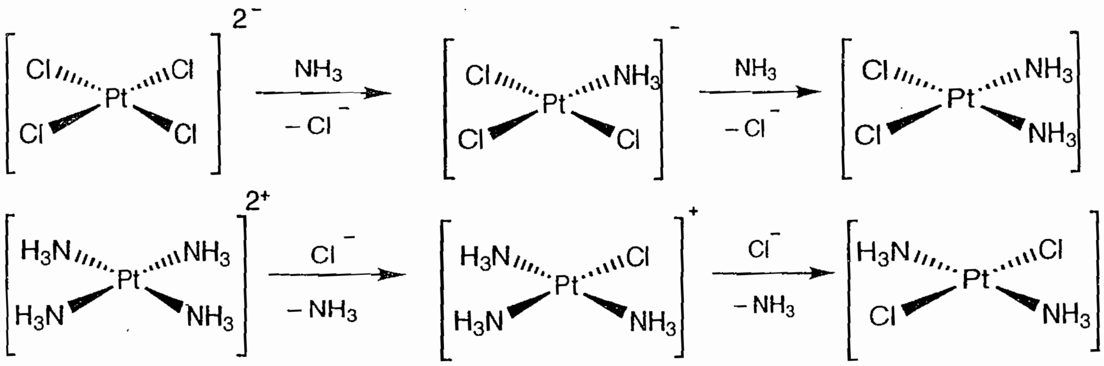
Trans effect

In 1926, the Russian chemist, I I Chernyaev discovered that certain ligands facilitate the substitution of a second ligand *trans* to the first by an external ligand. Ligands that are more effective at this labilisation are said to have a higher *trans* effect.[9] The effect is most marked in the substitution of Pt^{+2} complexes and the highest *trans* effect ligands either form strong σ bonds, as in H^-, Me or $SnCl_3^-$ or strong π bonds as in CO. The *trans* effect concerns the electronic effect of one ligand on the other when they are located *trans* to each other. If it involves two σ-donating ligands, the stronger ligand preferentially weakens the bond of the weaker σ-donor ligand *trans* to it, thus making it easier to dissociate and to bring about a ligand substitution reaction.[10-12]



(9.1)

Relative rate of substitution based on *trans* ligand L:
$Cl^- = 1$, $Ph^- = 100$, $CH_3^- = 10^3$, $H^- = 10^4$



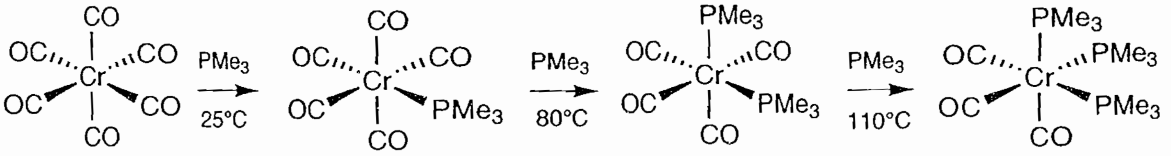
Scheme 9.2 *Trans* effect in the synthesis of cisplatin

The well known example of the *trans* effect is the synthesis of the anticancer drug *cisplatin*. Starting from $PtCl_4^{2-}$, the first NH_3 ligand is added to any of the four equivalent positions at random, but the second NH_3 is added only *cis* to the first one. This happens because Cl^- has a larger *trans* effect than NH_3. If, on the other hand, one starts from $Pt(NH_3)_4^{2+}$, the *trans* substituted product is obtained.[13, 14]

***Trans* effect of π-acceptor ligands**

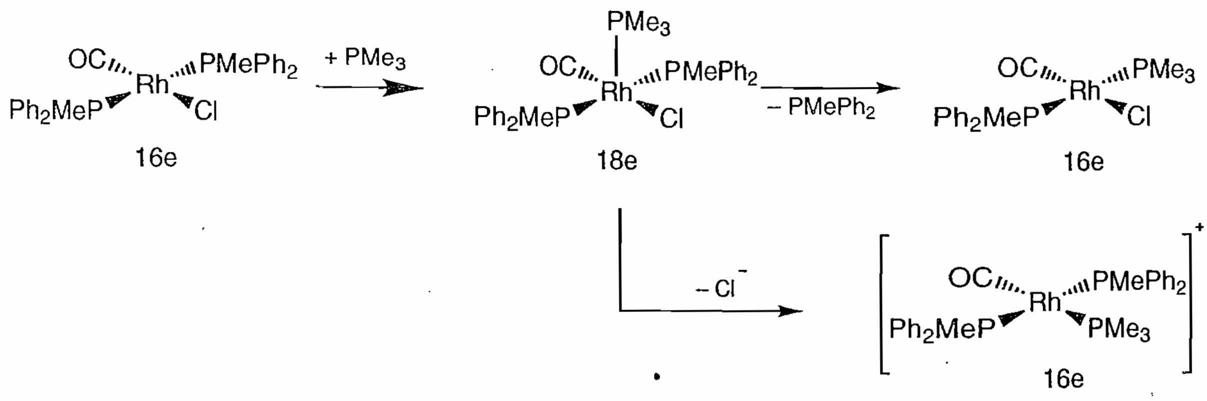
The bond between a π-acceptor ligand and a metal having two or more *d* electrons is weakened when there is another π-acceptor ligand *trans* to it. In metal carbonyls, the competition between the two *trans* π-acceptor ligands for the same *d* electrons reduces the amount of π-backbonding and, therefore, weakens the M–CO bond. Conversely, the M–CO bond is strengthened when the CO is *trans* to a good σ-donating ligand that cannot π-backbond (as in amines). Similarly, the M–CO bond is strengthened when CO is *trans* to any π-donor ligand.

As one CO ligand is replaced with a good σ-donor PMe_3, the next CO substitution becomes progressively more difficult requiring higher temperatures and longer times. Once $Cr(CO)_3(PMe_3)_3$ is formed, it is extremely difficult to replace another carbonyl ligand because the Cr–CO bond strength increases enormously.[15]

 (9.2)

9.2 ASSOCIATIVE SUBSTITUTIONS

In associative substitution reactions, the incoming ligand first adds to the metal complex and then the dissociation of one of the original ligands occurs. An unsaturated (17e or lower) complex is typically required in order to propose such an associative substitution mechanism. Though the axial d_{z^2} orbital can partially block the coordination of ligands using the empty p_z orbital in the third row metals, this does not occur in Rh(I) or Pd(II) and ligand association is common in these complexes. Scheme 9.3 shows associative substitution reactions on square planar rhodium complexes. Two different products are possible in this reaction as Cl^-, being a relatively weak ligand, can get substituted by PMe_3.[16]



Scheme 9.3 Associative substitution reaction on a rhodium complex

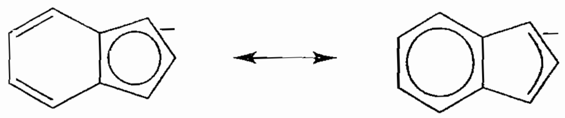
Stereochemistry at the metal centre is often retained. A simple associative substitution follows a second order rate law and a negative entropy of activation is observed (around –10 to –20 eu). Oxidative addition also comes under the associative mechanism as indicated by a negative activation of entropy. For example, the $\Delta S^{\ddagger}$ for oxidative addition of H_2 to Vaska's complex has been determined as –21 eu (1 eu = 1 cal K^{-1} mol^{-1} or 4.184 JK^{-1} mol^{-1}). Associative mechanism is seldom observed for 18e complexes. However if a polyhapto ligand that can adopt a lower hapticity is present, it occurs. The indenyl effect, the fluorenyl effect and the hapticity lowering associated with η^5-pentadienyl as well as η^3-allyl complexes discussed below clearly indicate the way in which an 18e complex undergoes ligand substitution by an associative mechanism.

9.2.1 Hapticity Change in Multidentate Ligands

A factor which often influences associative substitution reactions in organometallic complexes is the hapticity change in multidentate ligands. Multidentate ligands (those which donate more than 2e and occupy more than one coordination site on a metal) can often change their coordination number to donate fewer electrons (rather than their full capability), thus opening up a coordination site that can allow an associative substitution (or just ligand addition). The Cp ligand can do this by shifting its hapticity from η^5 to η^3 (or even η^1). But this shifting incurs a moderately high cost in energy due to the loss of aromaticity in the Cp ring. Such hapticity changes are not that common for Cp.

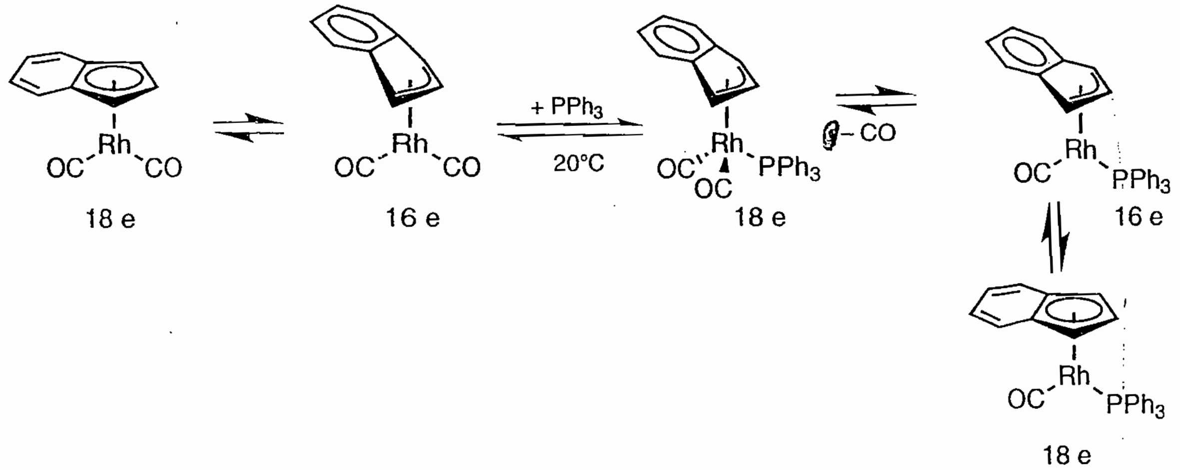
Indenyl and fluorenyl effects

The indenyl ligand family, however, dramatically enhances the rate of substitution reactions due to its ability to switch the aromaticity between the Cp and the arene ring via the following resonance structures. This dramatically lowers the barrier for the η^5 to η^3 shift, thus opening up a free coordination site and allowing easier ligand additions and substitution reactions.[17]



indenyl aromaticity switch

The reaction given in the Scheme 9.4 which proceeds by an associative mechanism is 10^8 times faster than the reaction of the analogous complex possessing only the Cp.

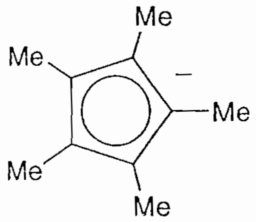
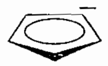
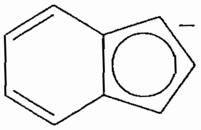
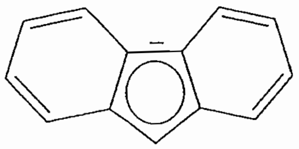


Scheme 9.4 Indenyl hapticity change in associative substitution reactions

A reaction of η^5-CpMn(CO)$_3$ with PPh$_3$ when attempted for 3 days in decalin at 140°C did not proceed. However, the analogous indenyl complex (η^5-C$_9$H$_7$)Mn(CO)$_3$ under identical reaction conditions yielded Mn(η^5-C$_9$H$_7$)(CO)$_2$(PPh$_3$).[18]

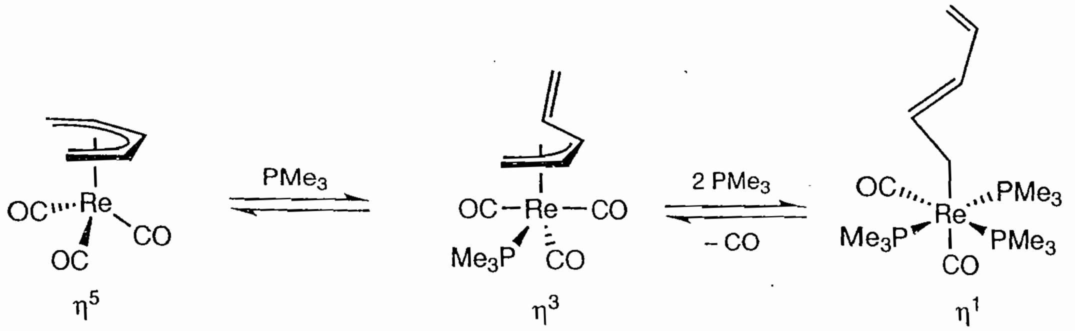
Extending this study to similar ligands (Table 9.1) indicated that the fluorenyl ligand accelerates the ligand substitution reaction by a factor of over 10^{10}. Although the indenyl effect should theoretically generate better catalysts due to its ability to readily open up free coordination sites on the metal, it unfortunately also makes the indenyl ligand considerably easier to be displaced from the metal.

Table 9.1 Comparison of cyclopentadienyl and related ligands for ligand substitution on Mn(η^5–L)(CO)$_3$ complexes

Ligand	Cp*	Cp	Indenyl	Fluorenyl
				
Relative rate of substitution	2.2×10^{-2}	1	3.8×10^{8}	$> 10^{10}$

Hapticity change in the pentadienyl ligand

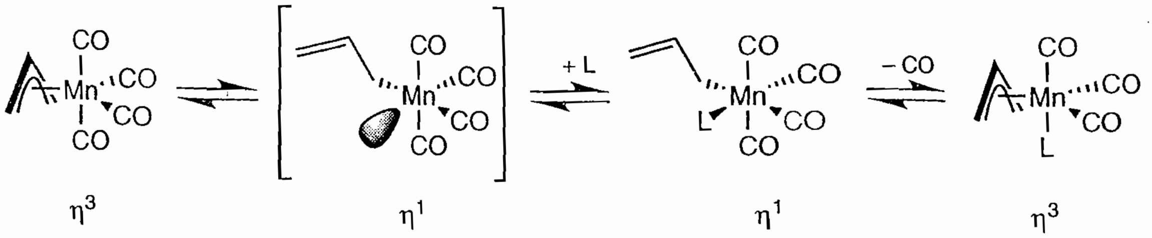
The pentadienyl ligand is an acyclic version of Cp^- that does not have any aromatic stabilisation. This has two important effects (i) no aromatic stabilisation means that the π-orbitals are higher in energy and are, therefore, better donors than Cp^- and the barrier for η^5 to η^3 and to η^1 coordination is of much smaller energy, and (ii) π^*-antibonding orbitals are lower in energy and are better π-acceptors than Cp^- (but the low electronegativity limits the amount of π-backbonding that can occur).[19]



(9.3)

Hapticity change in the allyl ligand

The allyl anion has a similar facile ability to switch between the η^1 and η^3 coordination modes that can promote ligand additions and/or substitutions.[20]

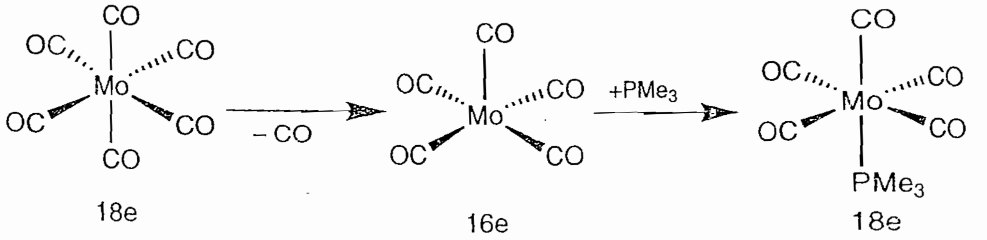


(9.4)

Similarly the nitrosyl, NO, can also shift between linear and bent geometries to allow an incoming ligand to bind to a metal centre.

9.3 DISSOCIATIVE SUBSTITUTIONS

Dissociative substitution is the commonly preferred mechanism of ligand substitution for coordinatively saturated 18e complexes which do not posses ligands capable of easy hapticity change. 18e octahedral metal complexes invariably have a dissociative substitution pathway; one of the existing ligands on the metal falls off to create a free coordination site to which the new ligand can coordinate. Dissociative substitution reactions usually have positive activation entropy. Examples of both retention as well as inversion are known for dissociative substitution reactions. Dissociation of ligands also depends upon steric effects.



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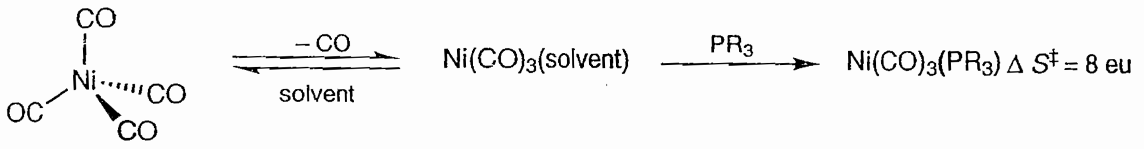
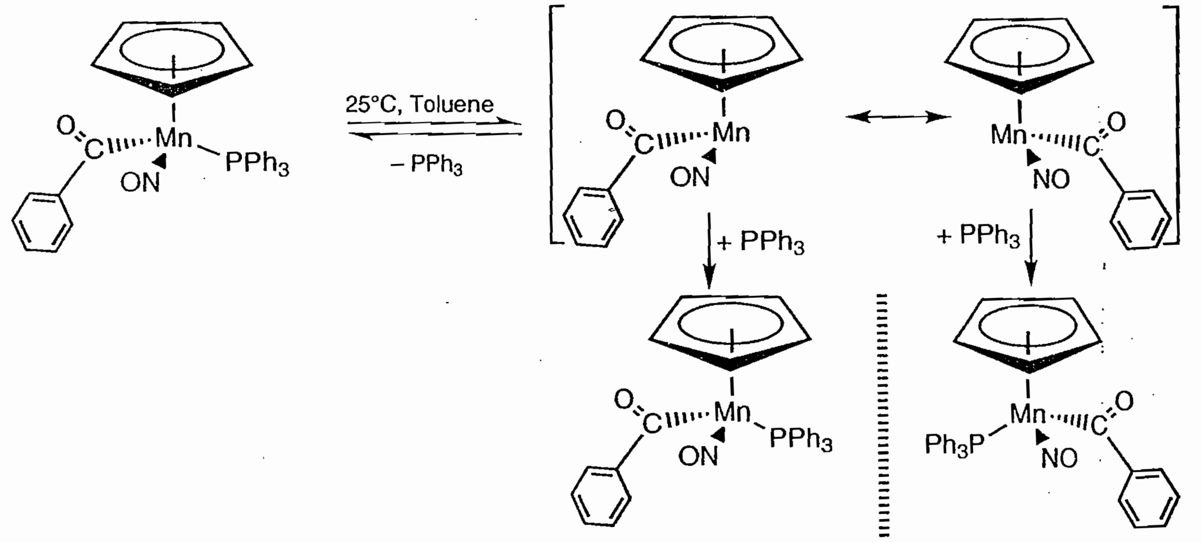


(9.6)

Racemisation of chiral organometallic complexes occurs by a dissociative mechanism. In the following example, the loss of a phosphine gives a tricoordinate fluxional intermediate which can give rise to both the enantiomers upon reattachment of the phosphine.[21]



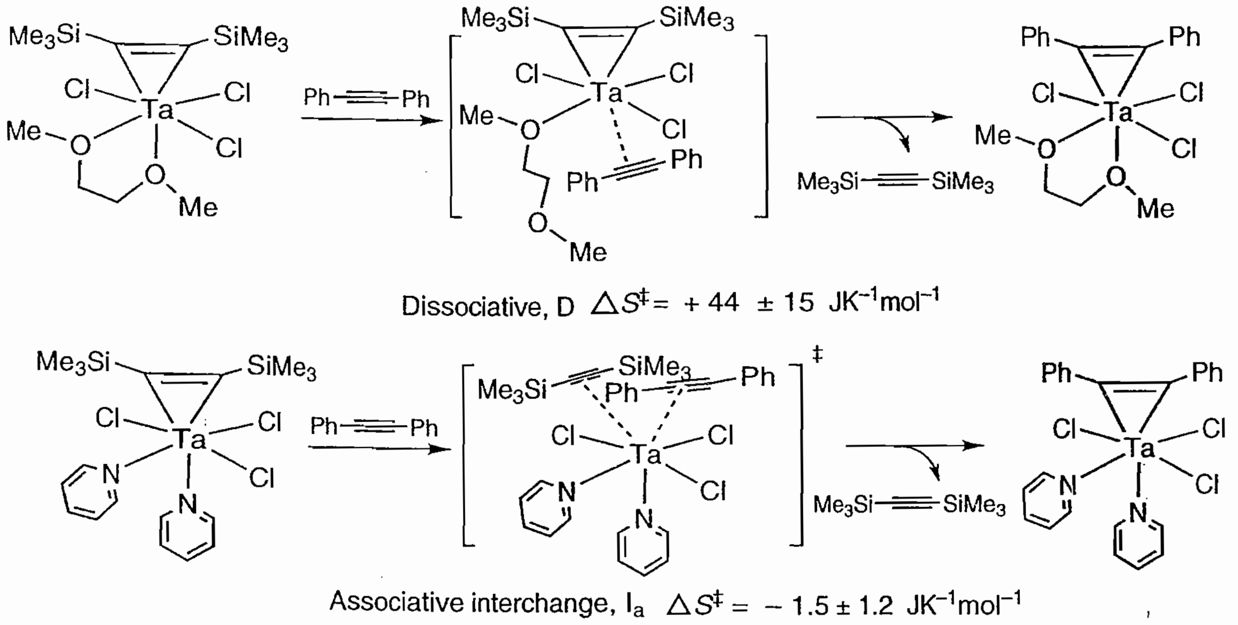
Scheme 9.5 Racemisation of chiral organometallic complexes by D mechanism

9.4 INTERCHANGE MECHANISMS

Dissociative and associative interchange mechanisms are observed in the substitution reactions of organometallic complexes but not very frequently. It has been observed that the formation of a 20e intermediate in a reaction is unlikely but a 20e transition state seems possible. Unlike an intermediate which is described as a species which has to survive as an independent entity, often briefly, a transition state has a much shorter lifetime which is comparable to that of a molecular vibration (about 10^{-13} s). Such transition states are common in interchange mechanisms. Detailed kinetic studies and careful determination of activation entropies are required to differentiate between I_a, I_d and A, D mechanisms. Often slight variations in the steric and electronic effects of ligands on a metal complex result in a change of dissociative or associative mechanism to an interchange mechanism.

9.4.1 Associative Interchange

In the tantalum complex when the dme ligand is replaced with two pyridines, the mechanism changes from dissociative to associative interchange (I_a).[22]



Dissociative, D $\Delta S^{\ddagger} = +44 \pm 15\ \mathrm{JK^{-1}mol^{-1}}$

Associative interchange, I_a $\Delta S^{\ddagger} = -1.5 \pm 1.2\ \mathrm{JK^{-1}mol^{-1}}$

Scheme 9.6 Associative interchange mechanism of tantalum alkyne complex

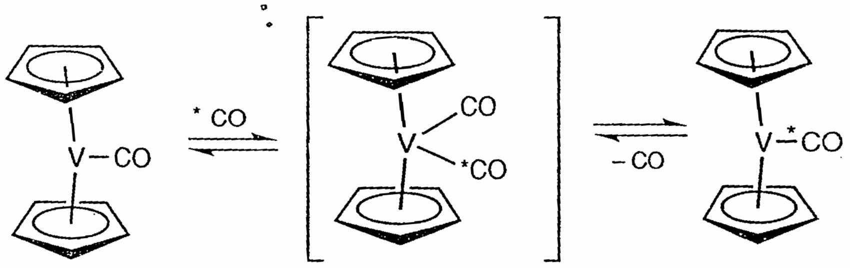
9.4.2 Dissociative Interchange

In the 17 electron vanadium complexes shown in Scheme 9.7, changing the cyclopentadienyl ligands to pentadienyl ligands result in a change from the associative (A) to dissociative interchange (I_d) mechanism as indicated by the activation entropy values.[23]

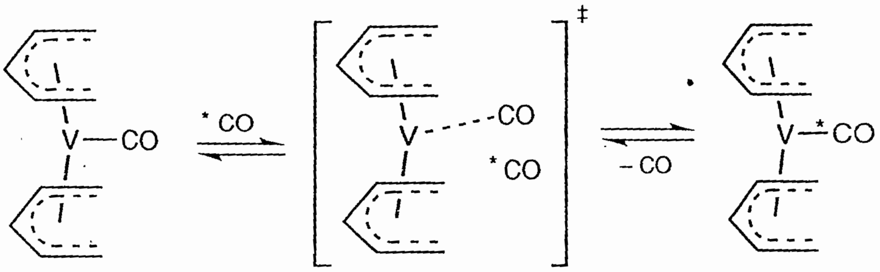
9.5 STEREOCHEMICAL NON-RIGIDITY IN ORGANOMETALLIC COMPLEXES

Although most molecules have a single well defined nuclear configuration and can be considered as rigid, their atoms experience harmonic vibrations about their equilibrium positions. In many cases, molecular vibrations or intramolecular rearrangements carry a molecule from one nuclear configuration into another. The molecule is designated as stereochemically non-rigid when such processes occur at a rate that can be detected by physical or chemical methods. When two or more configurations are chemically non-equivalent, the process of interconversion is called *isomerisation* or *tautomerisation*. However, when such configurations are equivalent then this type of stereochemically non-rigid molecule is referred to as *fluxional* and the process is called *fluxionality.*

NMR spectroscopy most often reveals the occurrence of stereochemical non-rigidity. Therefore, many a time, the term fluxionality is used for all molecules that undergo intramolecular rearrangements rapidily enough to influence NMR line shapes at temperatures within the practical range of an experiment. Why only NMR? The activation energy of these processes falls in the range 25–100 kJ/mol. Therefore, the rate of rearrangement can be brought to the NMR time scale (10^{-2} to 10^{-5} sec) by varying the temperature between +150 and –150°C. The process of fluxionality becomes slower at low temperatures and faster at higher temperatures.[24a]



Associative, A $\Delta S^{\ddagger} = -30$ cal $K^{-1}mol^{-1}$



Dissociative interchange, I_d $\Delta S^{\ddagger} = +2$ cal $K^{-1}mol^{-1}$

Scheme 9.7 Dissociative interchange mechanism of vanadium pentadiene complex

A common type of fluxional behaviour is the inversion of pyramidal molecules. In the case of NH_3 and simple non-cyclic amines, the activation energies, which are equal to the difference between the energies of the pyramidal ground configurations and planar transition states, are quite low (24–30 kJ/mol) and the rate of inversion is very high (for example, 2.4×10^{10} s^{-1} for NH_3). Four-coordinate complexes tend to be rigid but fluxional behaviour based on planar/tetrahedral interconversion is of considerable importance in transition metal complexes. This is especially true for Ni (II) complexes, where planar complexes of the type $Ni(PR_3)_2X_2$ have been shown to undergo square planar to tetrahedral rearrangement with activation energies of about 45 kJ/mol and at rates of $\sim 10^5$ s^{-1} at room temperature and higher temperatures.[24b]

Fluxionality is very common in 5-coordinate trigonal bipyramidal (TBP) complexes of the type AB_5 when all the ligands appended to the central atom are identical with the symmetry of the molecule being D_{3h}. In TBP, the two apical groups are equivalent but these are different from three equatorial groups that are equivalent among themselves. Therefore, the NMR spectrum should indicate the presence of two sets of signals in the intensity ratio 2:3. However, in many cases such as the ^{13}C spectrum of $Fe(CO)_5$ and the ^{19}F spectrum of PF_5, all the five B groups appear to be equivalent as indicated by a single resonance even at low temperatures although the TBP structure is confirmed by other studies like diffraction and vibrational spectroscopy. The phenomenon TBP–SPy–TBP interconversion (SPy = square pyramid) has been explained by Berry pseudorotation or turnstile rotation. NMR cannot differentiate between these two processes but theoretical studies on PF_5 and related species favour Berry pseudorotation.

9.5.1 Ring Whizzing of η^1-Cp Complexes

There is a second type of fluxionality that takes place irrespective of the coordination number. This is observed when two or more ligands of the same intrinsic identity are not bound to a metal atom in the same way. Two organo-ligands of the same kind may be bound in different ways, one having a higher hapticity than the other. $(\eta^1\text{-Cp})(\eta^5\text{-Cp})Fe(CO)_2$ was the first organometallic compound for which this phenomenon was studied (Fig. 9.3). The two Cp rings display different bonding modes and the expected structure based on the 18e rule is as follows. The IR data supports this structure.[25]

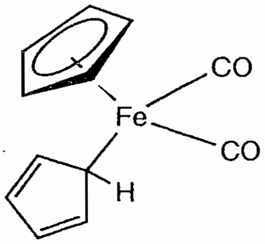


Fig. 9.3 Structure of $(\eta^1\text{-Cp})(\eta^5\text{-Cp})Fe(CO)_2$

The expected ^{1}H NMR spectrum at ambient temperature should show a singlet for η^5-Cp in the range δ 3.0–5.0 ppm, an AA′BB′ multiplet for the olefinic protons with a relative intensity of 4 in the range δ 6.0–6.2 ppm and a singlet of relative intensity 1, at a lower δ value for the C1 proton (Fig. 9.4). All the three separate resonances are observed in the low temperature NMR (–80°C) but surprisingly, the actual spectrum at ambient temperature consists of two singlets of almost equal intensity. The spectra have been explained invoking fluxionality and it was proposed that the iron atom migrates around η^1-Cp ring at a rate sufficient enough to average out all the proton resonances in the η^1-Cp. Such cyclopentadienyl rings have been termed as *ring whizzers*.

The solution NMR of this compound recorded between –80°C and +30°C gave more information.

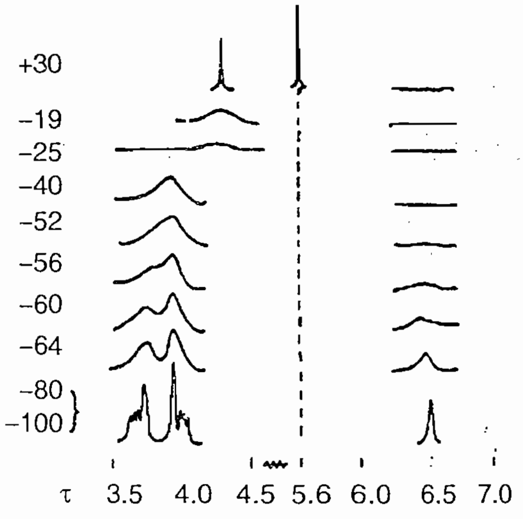


Fig. 9.4 Variable temperature ^{1}H-NMR spectrum of $(\eta^1\text{-Cp})(\eta^5\text{-Cp})Fe(CO)_2$ in CS_2 [The dotted line represents the position of the η^5-Cp protons. The amplitude of the spectrum at +30°C is shown × 0.1 relative to others. The chemical shift is given in τ values (10–δ). (The figure has been reproduced with permission from *J. Am. Chem. Soc.*, 1966, Vol. 88, 4371, copyright 1966, American Chemical Society).]

- At a low temperature of −80°C, a typical $AA'BB'$ multiplet spectrum for four protons of η^1-Cp was observed. As the temperature was raised, the lines collapsed to a singlet.
- The downfield part of the multiplet centred at δ 6.2 (τ 3.8) broadened faster than the other as the temperature was increased.
- However, the singlet due to the η^5-Cp did not change during this temperature change.

Based on these observations, all processes that cause random exchange, that is, dissociation and recombination, were discounted and were not considered. Two possible rearrangements, namely, the 1, 2 or 1, 3 shifts, were considered to explain the experimental data (Fig. 9.5).

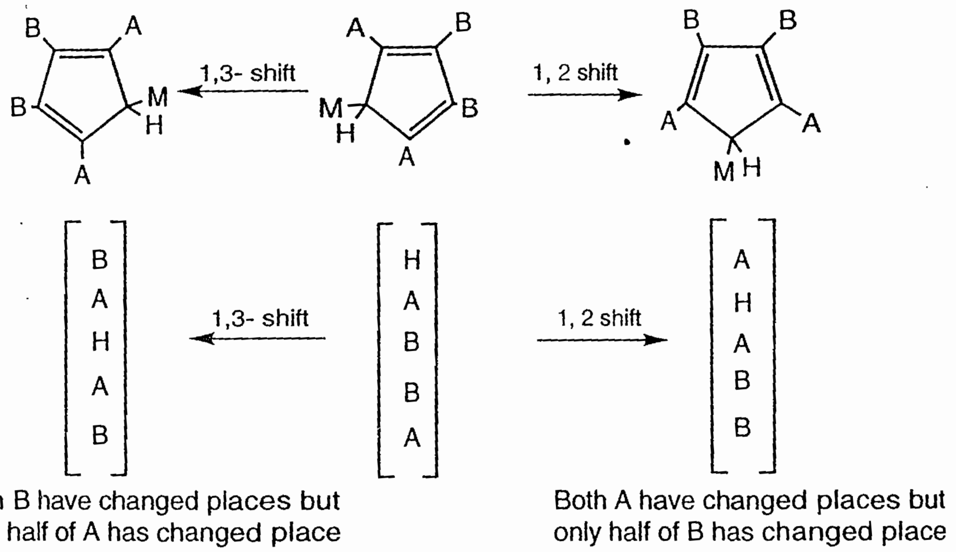
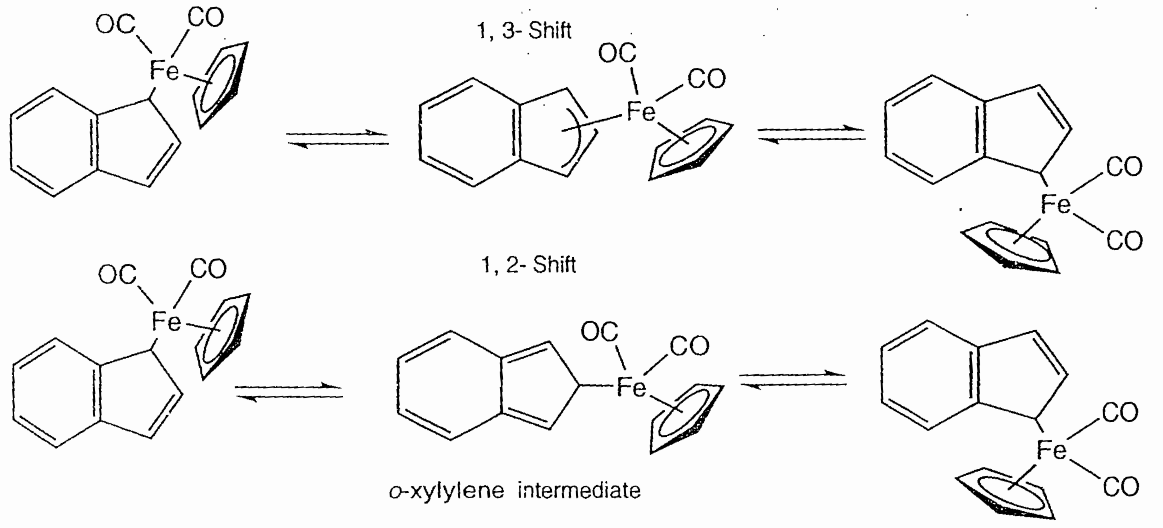


Fig. 9.5 Expected changes in the olefinic protons during 1,2 and 1,3 shifts

This means that irrespective of the mechanism (1,2 or 1,3), only half of the olefinic protons have a higher residence time than the other half in each case. Therefore, the precise mechanism cannot be easily arrived at. The following example using a related complex having an indenyl ligand has provided stronger evidence for the mechanism. The two hypothetical possibilities are shown below.[26]



Scheme 9.8 Mechanism involving 1,2 and 1,3 shifts on an indenyl complex

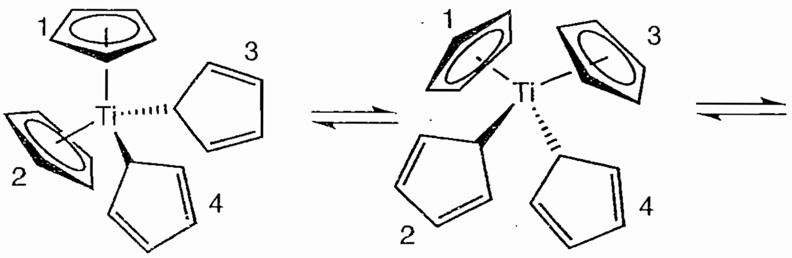
Two lines of argument were used to rationalise the exact mechanism.

- The indenyl system could rearrange quite rapidly if a direct 1,3 shift occurs possibly via a η^3-allyl intermediate or transition state.
- A direct 1,2 shift would be suppressed in the indenyl system as the molecule will have to go via a high energy *o*-xylylene intermediate.

Therefore, if the molecule shows fluxionality, it would mean that the 1,3 process is the preferred pathway while its absence would indicate a 1,2 shift. Using spectral studies, the molecule was found to be non-fluxional in nature. Based on this data and coupled with information on many other examples, the 1,2 shift is a generally accepted pathway for fluxionality in η^1-C_5H_5 and related η^1-five membered rings. For homologous (η^1-C_7H_7)M systems, both 1,2 and 1,3 shifts are observed depending upon M and the associated ligands.

9.5.2 Interchange of η^1- and η^5-Cp Rings

There are compounds in which Cp ligands exchange their modes of bonding and an interchange between η^1 and η^5-Cp rings has been observed. The classic example is $(\eta^1\text{-Cp})_2(\eta^5\text{-Cp})_2\text{Ti}$.[27, 28]



(9.7)

The ^{1}H NMR spectrum of this compound shows two sharp singlets at δ 5.9 and 5.2 at −27°C. Each peak broadens at +26°C and one sharp singlet is observed at +62°C. This means that at −27°C, the η^1-Cps undergo ring whizzing due to which all the protons become equivalent and a singlet is observed. η^5-Cp gives a singlet anyway. Therefore, the spectrum is justified. However, a singlet at a higher temperature, 62°C, means that the η^1 and η^5-Cp rings are also exchanging positions fast. The corresponding Mo complex, $(\eta^1\text{-Cp})_2(\eta^5\text{-Cp})_2\text{Mo}$, however, does not show any such exchange between the two types of Cp rings.

Theoretical calculations have been used to study the mechanism of all fluxional processes of the Cp ligand in a molybdenum bis(imido) complex, $[\text{Mo}(\eta^5\text{-Cp})(\eta^1\text{-Cp})(\text{N}t\text{-Bu})_2]$. The mechanism obtained for metallotropic migration along the ring carbons of η^1-Cp corresponded to a [1,2]-migration which was in agreement with experimental NMR studies. The mechanism for interchange between the two Cp ligands, η^1-Cp and η^5-Cp corresponded to a single-step path, and the calculated activation energy (15 kcal/mol) matched the experimental value. No η^3-Cp intermediates could be found in any process.

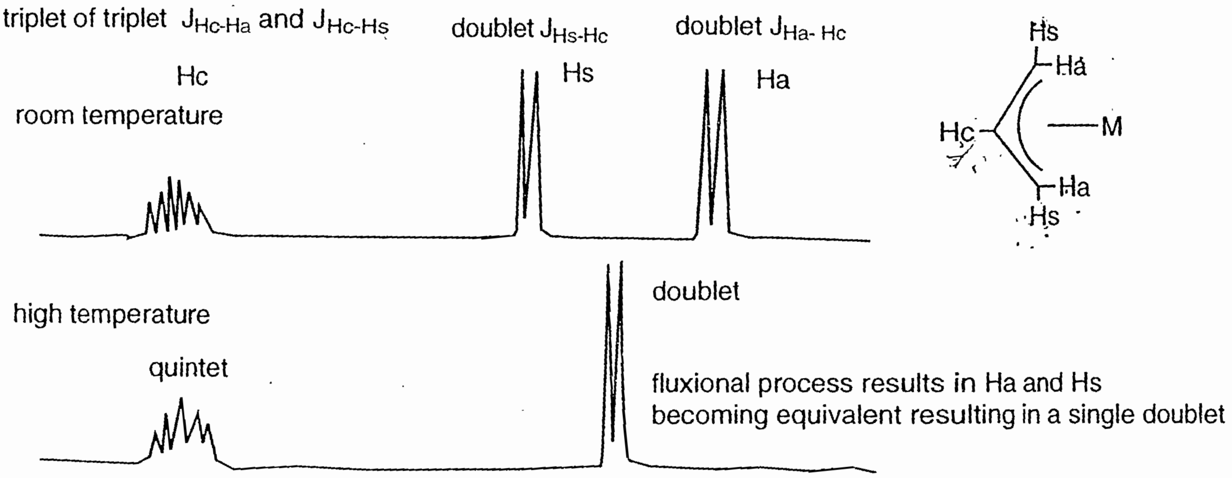
9.5.3 Allyl Complexes

Many η^3-allyl complexes are fluxional at room temperature or slightly above, and this property has been extensively studied by ^{1}H NMR spectroscopy (Fig. 9.6). These complexes have a characteristic NMR spectrum; the *anti* protons are closer to the metal, are shielded and appear at high field in comparison to the *syn* protons. A typical range is: *anti* δ 1–3, *syn* δ 2–5 and the proton at the middle carbon δ 4–6.5. Since the molecule is rigid, each of the three types of protons produces a distinct chemical shift depending upon its environment. The *syn* and *anti* protons do not couple with each other but these do couple with the proton on the central carbon and thus appear as doublets and the proton on the central carbon appears as a multiplet. Upon warming, the spectrum changes, the two doublets collapse into one and the multiplet changes to a quintet. This indicates that on a time average there are only two types of protons—four terminal and one nonterminal hydrogen.[29]

However, rapid interconversion occurs and the distinction between *syn* and *anti* protons is lost (Eq. 9.8).

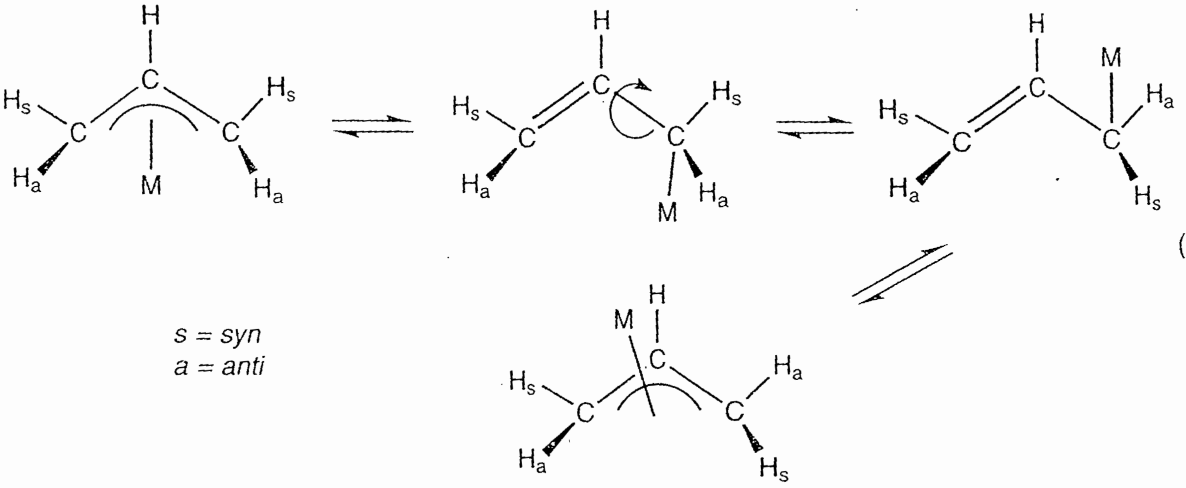
The process involves a π–σ–π transformation, that is, dissociation of a bond to one terminus to give the σ allyl (η^1) complex followed by rotation around the M–C bond, followed by collapse to the η^3-allyl complex. During the transformation $\eta^3 \rightarrow \eta^1$ (that is, π→σ), a vacant coordination site on the metal is generated.

t-t



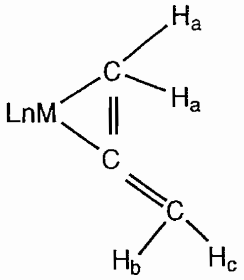
(2 (+1)
$2 \times \frac{1}{2}$

Fig. 9.6 Variable temperature ^{1}H NMR spectra of η^3-allyl complexes



(9.8)

9.5.4 Allene Complexes



An interesting aspect of allene–metal complexes is its structural dynamics. Three signals are observed in the ^1H NMR spectrum. The lowest δ value is seen for the a and b protons while the highest δ value is for the c proton. The coupling constant ($J_{H_a\text{-}H_b}$) is smaller for the coordinated allene than for the free allene. If the symmetry is lower, four signals may be observed.

Some allene complexes show dynamic properties, for example, tetramethylalleneirontetracarbonyl complex shows fluxional behaviour (Fig. 9.7). The ^1H NMR spectrum at 213 K in CS_2 exhibits three signals at δ 2.07, 2.00 and 1.77 in the ratio 1:1:2 representing the three *cis* and three *trans* hydrogen atoms and six hydrogens in a plane perpendicular to the Fe–C bond. At room temperature, the spectrum collapses to a single resonance at δ 1.84 for the average environment of the 12 hydrogens. The iron atom presumably migrates around the allene π system during this process as shown in (b).[30]

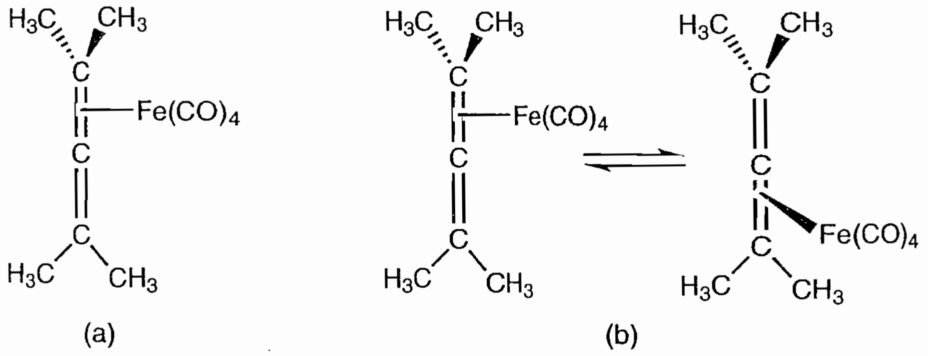


Fig. 9.7 Fluxional behaviour of tetramethylalleneirontetracarbonyl complex

A similar observation is made in $[Cp(CO)_2Fe(Me_2C{=}C{=}CMe_2]^+$. The ^1H NMR spectrum shows that the four methyl groups become equivalent with increasing temperature which suggests rotation about the Fe–allene axis and migration of the $Cp(CO)_2Fe$ fragment between both orthogonal alkene units (a 1,2 shift).[31]

9.5.5 Scrambling of Carbonyl Groups in Metal Carbonyls

Stereochemical non-rigidity of metal carbonyls has basically two forms.[32]

- The interconversion of permutational isomers and geometric isomers in mononuclear complexes: This presumably involves 'polytopal rearrangement' a term coined by Muetterties. The most celebrated example under this category is $Fe(CO)_5$. The interconversion of TBP–SPy–TBP structure leading to the equivalence of all five carbonyls in the ^{13}C NMR spectrum was explained by Berry pseudorotation. Unfortunately even cooling up to −120°C was not sufficient to observe this phenomenon in the NMR time scale.

- Interconversion of bridging and terminal arrangements and the migration and scrambling of CO groups in binuclear and polynuclear complexes: This arises because the energy of the system, $M_2(CO)_2$, does not vary a great deal (< 30 kJ/mol) over an entire range of configurations—from that in which there is one terminal CO on each M to that in which both the COs are symmetrically /unsymmetrically bridged (Fig. 9.8).

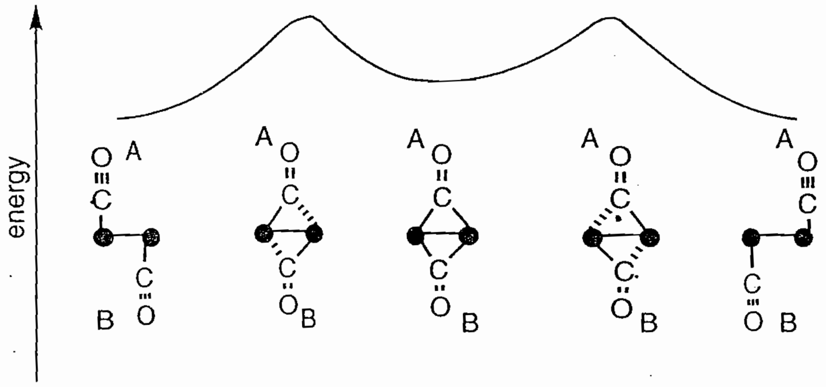


Fig. 9.8 Potential energy diagram indicating the concerted exchange of two carbonyl groups via a bridging intermediate

The above process is best exemplified by $Cp_2Fe_2(CO)_4$ which exists as a 1:1 mixture of *cis* and *trans* isomers (Fig. 9.9).

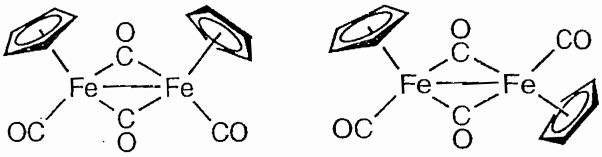


Fig. 9.9 *Cis* and *trans* isomers of $Cp_2Fe_2(CO)_4$

Two signals are expected since the *cis* and *trans* Cp ring should appear at different chemical shifts in the ^1H NMR spectrum (Fig. 9.10). This is observed at –70°C. However, only one signal appears at room temperature. Clearly, between –70°C and room temperature, a rapid interconversion of the *cis* and *trans* isomers occurs.

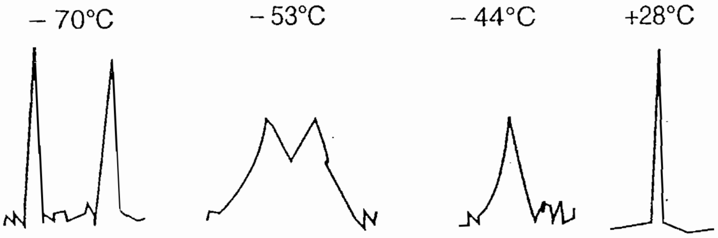


Fig. 9.10 ^1H NMR spectrum of *cis* and *trans* $[(\eta^5\text{-Cp})Fe(CO)_2]_2$ from –70°C to +28°C

The ^{13}C NMR spectrum further shows that the *cis* and *trans* interconversion is also accompanied by the exchange of the bridging and terminal carbonyl groups (Fig. 9.11). The overall process occurs this way: the CO bridges open in a concerted way to give the $Cp(CO)_2Fe\text{–}Fe(CO)_2Cp$ intermediate, the rotation around the Fe–Fe bond followed by reclosing of the bridges may give either the *cis* or *trans* isomer, regardless of which isomer was present before the bridge opening. At the same time, the CO groups that bridge may not be the same as those that bridged earlier. Hence, bridge–terminal carbonyl exchange also takes place.

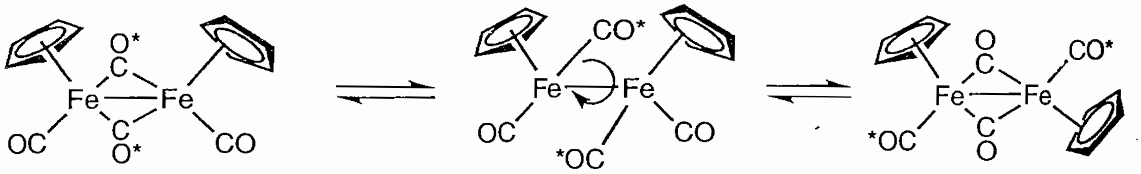
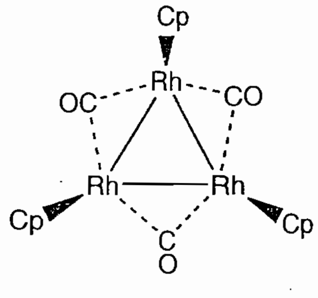
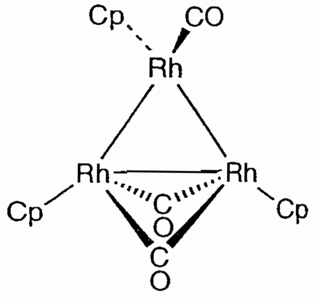


Fig. 9.11 *Cis* to *trans* interconversion of $[(\eta^5\text{-Cp})\text{Fe(CO)}_2]_2$

A different type of scrambling involving terminal, edge bridging and face bridging CO groups has been observed in one of the isomers of the trinuclear cluster compound, $[\text{CpRh(CO)}]_3$. The cluster exists as two isomers as shown below.[33]



A(C_{3v})

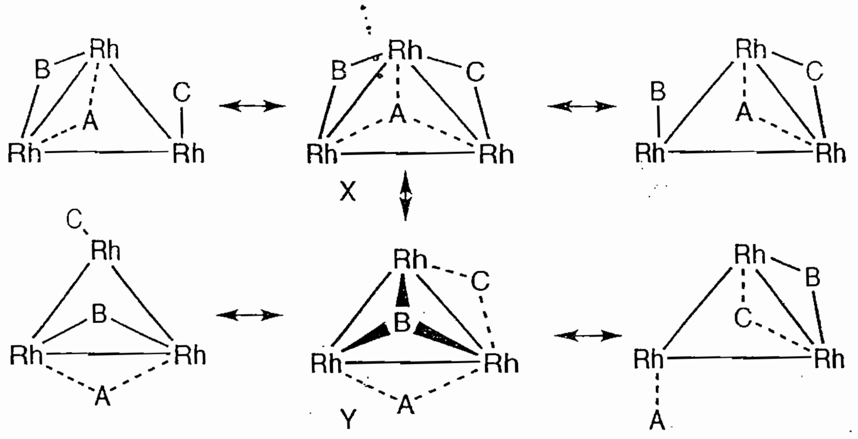


B(C_s)

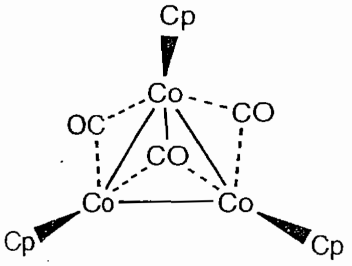
Since Rh has spin I = ½ the ^{13}C NMR spectra of isomer B should show three types of carbonyls, one terminal and two bridging. The two bridging carbonyls in B are not equivalent: one is *cis* to a Cp and the other is *cis* to the terminal CO. Hence the terminal CO should appear as a doublet and the bridging COs should appear as two different triplets. In contrast to this prediction, the ^{13}C NMR spectrum of B shows a quartet at room temperature for the CO groups. It does not show the predicted NMR even at low temperature but at −120°C shows two quartets in the approximate ratio of 1:2. How can this be explained?

For B, scrambling of the terminal and bridging CO groups over the three Rh atoms can be envisaged. However, one CO of B is unique since it is always on the top face of the Rh_3 plane while the other two are on the bottom face of the same plane. At -120°C, the scrambling of CO groups is restricted to their respective faces. Since crossing over from one face to the other is not facile at this temperature, the ^{13}C NMR spectrum corresponding to the COs in the fluxional molecule should comprise two sets of quartets in the ratio 1:2.

At room temperature the barrier for crossing over from one face to the other is also overcome possibly by following a scrambling as depicted in the scheme shown overleaf (A–C are CO groups) resulting in a single quartet.[34]



A combination of edge-face and terminal-edge carbonyl motions interconvert B with the intermediates X and Y without traversing an intermediate with all-carbonyl terminal. Interconversions between X and Y also provides for face to face scrambling facilitated by a bridging carbonyl C flipping from an upper edge position to a lower edge position. Further support to these face bridging intermediates comes from the reported crystal structure of an analogous cobalt cluster which interestingly showed the presence of one face bridging carbonyl group along with two edge bridging CO groups as shown below.



Problems and Exercises

9.1. Kinetic studies on the carbonyl ligand substitution by PPh_3 on $[\eta^5\text{-}C_5H_4(NO_2)]$ $Rh(CO)_2$ gave the following experimental results. Indicate the type of reaction mechanism by which the ligand substitution proceeds. $\Delta S^\ddagger = -17.9$ eu; a plot of the observed pseudo first order rate constant (k_{obs}) vs $[PPh_3]$ was linear with a zero intercept.

9.2. X-ray diffraction studies of the compound $[Ru(\eta^4\text{-}C_8H_8)(CO)_3]$ have confirmed that the complex is indeed a tetrahapto complex. However ^{1}H-NMR gives the following information:

- A single sharp peak is obtained at room temperature
- On cooling the sample, the signal broadens and then separates into four peaks. Explain these observations.

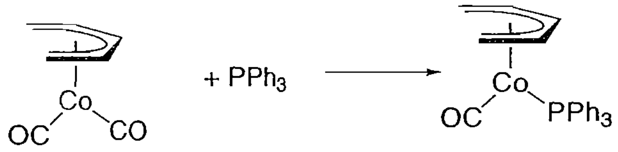
9.3. $Mo(CO)_3(PMe_3)_3$ is extremely inert, while $Mo(CO)_2[P(OMe)_3]_3(CH_3)$ is quite reactive and undergoes substitution readily. Give reasons.

9.4. Write the steps involved in the following reaction

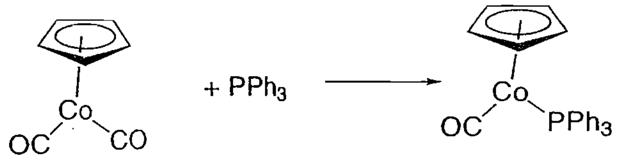
$$(\eta^5\text{-indenyl})Re(PMe_3)_3 + CO \longrightarrow (\eta^5\text{-indenyl})Re(PMe_3)_2(CO) + PMe_3$$

9.5. Which among the following reactions will be faster and why?

(a)

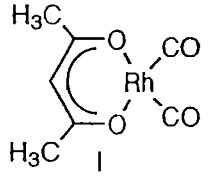


(b)

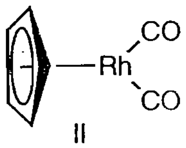


9.6. The compound (η^1-allyl)$Mn(CO)_5$ on heating releases a gas and forms a new compound which obeys the 18 electron rule. Identify this new compound and schematically draw its room temperature ^1H NMR. Will there be any change in its NMR spectrum when measured at high temperature? Explain.

9.7. Consider the substitution of CO by a phosphite in the following complexes I and II.



I



II

(a) Indicate whether the mechanism is associative or dissociative.

(b) Among I and II, which will react faster and why?

9.8. The substitution of CO by seven different phosphine ligands in $V(CO)_6$ shows that the basicity/nucleophilicity of the phosphines affects the rate of the reaction. It is also observed that the rate is unaffected by the concentration of CO. For PPh_3, $\Delta S^{\ddagger} = -28$ eu. Comment on the mechanism of this reaction.

$$V(CO)_6 + PR_3 \xrightarrow[\text{hexane}]{\sim 25°C} V(CO)_5PR_3$$

9.9. The rate law of the given reaction has the following unprecedented form.

Rate = $k_1[Mo(CO)_6] + k_2[Mo(CO)_6][L]$

$$Mo(CO)_6 + L \xrightarrow{\Delta} Mo(CO)_5L + CO$$

Comment on the two different terms in the rate law (*J. Am. Chem. Soc.*, 1966, 88, 3658)

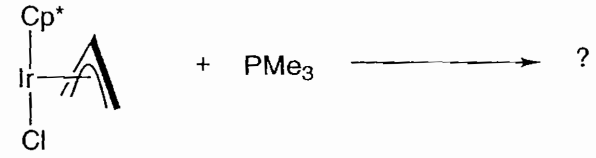
9.10. Consider the following ligand substitution reactions and propose the intermediate in each case.

(a)

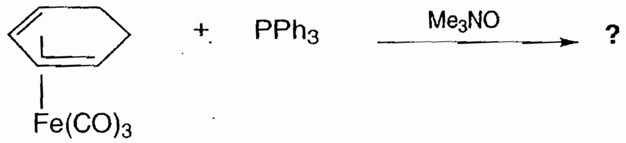
(b)

9.11. Predict reasonable products in the following reactions and justify their formation.

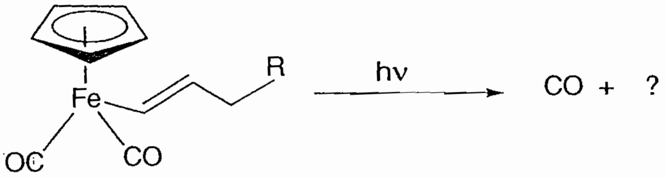
(a)



(b)



(c)



9.12. When freshly sublimed $Me_3NO.2H_2O$ is reacted with $Fe(CO)_5$, an Me_3N substituted iron carbonyl is formed along with CO_2. Show how these products are formed.

$$Fe(CO)_5 + Me_3NO.2H_2O \xrightarrow[-30°C]{THF} Fe(CO)_4(Me_3N) + CO_2 + 2H_2O$$

9.13. The following experimental observations were made in the thermal decomposition of two complexes, *trans*-$Ni(Me)(Ar)(PEt_3)_2$ (1) and *cis*-Ni(Me(Ar)(dmpe) (2) (dmpe is dimethylphosphinoethane)

(a) Both on thermolysis give the reductive elimination product Me–Ar.

(b) The *cis* isomer (2) decomposes much faster than the *trans* isomer (1); for example, (2) decomposes at RT in benzene at a considerable rate while (1) does not show any sign of decomposition under similar conditions.

(c) The addition of a phosphine accelerates the decomposition in (2) whereas phosphine addition in (1) retards the reaction.

Based on the above observations,

- Indicate if an associative or dissociative mechanism is operating in these examples giving reasons.
- Given that the phosphine addition reactions go through a trigonal bipyramidal intermediate, explain the observation in (c) by considering a suitable mechanism.

Supplementary reading

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METAL CLUSTERS

CHAPTER 10

10.1 INTRODUCTION

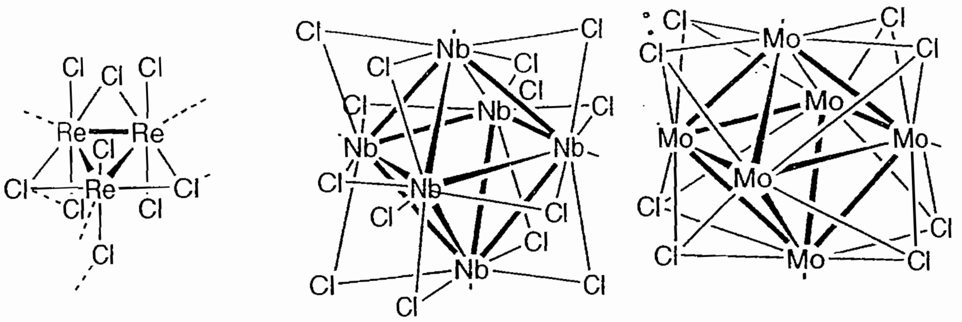
A metal cluster may be defined as a group of two or more metal atoms in which there are substantial and direct bonds between the metal atoms. It is an ensemble of bound metal atoms often with a sheath of ligands surrounding it and has a size intermediate between a molecule and a bulk solid. Thus, a metal cluster is more than just an ordinary polynuclear complex.[1]

The term *metal cluster* was coined by F A Cotton in the early 1960s concomitant with the discovery of many such units. It is unfortunate that some authors have used the term cluster indiscriminately to designate polynuclear complexes of the Werner type in which there is no significant amount of direct metal–metal bonding. $Mn_2(CO)_{10}$ was the first compound among metal carbonyls in which a direct M–M bond unsupported by any bridges was seen. Transition metals form two main classes of metal-metal bonded clusters—halide/oxide clusters and carbonyl clusters.[2]

Halide/oxide clusters are generally formed by early transition metals such as niobium, tantalum, molybdenum, tungsten and rhenium. They have halides and/or oxides as the main (often only) ligands and the examples are not too many in number. Few examples are given in Fig. 10.1. On the other hand, the carbonyl clusters are many and these form some of the structurally well studied and analysed examples of metal clusters.

Interest in metal cluster compounds stems from their unique structural diversity, as model compounds for studying fundamental reactions on surfaces especially heterogeneous catalysis and many other potential applications. The nature of bonding in cluster compounds is an area wherein theory and experiment are continuously challenging each other resulting in new electron counting methods for predicting their stability. The two general types of metal cluster compounds differ from each other in many ways. There is little in the way of chemical reactions to interrelate them.[3]

Many metal clusters – especially those containing carbonyl ligands – have been evaluated for their utility as catalysts. Although direct industrial applications are still nonexistent, the clusters $Ir_4(CO)_{12}$ and $Ru_3(CO)_{12}$ have been found to catalyse the well known *water gas shift* reaction.[4] $Rh_6(CO)_{16}$ catalyses the conversion of CO into hydrocarbons which serves as a model for the Fischer–Tropsch process. Many discrete clusters are also



$ReCl_3$ exists as Re_3Cl_9

$NbCl_2$ exists as $[Nb_6Cl_{12}]^{2+}$ with Cl bridging all edges

$MoCl_2$ exists as $[Mo_6Cl_8]^{4+}$ having faces capped with Cl

Fig. 10.1 Examples of metal–halide clusters

part of metalloenzymes. A relatively recent potential application of clusters is, in the area of cluster-based single molecular magnets. This new field was opened up in 1993 when it was discovered that a cluster of 12 manganese ions, $[Mn_{12}O_{12}(OAc)_{16}(H_2O)_4].2HOAc.4H_2O$, with a ground state (S = 10) showed slow relaxation of the magnetisation at low temperature (of the order of a month at 2 K) and could be used to store magnetic information.[5] There are two broad generalisations pertinent to the area of M–M bonding.

(i) M–M bond formation is most likely to occur when the metal atoms are in their lower oxidation states. Therefore, the most extensive class belongs to carbonyl clusters in which the formal oxidation state of the metal is zero or negative. In lower halide clusters, the metal oxidation states are usually +2 to +3 or sometimes +4.

(ii) For any group in the periodic table, the tendency to form an M–M bond is usually greater for heavier metals.

There are enough exceptions to the above rules and they should therefore be used with caution. The discussion in this chapter is restricted mostly to the carbonyl clusters.

10.2 DINUCLEAR CLUSTERS

Strictly speaking, the term cluster may not suit compounds built around two metal units. However, this class of compounds is important due to the variety of metal-metal multiple bonds present in many of them. Indeed, shortly after the discovery of the first example of an inorganic compound containing a metal-metal quadruple bond, $[Re_2Cl_8]^{2-}$, its organometallic analogue, $[Re_2Me_8]^{2-}$ was prepared by Cotton and Wilkinson according to Eq. 10.1.[6]

$$Re_2Cl_{10} \xrightarrow{CH_3Li,\ Et_2O} Li_2[Re_2(CH_3)_8].\ 2\ Et_2O \qquad (10.1)$$

The compound was obtained as a red, air and moisture sensitive solid, stable at room temperature and whose Re–Re distance (218 pm) was much shorter compared to the rhenium–rhenium single bond distance of 274 pm (Re metal). Since the van der Waals radius of CH_3 is larger than that of Cl^-, one should expect a staggered conformation but structural analysis showed that the molecule was indeed eclipsed (D_{4h} point group).

As shown in Fig. 10.2, the *d* orbitals with end to end (d_{z^2}), side to side (d_{xz} and d_{yz}) and face to face (d_{xy}) overlap can lead to the maximum of a quadruple bond which will have one σ bond, two π bonds and one δ bond. The $d_{x^2-y^2}$ orbitals are used for bonding with the ligands in quadruple bonded systems.

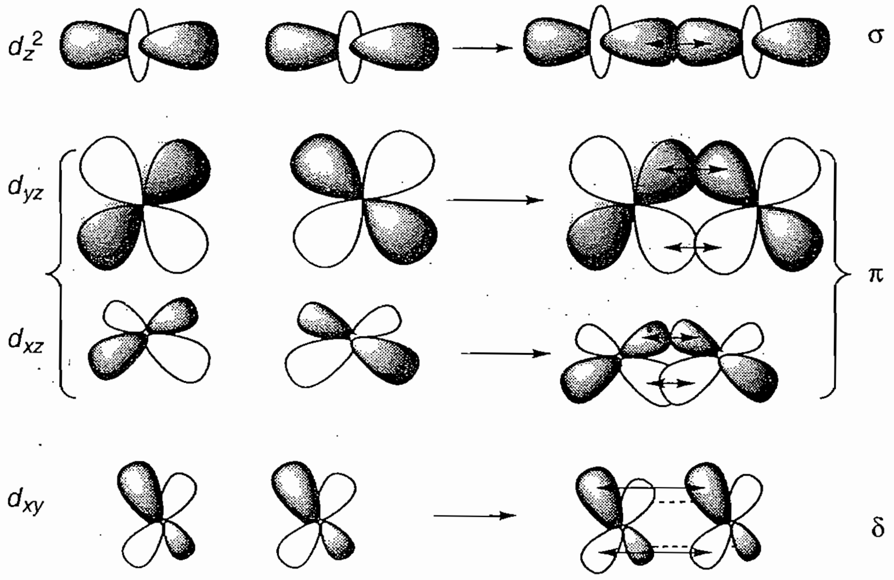
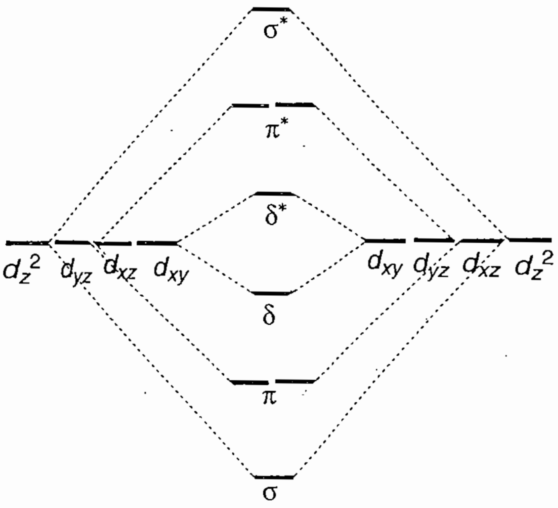


Fig. 10.2 *d* orbital overlap resulting in σ, π and δ bonds



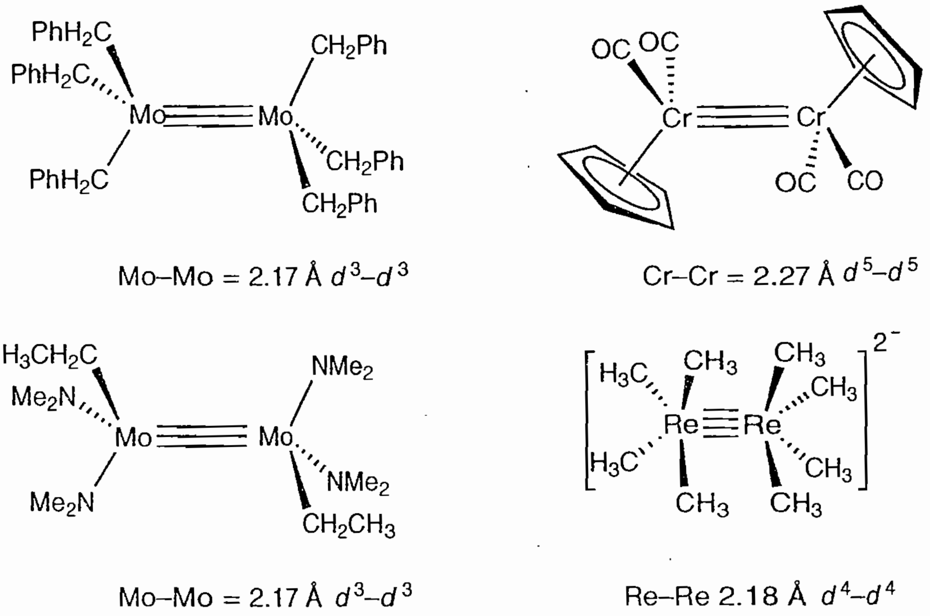
Metal(1)–Metal(2) *d* electron occupancy	M–M bond
$d^1 - d^1$	Single
$d^2 - d^2$	Double
$d^3 - d^3$	Triple
$d^4 - d^4$	Quadruple
$d^5 - d^5$	Triple
$d^6 - d^6$	Double
$d^7 - d^7$	Single

Fig. 10.3 Qualitative MO picture indicating relative energies of orbitals involved in metal–metal multiple bonding

A qualitative MO diagram of this interaction showing the metal–metal bond formation is depicted in Fig. 10.3. The filling of the electrons in the MOs is done in such a way that one M–M bond is formed for each pair of electrons added. The bonding orbitals get filled up with a total of 8 electrons which gives the optimum bonding (quadruple bond). When more than 8e are added, the antibonding orbitals start to get filled up resulting in the cancellation of metal–metal bonds (see table in Fig. 10.3). The table specifically refers to two metals in square planar geometry interacting to form metal–metal bonds.

Metal centres with other geometries can often adopt bond orders different from that given here. Generally, the *d* occupancy gets correlated with the multiplicity of the bond as given in the table. Also, when no *d* electrons are present, there is generally no M-M bonding; also, a higher M-M bond order than the number of *d* electrons being shared between the metal centres is not possible. Organometallic compounds with quadruple bonds are obtained when there is a d^4–d^4 electronic configuration for the two metals.

A variety of other organometallic compounds have also been prepared with metal-metal double, triple and quadruple bonds. Some of the examples are given in Fig. 10.4. By finding out the *d* electron occupancy, the nature of the multiple bond between the two metal atoms can easily be determined.



Mo–Mo = 2.17 Å d^3–d^3

Cr–Cr = 2.27 Å d^5–d^5

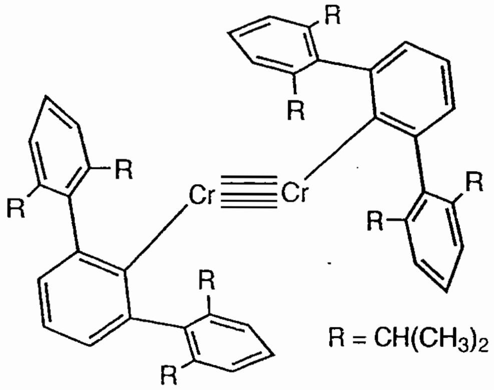
Mo–Mo = 2.17 Å d^3–d^3

Re–Re 2.18 Å d^4–d^4

Fig. 10.4 Examples of dinuclear clusters with M–M multiple bonds

10.2.1 A Five-fold Bonded Organometallic Compound

The research in multiple bonded organometallic compounds reached new heights with the report of an aryl substituted quintuple bond by Philip Power and coworkers in 2005. While examples of quadruple bonded organometallic compounds were known for quite some time, the preparation of this compound with five electron pairs between two metal atoms was an exciting development that also raised fundamental questions in theoretical and experimental chemistry. The bulky aryl group C_6H_3-2,6-$[C_6H_3\text{-}2,6\text{-}(i\text{-Pr})_2]_2$ stabilises the molecule with chromium having a low coordination number. The dark red crystalline air sensitive molecule is stable up to 200°C. The chromium is formally in the +1 oxidation state and each of the chromium atoms has six electrons with one of the electrons used for bonding with the aryl carbon. The remaining ten electrons from the two chromium atoms are expected to occupy molecular orbitals in the $\sigma^2\pi^4\delta^4$ configuration. The five fold bond is indicated by a very short chromium-chromium distance of 183.5 pm which is shorter than a chromium–chromium quadruple bond $[Cr_2(O_2CMe)_4(NC_5H_5)_2$: 236.9 pm]. In contrast to the expected linear geometry, the geometry of this compound was found to be *trans* bent with the Cr–C bonds oriented at an angle of 103° on both ends of the Cr–Cr bond. The discoverers of this compound were therefore cautious about using the word 'quintuple' to describe the bonding in the new molecule, preferring to call it 'five fold bonding' because the actual bond order is likely to be less than five. The discovery of this molecule has led to exciting possibilities for chemists to look deeper into the complexities of chemical bonding.[7, 8]



10.3 MULTINUCLEAR CLUSTERS

The largest and structurally most complex cluster compounds having three and more metal atoms are metal carbonyls with the metal in low oxidation states. There are many compounds that contain M–M bonds and fall into the category of metal carbonyl clusters. For the sake of comparison and classification, these are divided into low nuclearity carbonyl clusters (LNCC) and high nuclearity carbonyl clusters (HNCC).[9]

10.3.1 Low Nuclearity Carbonyl Clusters

Calculations of M–M bonds

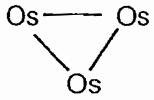
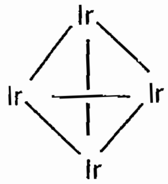
In order to assign a tentative structure to the given molecular formula, we require information about the total number of metal–metal bonds in the complex and the number of bonds each metal makes with other metals. The detailed procedure which applies to complexes with a nuclearity ≤ 4 was outlined in Chapter 2. To draw the most probable structure of the given compound, the metal core is written first. The carbonyl groups and other ligands are arranged on metals in such a way that each metal follows the 18 electron rule. The CO group can occupy either the terminal or bridged position since it contributes 2e in each case.

$M_3(CO)_{12}$ and $M_4(CO)_{12}$ clusters are electronically saturated; which means that these have sufficient number of electrons to provide each metal atom with an 18e closed shell configuration. In such systems, there must be a total of 48 and 60e respectively, assuming that each M–M bond order is 1.

The $H_2Os_3(CO)_{10}$ cluster can be derived from $Os_3(CO)_{12}$ and has only 46e.[10] This molecule, categorised as an unsaturated cluster, has a different structure (Fig. 10.5) in which one edge of the Os_3 triangle is shorter than the other and is bridged by two hydrogen atoms. By having one Os=Os double bond, each osmium atom attains the 18e configuration.

In four-atom clusters, besides the tetrahedral geometry, other geometries like butterfly and planar are also known (Fig. 10.5).

Table 10.1 Examples of low nuclearity carbonyl clusters[11]

Molecule	TEC	Total M-M bonds	Bonds per metal	Basic geometry of metal atoms
$Os_3(CO)_{12}$	48	54 – 48 = 6/2 = 3	48/3 = 16; 2	
$Ir_4(CO)_{12}$	60	72 – 60 = 12/2 = 6	60/4 = 15; 3	
$[\eta^5\text{-Cp Mo (CO)}_3]_2$	34	36 – 34 = 2/2 = 1	34/2 = 17; 1	Mo–Mo
$(CO)_3Co(\mu\text{-}CO)_2Co(CO)_3$	34	36 – 34 = 2/2 = 1	34/2 = 17; 1	Co–Co

TEC: total valence electron count

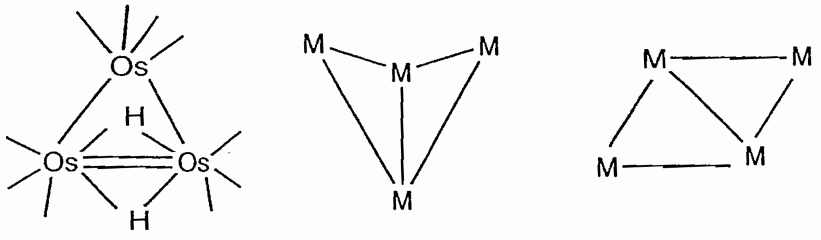


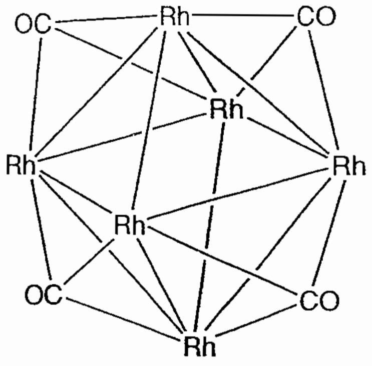
Fig. 10.5 Shapes of three- and four-metal atom clusters

10.3.2 High Nuclearity Carbonyl Clusters (HNCC)

High nuclearity carbonyl clusters have five or more metal atoms, each forming at least one M–M bond. The first HNCC, $Rh_6(CO)_{16}$ was structurally elucidated in 1963. Today, there are a large number of such clusters. One of the reasons for the interest in the very large clusters is that they are expected to show properties verging on those of bulk metals. The study was started to seek answers to the question of how large a particle of metal has to be before bulk metal properties begin to appear.

10.3.3 Electron Counting Schemes for High Nuclearity Clusters

The rules that apply to LNCC do not always follow for HNCC clusters, that is, the bonding skeleton cannot be described in terms of localised 2c-2e M–M bonds with each metal attaining 18e. Consider the example of $Rh_6(CO)_{16}$ [total valence electron count (TEC) 86e, Fig. 10.6] in terms of the 18e rule. Each Rh acquires four electrons from two terminal carbonyls, has a share of four electrons in four Rh–Rh bonds that it makes and it has nine electrons to begin with. Therefore, it has a total of 17e and so the Rh_6 cluster is short by 6e. Four triply bridged carbonyls contribute a total of 8e. Now the entire molecule has 2e too many in terms of the 18e rule.[12]



Rh = Rh (CO)2

Fig. 10.6 The structure of $Rh_6(CO)_{16}$

The same problem exists in other clusters like $Ru_6(CO)_{17}C$, $[Co_6(CO)_{14}]^{4-}$ and $H_2Ru_6(CO)_{18}$. All of these clusters are isoelectronic with a TEC of 86e.[13, 14]

The HNCC are large, often structurally complex and most of them contain heavier (2nd and 3rd series) transition metals. These are not amenable to conventional interpretation of their electronic structures. Much effort has been devoted to find some relationship between their structure and the number of electrons available for cluster formation. All of these large clusters are regarded as electron deficient since there are insufficient electrons to permit the assignment of an electron pair bond between each adjacent pair of metal atoms.

In order to resolve the problems associated with the electron counting in HNCC, Wade has proposed a qualitative model which is an extension of his earlier model originally proposed for boron hydrides, $[B_nH_n]^{2-}$. He has correlated the structure of a borane or its derivatives with the number of electrons involved in the bonding in the framework of the deltahedron. The number of vertices in the deltahedron is one less than the number of bonding pairs in the framework. This approach is sometimes called the *polyhedral skeletal electron pair theory* or more often *Wade's rules.* It may be noted that the prediction of structures of the transition metal carbonyl clusters using Wade's rules are often, but not always, correct.[15]

In $[B_nH_n]^{2-}$, one B–H unit uses one boron orbital and two electrons. This leaves three orbitals and two electrons on boron to be used in forming the B_n cage. One of the orbitals is an s, p_z or sp_z hybrid orbital that points towards the centre of the polyhedron. The other two orbitals, p_x and p_y, lie more or less on the surface of the polyhedron (Fig. 10.7). For B_nH_n polyhedra, the $2n$ surface orbitals will overlap to generate n bonding and n antibonding orbitals. The set of n orbitals pointing towards the centre of polyhedron strongly overlap at the centre of the polyhedron to generate one strongly bonding orbital and $n - 1$ weakly bonding, nonbonding or antibonding orbitals. Thus in a B_nH_n cage, there are $n + 1$ bonding orbitals. Since there are only n electron pairs contributed by n B–H units, an additional electron pair is required for $[B_nH_n]^{2-}$. This is the reason why the $[B_nH_n]^{2-}$ ions are more stable than B_nH_n itself.

Wade has treated the $M(CO)_3$ unit as analogous to the B–H unit (Fig. 10.7). Say, the metal M is Ru. This transition metal has nine valence orbitals (s, p and d) compared to four (s and p) in the case of boron. Six orbitals and three electron pairs are used in forming the $M(CO)_3$ unit. This leaves the Ru atom with three orbitals and two electrons—a situation similar to the B–H unit. A total of $n + 1$ electron pairs would be needed to completely fill the cluster

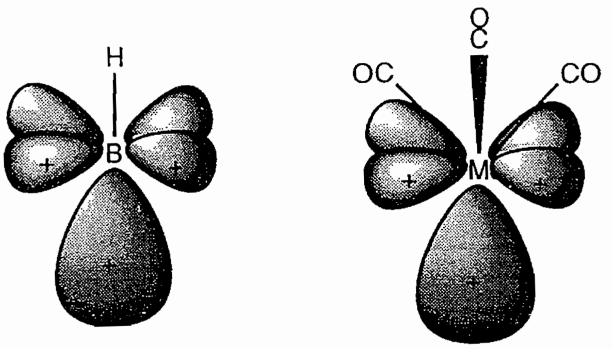


Fig. 10.7 Orbital pictures of the BH and $M(CO)_3$ units

bonding orbitals in an $M_n(CO)_{3n}$ structure. Thus, for $Ru_6(CO)_{18}$, we expect the stable species to be $[Ru_6(CO)_{18}]^{2-}$. This is the anion of the corresponding $H_2Ru_6(CO)_{18}$.

The TEC in the cluster has the contribution from (i) the number of valence electrons of each metal, (ii) 2e for each CO group irrespective of its bonding, terminal or bridged, (iii) 1e for each negative charge and (d) number of valence electrons for each hetero atom and/or interstitial atom, for example, 1 for H, 4 for C, 5 for N and so on. The polyhedral electron count (PEC) is calculated as follows:

$$\text{PEC} = \text{TEC} - 12\text{e per skeletal metal atom}$$

If a non-transition element is present on the vertex, then subtract 2e per element instead of 12e. Once we have the TEC and PEC, then, on the basis that $n + 1$ pairs of electrons are required for a polyhedron with n vertices (or alternatively, the number of vertices of the parent polyhedron is one less than the PEC), the most likely structure may be selected (Table 10.2).

Table 10.2 Correlation of PEC with structure

Boranes	Metal cluster	PEC	Structure
$4n + 2$	$14n + 2$	$n + 1$	*Closo*
$4n + 4$	$14n + 4$	$n + 2$	*Nido*
$4n + 6$	$14n + 6$	$n + 3$	*Arachno*
$4n + 8$	$14n + 8$	$n + 4$	*Hypho*

The examples in Table 10.3 illustrate this point.

10.3.4 Capping Rules

What happens when the PEC $\leq n$? In such cases one or more metal atoms are placed over the triangular face of the basic polyhedron. These appended groups are called capping atoms. The addition of a capping atom does not change the PEC but it increases the TEC by 12e. Let us study a few examples.

$Os_7(CO)_{21}$: TEC 98, PEC = 7e pairs; $n = 7$. This leads to a *closo* structure for a six vertex deltahedron, that is, an octahedron. One metal atom is capped on one triangular face of the octahedron. This is indeed found to be the actual structure.

Table 10.3 TEC, PEC and predicted structures of some high nuclearity carbonyl clusters

Compound	TEC	n#	PEC	Predicted structure
$Rh_6(CO)_{16}$	86	6	86 – (12 × 6) = 7e pair; (*n* + 1)	*Closo* (Oct)
$Ru_6(CO)_{17}C$	86	6	86 – (12 × 6) = 7e pair; (*n* + 1)	*Closo* (Oct)
$Os_5(CO)_{15}C$	74	5	74 – (12 × 5) = 7e pair; (*n* + 2)	*Nido*-Oct (Sq Py)
$[Fe_4(CO)_{12}C]^{2-}$	62	4	62 – (12 × 4) = 7e pair; (*n* + 3)	*Arachno* (Oct) (butterfly)
	62	5	62 – (12 × 4) – 2 = 6e pair; (*n* + 1)	*Closo* (TBP)**
$Os_5(CO)_{16}$	72	5	72 – (12 × 5) = 6e pair; (*n* + 1)	*Closo* (TBP)
$[Os_5(CO)_{15}]^{2-}$	72	5	72 – (12 × 5) = 6e pair; (*n* + 1)	*Closo* (TBP)
*$[HOs_5(CO)_{15}]^-$	72	5	72 – (12 × 5) = 6e pair; (*n* + 1)	*Closo* (TBP)
*$[H_2Os_5(CO)_{15}]$	72	5	72 – (12 × 5) = 6e pair; (*n* + 1)	*Closo* (TBP)
$Ru_5C(CO)_{16}$	76	5	76 – (12 × 5) = 8e pair; (*n* + 3)	*Arachno* (pentagonal bipyramid)

#Number of vertices in parent polyhedron, *Wades rule cannot predict the position of H, ** carbon is on the vertex.

Question: Can this be a bicapped TBP? No. Because, for a cluster to have closo TBP structure, the PEC required is 6e pairs. Similarly, this cannot be a pentagonal bipyramid because the PEC required for this is 8e pairs.

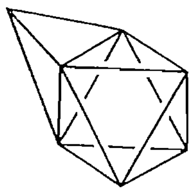
$[Rh_7(CO)_{16}]^{3-}$: TEC 98, PEC = 7e pairs; $n = 7$. This is isoelectronic and isostructural to $Os_7(CO)_{21}$.

$[Os_8(CO)_{22}]^{2-}$: TEC 110, PEC = 7e pairs; $n = 8$. The PEC of 7e pairs suggests that it is a closo structure for a six vertex polyhedron. Thus, it will be an octahedron with two metals on the triangular faces, that is, a bicapped octahedron (Fig. 10.8).

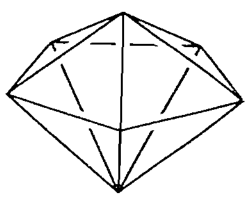
$[Os_{10}(CO)_{24}C]^{2-}$: TEC 134e, PEC = 7e pairs; $n = 10$. It is a tetracapped octahedron.

Note 1: In all the examples discussed above, the PEC is less than or equal to the nuclearity.

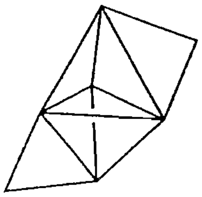
Note 2: The PEC for a regular octahedron and a monocapped octahedron is the same.



monocapped octahedron



pentagonal bipyramid



bicapped (edge) TBP

10.3.5 Limitations and Exceptions

(i) The capping rule does not predict which isomer will be formed; for example, a bicapped octahedron can have any of the three isomers (Fig. 10.8).

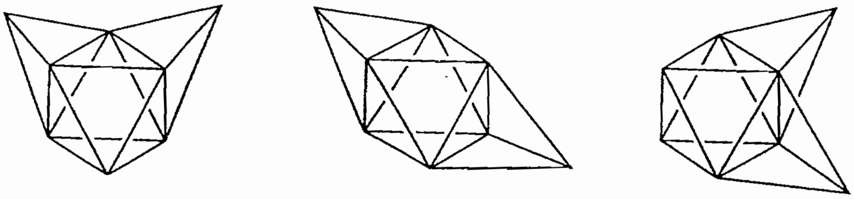


Fig. 10.8 The possible isomers of a bicapped octahedron

(ii) Consider the compounds (i) $[Os_6(CO)_{18}]^{2-}$, (ii) $H_2Os_6(CO)_{18}$ and (iii) $Os_6(CO)_{18}Py$. All these molecules are isoelectronic with a TEC of 86e and a PEC of 7e pairs. Hence, the structure predicted is an octahedron. The actual structure of (i) is an octahedron—the same as predicted, but (ii) and (iii) have different structures—nido and arachno respectively. The nido structure is a monocapped square pyramid and the arachno structure is an edge capped TBP; both can be derived from a monocapped octahedron.

(iii) $Os_5C(CO)_{15}$ (d) and $H_2Os_5(CO)_{16}$ (e) are isoelectronic with TEC of 74e, PEC of 7e pairs and $n = 5$. The predicted structure in both cases is *nido* of octahedron, that is, square pyramid. The actual structure of (d) is the same as predicted but (e) has an edge capped tetrahedron structure which can be derived from monocapped octahedron.

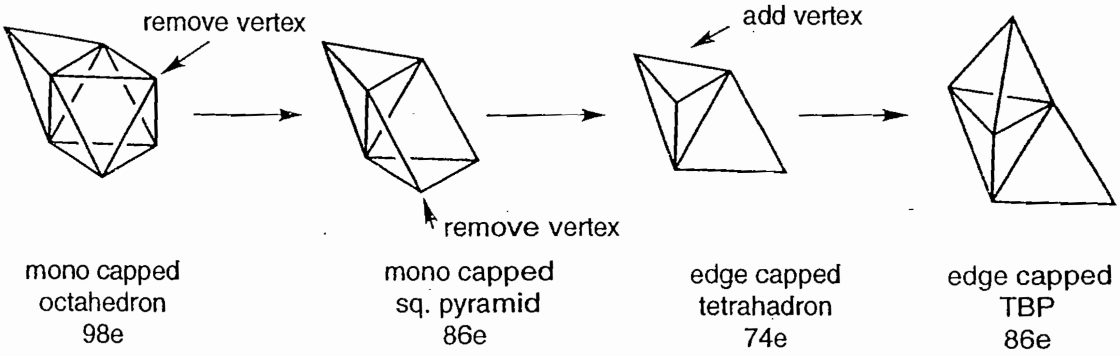


Fig. 10.9 Deriving an edge capped trigonal bipyramid from a monocapped octahedron

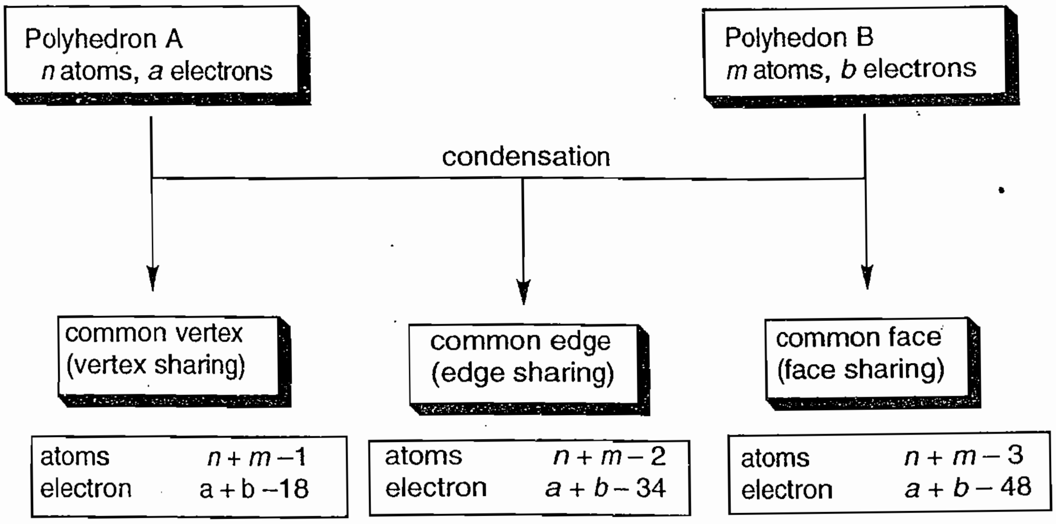
We have seen three possible structures – octahedron, monocapped square pyramid and edge capped TBP – for a TEC of 86e although the predicted structure as per Wade's rules should be an octahedron. Thus, one cannot always predict the actual structure by calculating the PEC and correlating to the geometry.

10.3.6 Polyhedral Skeletal Electron Pair Approach or Mingo's Rules

It has become apparent in recent years that the majority of high nuclearity transition metal clusters is derived by the condensation of smaller clusters like the tetrahedron, octahedron and trigonal prism. The condensation process occurs by vertex, edge or face sharing. It has become possible to derive rules that account for polyhedral electron count in such condensed polyhedra based on a fragment molecular orbital analysis of the condensation process. The condensed polyhedra are viewed as a complex between two individual polyhedra with one polyhedron acting as a ligand towards the other polyhedron. This is how the process works.[16, 17]

(i) The number of atoms and number of electrons in the individual polyhedron should be known.

(ii) Once the condensation has occurred, it is necessary to know the polyhedron electron count (PEC). Note that the meaning of this term is different from the term used in Wade's rules. PEC in Mingo's rule is the same as TEC in Wade's rules.



Scheme 10.1 Condensation of polyhedra indicating atom and electron counting

The procedure applies to only those metal carbonyl cluster compounds that adhere to the inert gas formalism, that is, that have the following electron count (Table 10.4).

Table 10.4 Electron count of the individual polyhedra used in the condensation process

Metal atoms	Structure of framework	Cluster valence electron count	Edges*
1		18	0
2		34	1
3	Closed triangle	48	3
	Open triangle	50	2
4	Tetrahedron	60	6
	Butterfly	62	5
	Square planar	64	4
5	TBP	72	9
	Square pyramid	74	8
6	Octahedron	86	12
	Trigonal prism	90	9

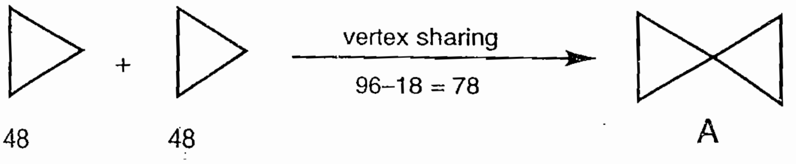
* Considering that all edges are 2c-2e bonds

Examples of condensed polyhedra

The following examples show how the observed structure can be constructed by condensing smaller polyhedra.

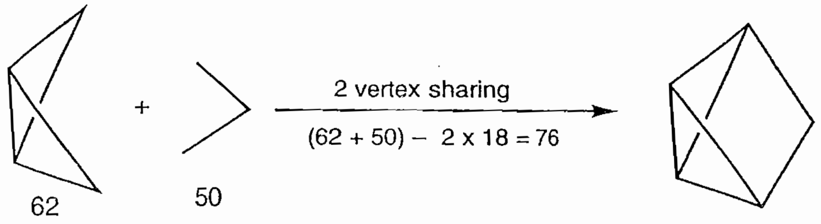
Vertex sharing

$Os_5(CO)_{19}$: The observed structure is A.



(10.2)

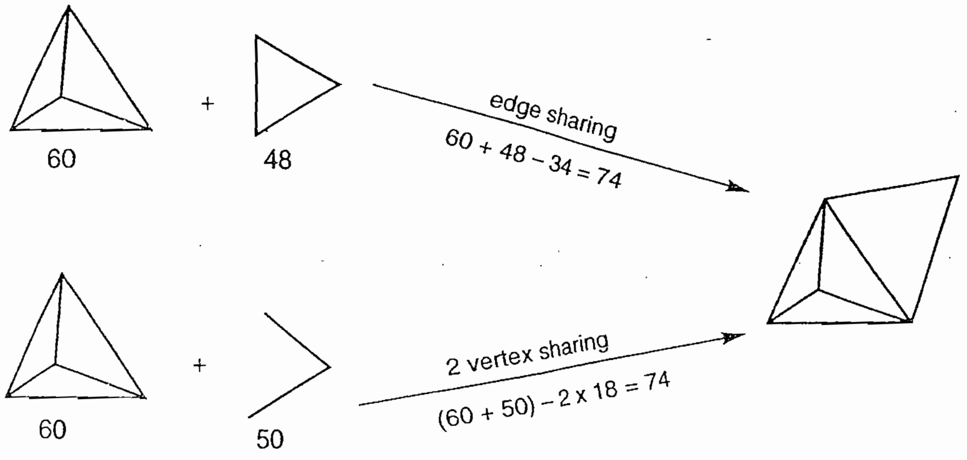
$Ru_5C(CO)_{16}$: A butterfly cluster with PEC of 62 condenses through the two wing-tip vertices to give the 'arrow head' cluster.



(10.3)

Edge/vertex sharing

$H_2Os_5(CO)_{16}$: The structure of this molecule can be derived in more than one way as shown.



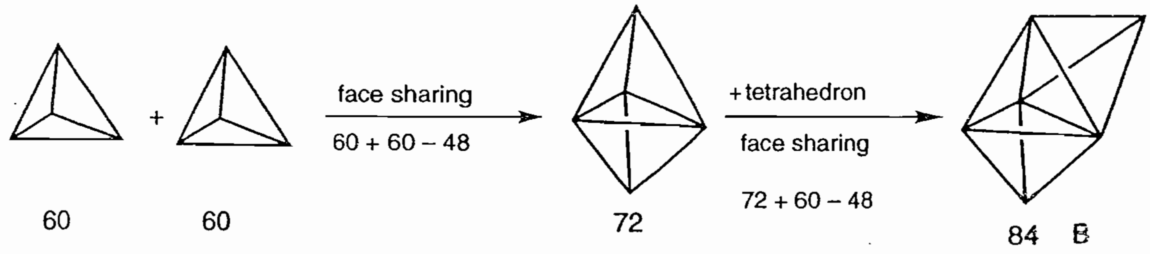
(10.4)

Face sharing

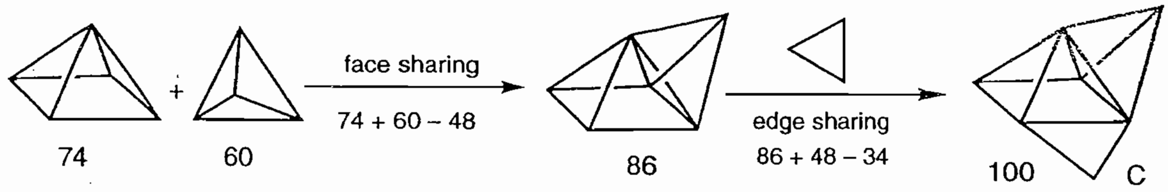
$Os_6(CO)_{18}$: The condensation of a tetrahedron to a second polyhedron through the triangular face has the net effect of capping. The condensation rule suggests an increment of 12 electrons in the PEC for capping.

$H_2Os_7(CO)_{21}$: The observed structure is C (bicapped square pyramid).

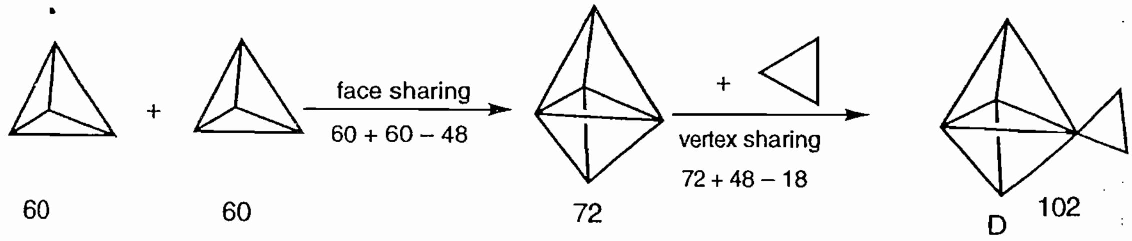
$H_2Os_7(CO)_{22}$: The observed structure is D.



(10.5)

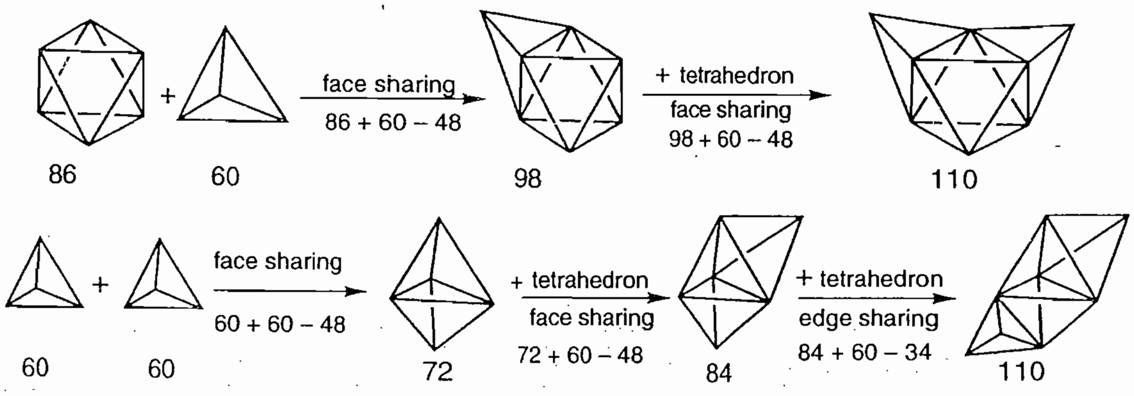


(10.6)



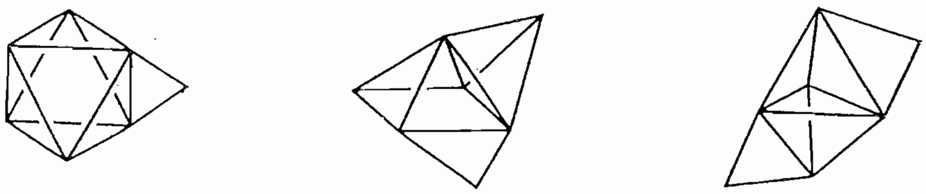
(10.7)

The following examples illustrate how the condensation rules can be used sequentially to build up alternative geometries for an eight atom cluster with a PEC of 110 electrons.



(10.8)

Similarly, there can be three possible structures with a PEC of 100.



edge capped oct bicapped sq. pyramid bicapped (edge) TBP

(10.9)

10.3.7 Carbide Clusters

In recent years, many compounds have been synthesised in which one or more atoms have been partially or completely encapsulated within a metal cluster. The most common of these have been the carbide clusters, with carbon exhibiting coordination numbers and geometries not found in classical organic compounds. Encapsulated atoms contribute their valence electrons to the total electron count. Some examples have been given in Section 10.4.1. In Ru$_6$(CO)$_{17}$C, carbon contributes its four valence electrons to give a TEC of 86 electrons. This corresponds to a *closo* structure and the molecule is octahedral.[13]

How can carbon, with only four valence electrons, form bonds to more than four surrounding transition metals? Ru$_6$C(CO)$_{17}$ with a central core of O_h symmetry, is an interesting example. The 2*s* orbital of carbon has A_{1g} symmetry and the 2*p* orbitals have T_{1u} symmetry in the O_h point group. The octahedral Ru$_6$ core has skeletal bonding orbitals of the same symmetry, a centrally directed A_{1g} group orbital and two sets of orbitals with T_{1u} and T_{2g} symmetry, oriented tangentially to the core. Therefore, there are two ways in which the symmetry match is correct for interactions between the carbon and the Ru$_6$ core. It must be mentioned here that the T_{2g} orbitals participate in Ru–Ru bonding but not in bonding with the central carbon. The net result is the formation of four C–Ru bonding orbitals occupied by electron pairs in the cluster and four unoccupied antibonding orbitals.

10.4 THE ISOLOBAL ANALOGY

Wade's rules which were initially developed to deal with structures of borane clusters have been extended to organometallic clusters as well. Application of the skeletal electron theory required an *a priori* division of metal orbitals into skeleton binding and ligand binding functions. They depend on a preconception of the structure of the molecule under consideration. The *isolobal analogies* developed by Roald Hoffman is an alternative approach which is based on the bonding characteristics of cluster fragments ML$_n$ in the frontier orbital region by means of the extended Hückel method and by comparing them with the units of CH$_n$ and BH$_m$ (Fig. 10.10).[18]

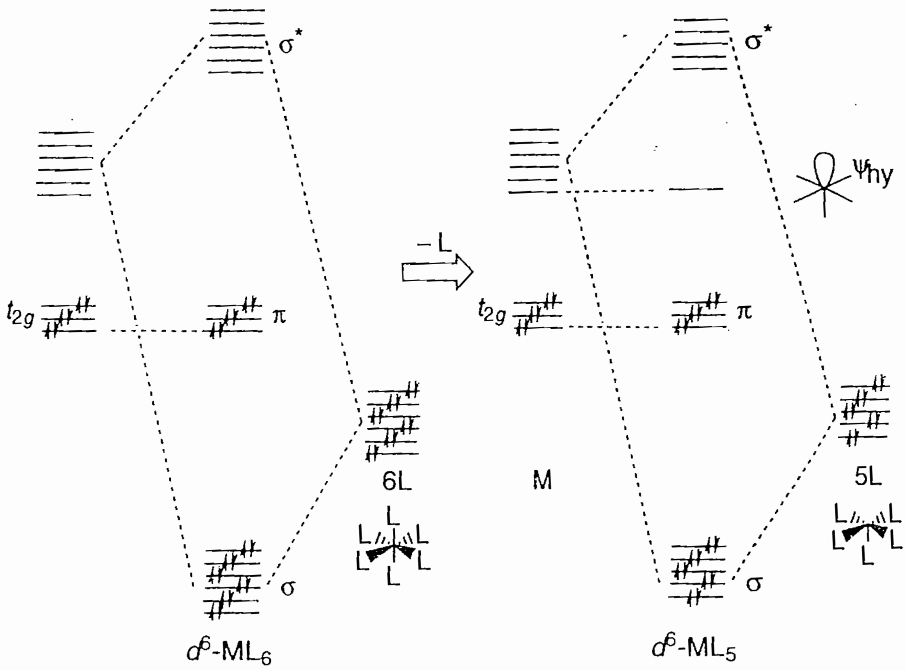


Fig. 10.10 MO picture indicating changes resulting from the removal of a ligand

Two fragments are considered *isolobal* if the number, symmetry properties, approximate energy and shape of their frontier orbitals as well as the number of electrons occupying their frontier orbitals are similar (not identical).

Example: •CH_3 is isolobal with •$Mn(CO)_5$. The symbol ($\underset{o}{\longleftrightarrow}$) is used for isolobal fragments as well as for the molecules they constitute. A simplified MO picture of an octahdedral complex is the starting point for the derivation of isolobal properties of organometallic fragments. If we remove one ligand, it converts a bonding σ MO of the complex ML_6 into a nonbonding frontier orbital ψ_{hy} of the fragment ML_5 (Fig. 10.10). The removal of two ligands creates two and removal of three ligands creates three new frontier orbitals ψ_{hy} (Fig. 10.11). The orbitals t_{2g} and ψ_{hy} are filled with *n* electrons of the central metal atom. This provides $Mn(CO)_5$ with one, $Fe(CO)_4$ with two and $Co(CO)_3$ with three singly occupied orbitals ψ_{hy} with a specific spatial orientation of the orbitals.

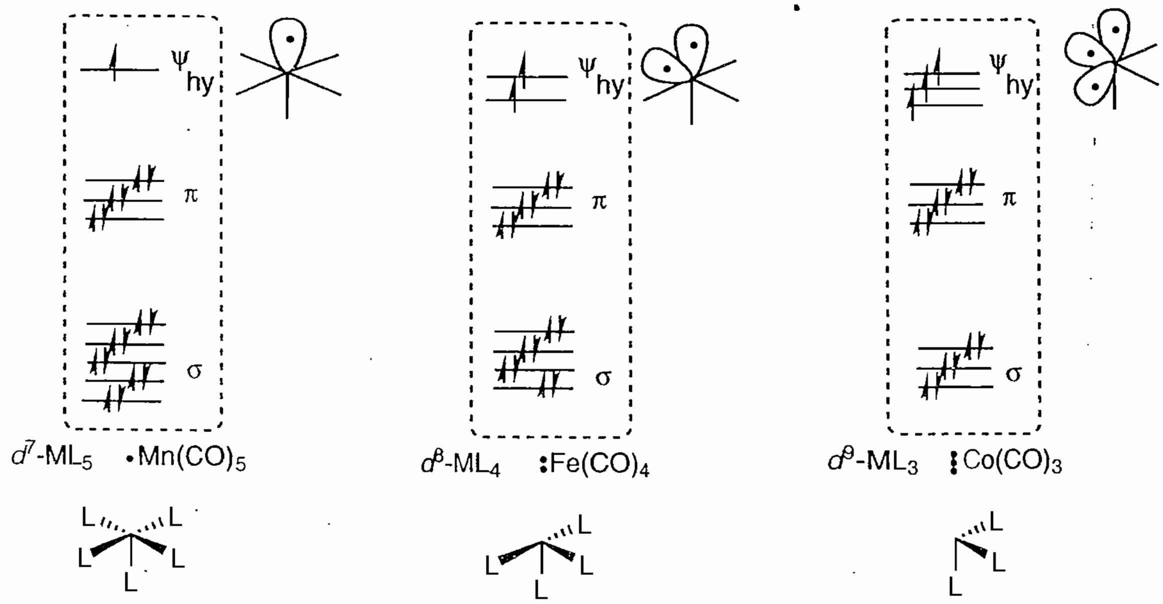


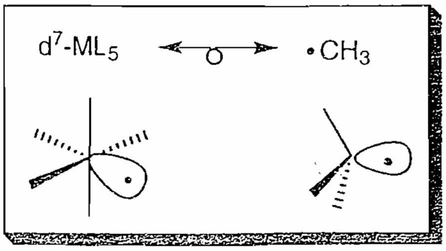
Fig. 10.11 Electron occupancy of σ, π and nonbonding (ψ_{hy}) frontier molecular orbitals of d^7-ML_5, d^8-ML_4 and d^9-ML_3 molecular fragments

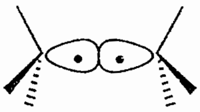
One can see that these organometallic fragments are complementary to the following organic or borane analogues.

d^7-ML_5 $\underset{o}{\longleftrightarrow}$ •CH_3 $\underset{o}{\longleftrightarrow}$ BH^+ or BH_2

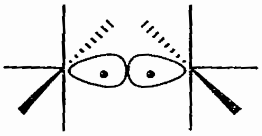
d^8-ML_4 $\underset{o}{\longleftrightarrow}$:CH_2 $\underset{o}{\longleftrightarrow}$ BH

d^9-ML_3 $\underset{o}{\longleftrightarrow}$ ⋮CH $\underset{o}{\longleftrightarrow}$ BH^-

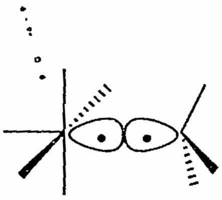




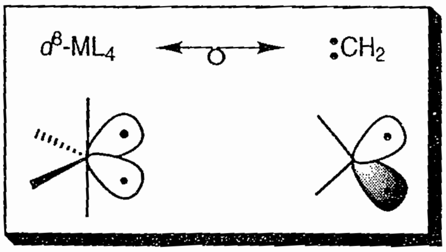
C_2H_6

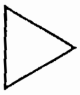


$(CO)_5MnMn(CO)_5$

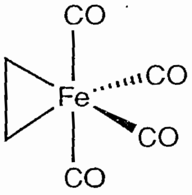


$(CO)_5MnCH_3$

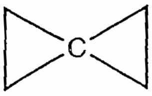




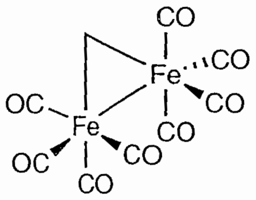
Cyclopropane

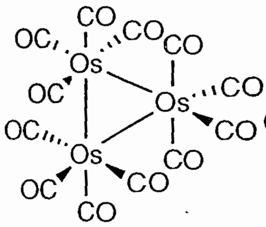


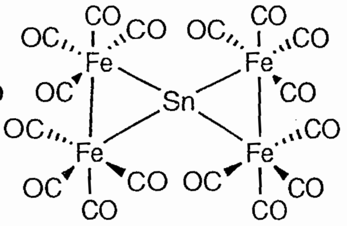
$(C_2H_4)Fe(CO)_4$

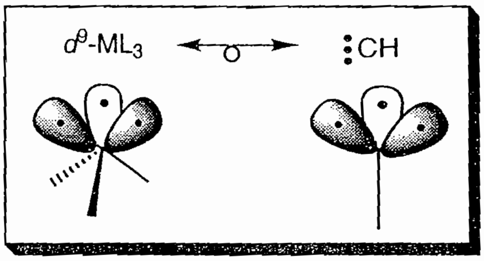


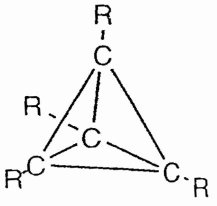
Spiropentane

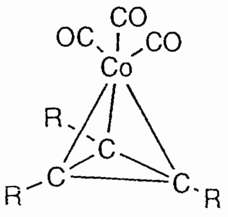


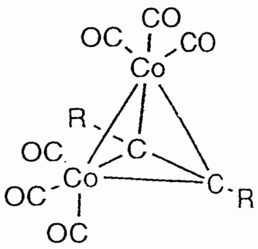


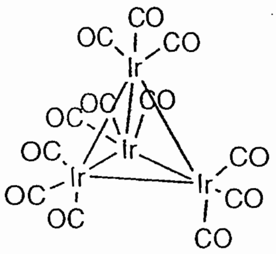








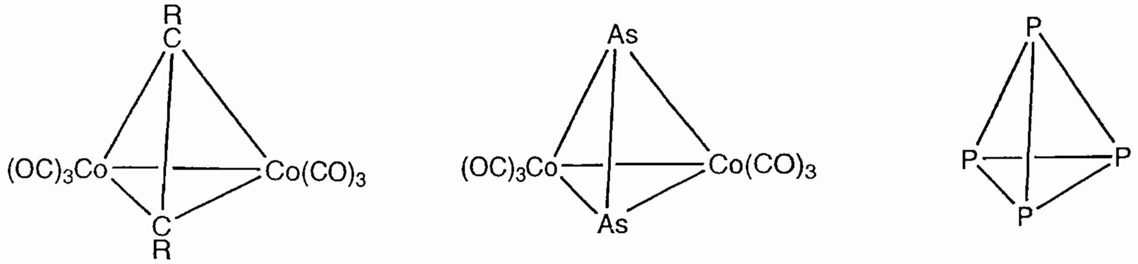




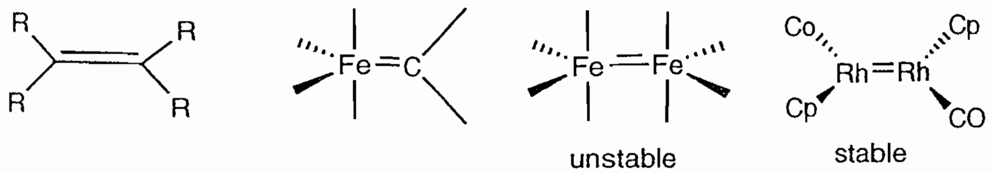
The isolobal analogy allows a joint consideration of inorganic, organic and organometallic structures. The analogy can be extended to molecules such as P_4 and As_4 as CH is isolobal with P. The ligand η^5-$C_5H_5^-$, a three electron-pair donor, formally occupies three coordination sites. Therefore the following analogies can be made.[19]

$Fe(CO)_4 \underset{\circ}{\longleftrightarrow} CpFe(CO)^- \underset{\circ}{\longleftrightarrow} CpRh(CO)$ $|d^8\text{-}ML_4|$

$CH \underset{\circ}{\longleftrightarrow} P, As \underset{\circ}{\longleftrightarrow} BH^-$ $|d^9\text{-}ML_3|$



It should also be mentioned that application of the isolobal principles may or may not furnish stable molecules. For example, although $Fe(CO)_4$ is isolobal with CH_2, its dimer has only a transient existence, observed in low temperature matrices.



The applicability of isolobal analogy is considerably extended if the mutual replacement of σ donor ligands with the metal electron pairs at the metal atom is introduced. This means that $Cr(CO)_5$, a d^6-ML_5 system, is isolobal with $Fe(CO)_4$ or CH_2 (d^8-ML_4).

$d^1\ ML_8 \underset{\circ}{\longleftrightarrow} d^3\ ML_7 \underset{\circ}{\longleftrightarrow} d^5\ ML_6 \underset{\circ}{\longleftrightarrow} d^7\ ML_5 \underset{\circ}{\longleftrightarrow} d^9\ ML_4$

$d^2\ ML_7 \underset{\circ}{\longleftrightarrow} d^4\ ML_6 \underset{\circ}{\longleftrightarrow} d^6\ ML_5 \underset{\circ}{\longleftrightarrow} d^8\ ML_4 \underset{\circ}{\longleftrightarrow} d^{10}\ ML_3$

$d^3\ ML_6 \underset{\circ}{\longleftrightarrow} d^5\ ML_5 \underset{\circ}{\longleftrightarrow} d^7\ ML_4 \underset{\circ}{\longleftrightarrow} d^9\ ML_3$

It is also possible to derive isolobal relationships between fragments which basically belong to the 18e octahedral and 16e square planar situations (Fig. 10.12). For example, in the ML_5 and ML_4 cases, when a pair of axial ligands is removed to infinity, an interesting extension of the isolobal analogy is obtained.

As the z-axis is oriented in the direction of the removed ligands, the metal d_{z^2} orbital is lowered in energy and it gets stabilised. From the MO picture it can be seen that the d_{z^2} orbital comes down from the metal–ligand σ antibonding manifold to become a nonbonding orbital. The frontier orbitals remain the same. Therefore, one can observe an isolobal relationship between, say, d^8-ML_4 and d^{10}-ML_2 such as $Fe(CO)_4$ and $Ni(PPh_3)_2$. Figure 10.13 summarises the realm of isolobal analogy.

The possibilities are therefore numerous for isolobal analogy. It is also possible to go up or down in a group of the periodic table. For example, the CH_2 unit can be isolobal to many other fragments as shown below.

$$CH_2 \underset{\circ}{\longleftrightarrow} Fe(CO)_4 \underset{\circ}{\longleftrightarrow} CpFe(CO)^- \underset{\circ}{\longleftrightarrow} CpRh(CO) \underset{\circ}{\longleftrightarrow}$$

$$SiH_2 \underset{\circ}{\longleftrightarrow} Ru(CO)_4 \underset{\circ}{\longleftrightarrow} Pt(CO)_2 \underset{\circ}{\longleftrightarrow} Pd(PPh_3)_2 \underset{\circ}{\longleftrightarrow}$$

$$Rh(CO)_2^- \underset{\circ}{\longleftrightarrow} Cr(CO)_5 \underset{\circ}{\longleftrightarrow} Pt(CO)[P(OR)_3] \underset{\circ}{\longleftrightarrow} Os(CO)_3$$

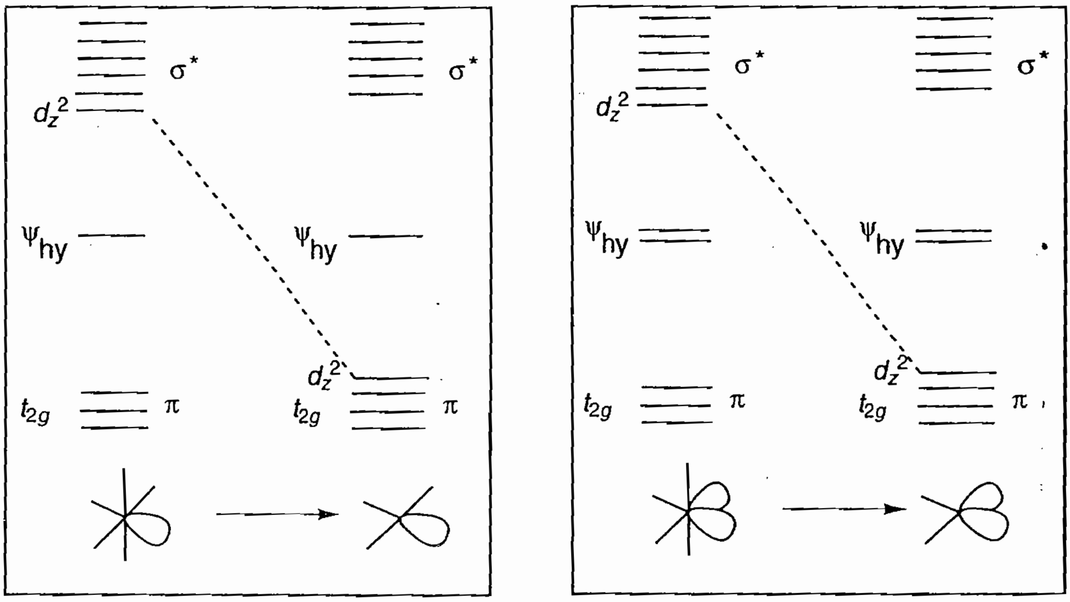


Fig. 10.12 Isolobal relationship between the 18e octahedral and 16e square planar fragments

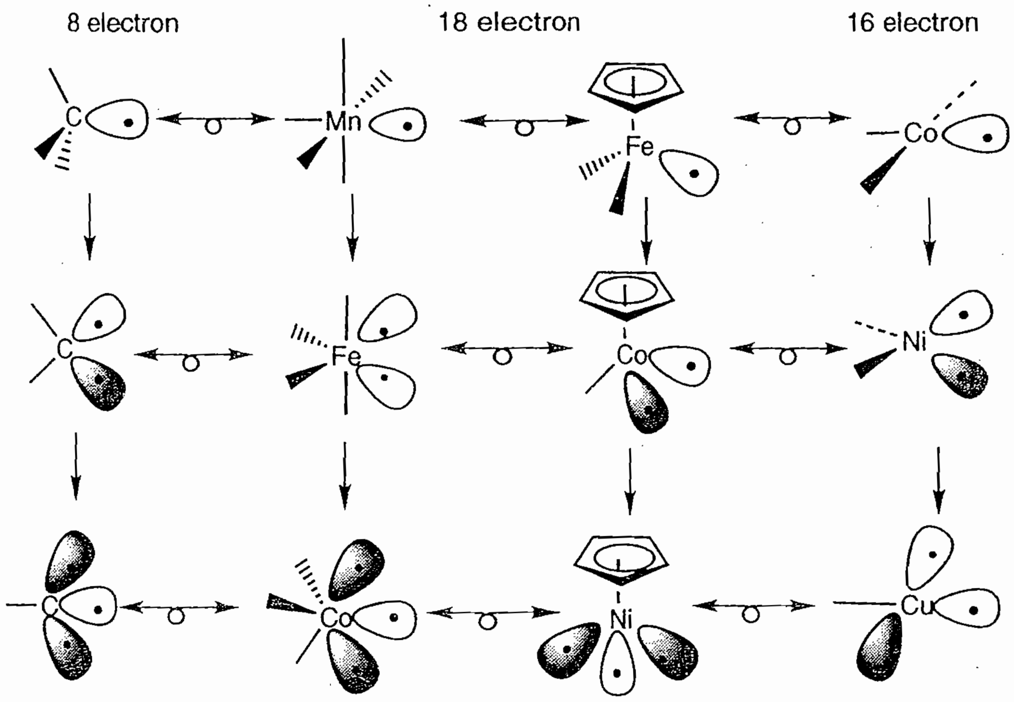
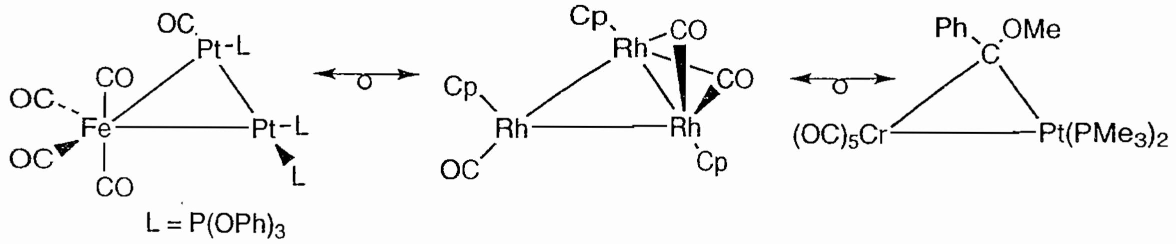


Fig. 10.13 Scheme showing isolobal analogy between 8e, 18e and 16e fragments

As a consequence, many organometallic analogues of cyclopropane can be found in the literature. It is also important to note that there can be relaxations in geometry especially in cases such as those compounds having bridging and terminal carbonyl groups.[20]



While polyhedral electron counting of boranes and simple clusters requires mostly four structural types to describe cluster geometries, the diversity of metal cluster geometries requires an extension of the relations between the number of skeletal electron pairs and the number of apical units (*n*). Therefore, a few more structural types are required to describe them (Table 10.5).[21]

Table 10.5 Wade nomenclature for metal cluster geometries

Skeletal electron pair	Borane analogue	Wade nomenclature	Metal cluster geometry
$n - 1$	$(B_nH_n)^{2+}$	*superhypercloso*	Polyhedron with 2 faces metal capped
n	B_nH_n	*hypercloso*	Polyhedron with 1 face metal capped
$n + 1$	$(B_nH_n)^{2-}$	*closo*	Regular polyhedron (tbp, Oh etc)
$n + 2$	$(B_nH_n)^{4-}$	*nido*	Polyhedron with 1 vertex unoccupied
$n + 3$	$(B_nH_n)^{6-}$	*arachno*	Polyhedron with 2 vertices unoccupied
$n + 4$	$(B_nH_n)^{8-}$	*hypho*	Polyhedron with 3 vertices unoccupied

Since $Co(CO)_3 \underset{\circ}{\longleftrightarrow} CH \underset{\circ}{\longleftrightarrow} BH^-$

therefore, $Fe(CO)_3 \underset{\circ}{\longleftrightarrow} Os(CO)_3 \underset{\circ}{\longleftrightarrow} BH$

One can thus consider, $[Os_5(CO)_{15}]^{2-} \underset{\circ}{\longleftrightarrow} [B_5H_5]^{2-}$

which will have a closo geometry. In reality, $[Os_5(CO)_{15}]^{2-}$ has a trigonal bipyramidal arrangement of Os atoms in the cluster.

In a similar manner, one can assign the cluster geometry for the following clusters which have been found to agree with the experimentally observed structure.

$[Os_6(CO)_{18}]^{2-}$	$\underset{\circ}{\longleftrightarrow}$	$[B_6H_6]^{2-}$	*closo*	regular octahedron
$[Os_6(CO)_{18}]$	$\underset{\circ}{\longleftrightarrow}$	$[B_6H_6]$	*hypercloso*	tbp with one face capped

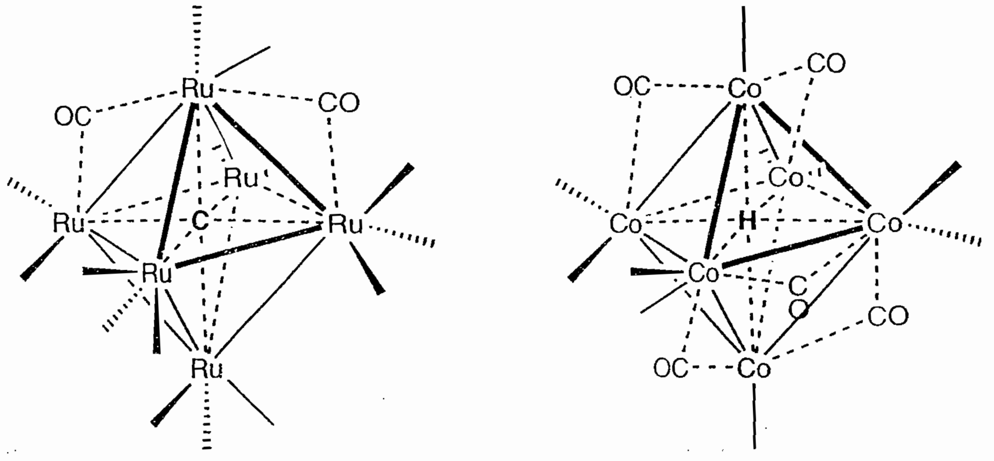
$[Os_7(CO)_{21}] \underset{\text{o}}{\longleftrightarrow} [B_7H_7]$ *hypercloso* monocapped octahedron

$[Os_8(CO)_{23}] \underset{\text{o}}{\longleftrightarrow} [Os_8(CO)_{24}]^{2+} \underset{\text{o}}{\longleftrightarrow} [B_8H_8]^{2+}$ *superhypercloso*

10.4.1 Clusters Having Interstitial Main Group Elements

There are many examples of clusters where a main group element such as carbon, nitrogen, boron, hydrogen or phosphorus is embedded inside the cavity of medium and large size clusters. The most unusual aspect of such clusters is the coordination numbers of the embedded atoms which tend to stabilise the cluster framework. Carbido clusters with carbon present in a penta or hexacoordinate environment form the best examples of such compounds. The structural predictions for clusters using the isolobal analogy is also applicable to many such examples. The method is to formally dissect the cluster into two parts, removing the embedded main group element and compensating the main transition metal containing fragment with the required charge.

The carbido cluster $Ru_6(CO)_{17}C$ has a perfect octahedral arrangement of ruthenium atoms with the carbon occupying the centre of the octahedron. In the isolobal analogy, the cluster is dissected into $[Ru_6(CO)_{17}]^{4-}$ and C^{4+} (Fig. 10.14).



$Ru_6(CO)_{17}C$ $[HCo_6(CO)_{15}]^-$

Fig. 10.14 Structures of $Ru_6(CO)_{17}C$ and $[HCo_6(CO)_{15}]^-$

$[Ru_6(CO)_{17}]^{4-} \underset{\text{o}}{\longleftrightarrow} [Ru_6(CO)_{18}]^{2-} \underset{\text{o}}{\longleftrightarrow} [B_6H_6]^{2-}$ *closo*

In a similar manner, one can assign cluster geometries for the following compounds.[22]

$[HCo_6(CO)_{15}]^- \underset{\text{o}}{\longleftrightarrow} [Co_6(CO)_{15}]^{2-} \underset{\text{o}}{\longleftrightarrow} [Fe_6(CO)_{18}]^{2-}$

$[B_6H_6]^{2-}$ *closo*

(six electrons are made equivalent to 3 carbonyl groups)

$$[Fe_5(CO)_{15}C] \underset{\circ}{\longleftrightarrow} [Fe_5(CO)_{15}]^{4-} \underset{\circ}{\longleftrightarrow} [B_5H_5]^{4-} \quad \textit{nido}$$

Similarly $Fe_4(CO)_{13}C$ will be isolobal with $[B_4H_4]^{6-}$ and gives an *arachno* structure; $Fe_5C(CO)_{15}$ is isolobal with $[B_5H_5]^{4-}$ and gives a *nido* structure.

It should however be noted that unlike boranes and carboranes, the number of clusters which do not obey the rules are more in number in case of transition metal clusters. The exceptions are more for the later transition elements where the 16 electron versus 18 electron issue crops up and also wherever there is a dominance of steric factors over electronic factors. Large transition metals tend to bring about significant geometrical distortion. Also, often a kinetically favoured structure may not be able to convert to a more thermodynamically favourable structure. The following examples of nickel clusters illustrate this point.

$$BH \underset{\circ}{\longleftrightarrow} Os(CO)_3 \underset{\circ}{\longleftrightarrow} Ni(CO)_2$$

$$\text{so, } [Ni_5(CO)_{12}]^{2-} \underset{\circ}{\longleftrightarrow} [Ni_5(CO)_{10}]^{6-} \underset{\circ}{\longleftrightarrow} [B_5H_5]^{6-} \quad \textit{arachno}$$

However, in reality $[Ni_5(CO)_{12}]^{2-}$ has a closo structure with a trigonal bipyramidal geometry.

$$\eta^5\text{-}CpNi \underset{\circ}{\longleftrightarrow} Co(CO)_3 \underset{\circ}{\longleftrightarrow} BH^-$$

$$[CpNi]_6 \underset{\circ}{\longleftrightarrow} [B_6H_6]^{6-} \quad \textit{arachno}$$

In reality, the six nickel atoms form an octahedron with the 6 Cp units at each of the nickel atoms.

10.5 SYNTHESIS OF METAL CARBONYL CLUSTERS

Pyrolysis of mono-, di- and trinuclear carbonyls has been one of the well known established methods for preparing metal carbonyl clusters with higher metal content. Reactions of metal complexes, oxides and halides with CO at high temperatures and pressures also yield a few carbonyl clusters.

$$3\,Ru(CO)_5 \xrightarrow[50°C]{} Ru_3(CO)_{12} + 3\,CO \qquad (10.10)$$

$$2\,Co_2(CO)_8 \xrightarrow[70°C]{} Co_4(CO)_{12} + 4\,CO \qquad (10.11)$$

$$Ru(acac)_3 + CO + H_2 \xrightarrow[150°C,\ 155\ atm]{MeOH} Ru_3(CO)_{12} + MeC(O)CH_2C(O)Me \qquad (10.12)$$

$$RuO_2.\,x\,H_2O + CO \xrightarrow[20\ atm,\ 160°C]{toluene} Ru_3(CO)_{12} + CO_2 \qquad (10.13)$$

$$OsO_4 + CO \xrightarrow[125°C/75\ atm]{MeOH} Os_3(CO)_{12} + 4\,CO_2 \qquad (10.14)$$

$$Os_3(CO)_{12} \xrightarrow[\text{pressure}]{\Delta} Os_5(CO)_{16} + Os_6(CO)_{18} + Os_7(CO)_{21}..\text{etc} \qquad (10.15)$$

$$Na_3IrCl_6 + CO \xrightarrow[\text{reflux, 1atm}]{\text{MeOH}} Ir_4(CO)_{12} \qquad (10.16)$$

$$[Rh(CO)_2Cl]_2 \xrightarrow[\text{CO, }H_2O\text{, }NaHCO_3]{\text{heptane}} Rh_4(CO)_{12} \qquad (10.17)$$

$$RhCl_3.\,3H_2O + CO \xrightarrow[60°C\text{, 40–50 atm}]{\text{MeOH}} Rh_6(CO)_{16} \qquad (10.18)$$

Addition of carbonyl metallates to trinuclear carbonyls

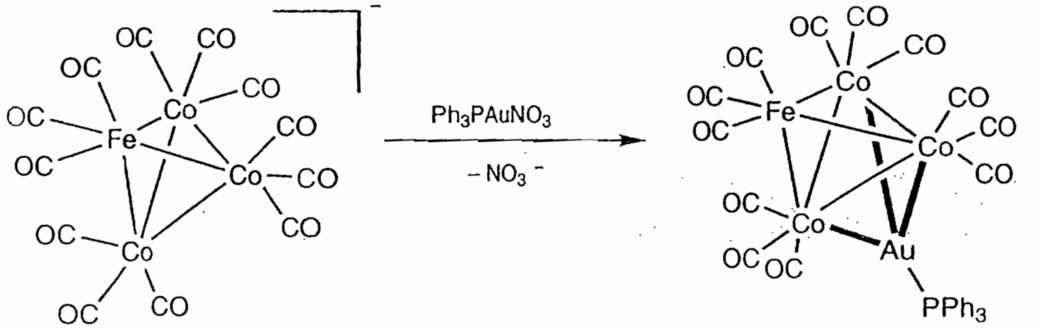
A method for preparing bimetallic tetrahedral clusters is by the addition of carbonyl anions to trinuclear carbonyls. Triangular 48 VE clusters can be transformed to tetrahedral 60 VE clusters by this method.

$$Ru_3(CO)_{12} + [Fe(CO)_4]^{2-} \xrightarrow{-3\text{ CO}} [FeRu_3(CO)_{13}]^{2-} \qquad (10.19)$$

$$Os_3(CO)_{12} + [Co(CO)_4]^{-} \xrightarrow{-3\text{ CO}} [CoOs_3(CO)_{13}]^{-} \qquad (10.20)$$

Cluster expansion by capping of metallates

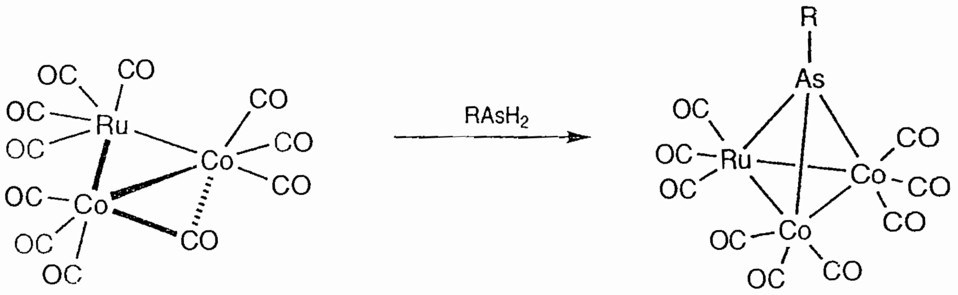
A variety of cationic capping agents can be used for cluster expansion. A well known example is the replacement of H by Ph_3PAu. Ph_3PAu^+ and H^+ are isolobal with each other as seen in the metal complex pair $(CO)_4CoH$ and $(CO)_4CoAuPPh_3$.[23]



(10.21)

Cluster expansion by introducing main group fragments

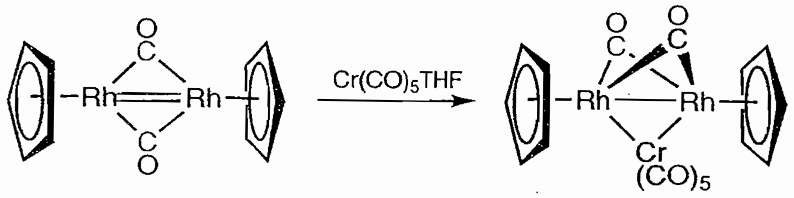
Triangular clusters can also be converted to tetrahedral clusters by capping with a main group unit.[24]



(10.22)

Addition to metal–metal multiple bonds

Multi-metal clusters are also synthesised by the addition of metal carbonyls to metal–metal multiple bonds.



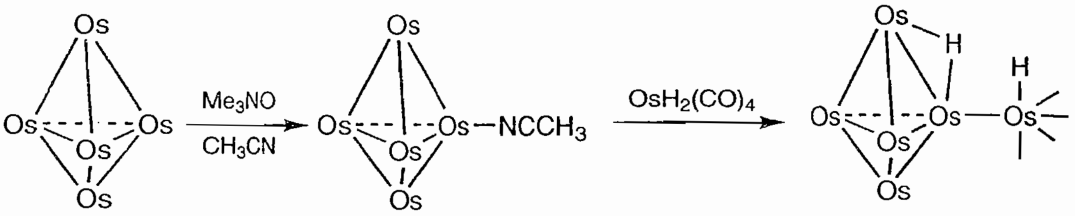
(10.23)

10.6 REACTIONS OF METAL CARBONYL CLUSTERS

A few unique reactions of metal carbonyl clusters are discussed below.

Removal of carbon monoxide

Reaction of carbonyl clusters with amine oxide Me_3NO in the presence of acetonitrile results in the removal of a CO as CO_2 and MeCN occupying the empty site.[25]

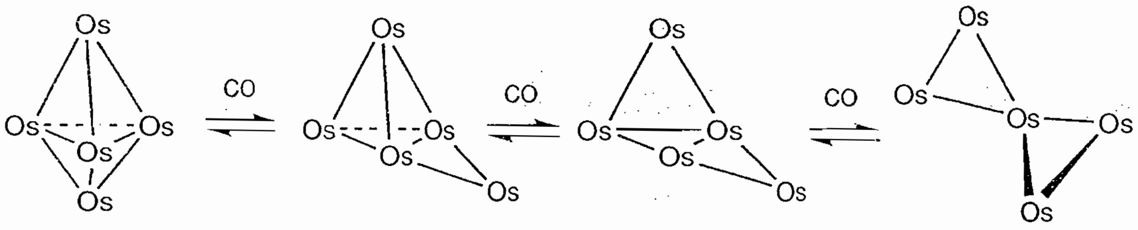


(10.24)

$Os_5(CO)_{16}$ $Os_5(CO)_{15}(CH_3CN)$ $Os_6(CO)_{19}H_2$

Addition of carbon monoxide

Stepwise addition of carbon monoxide to polyhedral carbonyl clusters results in opening up of the structure.[26]



(10.25)

$Os_5(CO)_{16}$ $Os_5(CO)_{17}$ $Os_5(CO)_{18}$ $Os_5(CO)_{19}$

Oxidative additions of hydrogen and chlorine

There is a considerable difference observed in the oxidative addition of hydrogen and halogens to metal clusters. The difference mostly arises due to the fact that H is a one electron donor while a bridging Cl is a three electron donor. The addition of H_2 to $Os_3(CO)_{12}$ is accompanied by the loss of CO to give a bis-hydrogen bridged cluster. In contrast, Cl_2 directly oxidises by breaking a metal-metal bond and forming a linear cluster. The linear cluster on pyrolysis gets converted to a chloro-bridged cluster.

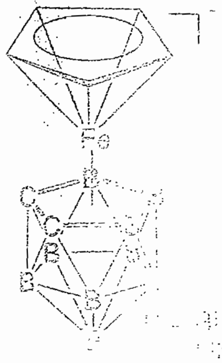
Jemmis' *mno* rules[27, 28]

Recent developments in organometallic clusters have resulted in the discovery of a large number of metal clusters consisting of more than one polyhedron and such systems are generally called *macropolyhedral clusters*. While the polyhedral skeletal electron pair theory (Wade's rule) helps to predict the stability of a single polyhedral system, it is not generally applicable to macropolyhedral clusters. In 2001, E D Jemmis and coworkers came up with a novel and very simple rule which could predict the stability of macropolyhedral systems. *Jemmis' mno rule* states that *$m + n + o$ skeletal electron pairs are necessary for a closed macropolyhedral system to be stable* [or $(m + n + o + p)$ for systems having open polyhedra as well].

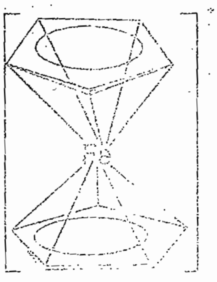
Here m = number of condensed polyhedra
n = number of vertices
o = number of single atom bridges between two polyhedra
p = number of vertices missing for open polyhedra if present.

For example, for *nido* clusters $p = 1$ and for *arachno* clusters $p = 2$. For a benzene ring or cyclopentadienyl ring as such $p = 2$ and if it is already in an η^6 or η^5 mode, p= 1. For transition metals, the oxidation state of the metal should be known and the number of electrons for the electron count should be taken as the same as the number of electrons lost by the neutral metal atom to reach that oxidation state; for example, Fe^{3+} gives 3 electrons.

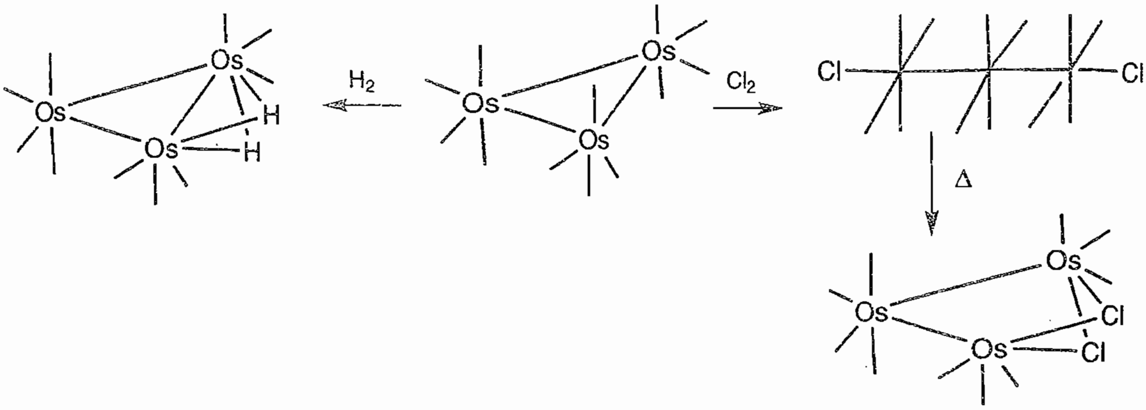
The uniqueness of Jemmis' *mno* rules is that they are not only applicable to macropolyhedral clusters but can also be applied to polyhedra, polyhedra having metallocenyl fragments, metallocenes, and even unsaturated cyclic organic and main group compounds. Interestingly, Jemmis' rules get reduced to Wade's rules when $m = 1$ and $o = 0$ (one polyhedron). Wade's rules, in principle, can also be used for predicting the stability of cyclic unsaturated organic molecules, but only for single ring systems. For example, it can be used for benzene but not for naphthalene. The Jemmis' *mno* rule, in contrast, is applicable to condensed systems such as naphthalene as well. It is also seen that the *mno* rule is the same as the Hückel rule if we add the σ electrons to the Hückel π electron count. The following examples illustrate the counting of electrons according to the *mno* rules and predicting stability.



$[(7,8\text{-}C_2B_9H_{11})Fe(Cp)]^-$
Jemmis' *mno* rule
$m+n+o+p = 2+17+1+1= 21$
Skeletal electron pairs
$9\ BH + 7CH + Fe^{2+} + (-1)$
9 + 10.5 + 1 + 0.5 = 21 paris
stable



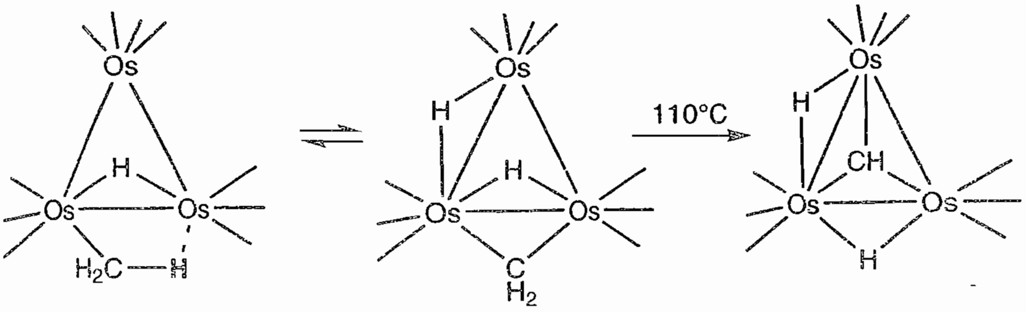
$[Cp_2Fe]^+$
Jemmis' *mno* rule
$m+n+o+p = 2+11+1+2 = 16$
Skeletal electron pairs
$10\ CH + Fe^{3+}$
15 + 1.5 = 16.5 paris
unstable



(10.26)

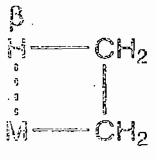
Selectivity in C–H oxidative additions

- Generally, an alkyl group bound to a mononuclear complex undergoes β-elimination of a hydride. However, an alkyl in a cluster usually undergoes an α-elimination of the hydride. However, an interesting similarity with β-elimination can be seen, since the C–H bond broken by the cluster is not by the metal to which the ligand is bound, but by the adjacent metal. The hydride often ends up as a bridging hydride in the cluster.

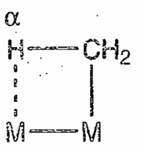


(10.27)

The representation of the 4-membered intermediate for conventional β-hydrogen elimination in mononuclear complexes and α-hydrogen elimination in metal clusters is given as follows.



A mononuclear complex



A metal cluster

Problems and Exercises

10.1. The compound $Co_3CH(CO)_9$ is formed from the reaction of chloroform with $Co_2(CO)_8$. The infrared spectrum shows the presence of terminal carbonyls only and the presence of CH is confirmed by ^{1}H-NMR. Propose a structure for the compound based on Wade's rules.

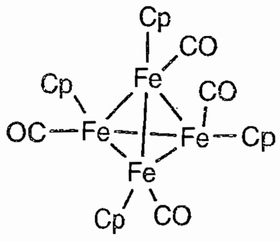
10.2. Consider the following molecules. Calculate the total valence electron count (TEC), polyhedral electron count (PEC) and assign each one as *closo*, *nido*, *arachno* or *hypho*.

(a) $[Ni_5(CO)_{12}]^{2-}$ (b) $Os_6(CO)_{17}[P(OMe)_3]_3$

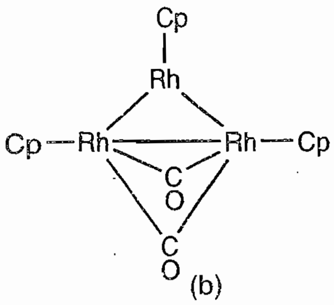
(c) $[Ru_5N(CO)_{14}]^-$ (d) $Os_4(CO)_{12}(\mu^4\text{-}C_2Me_2)$

10.3. $Os_6(CO)_{18}$ has a monocapped TBP structure. Upon adding two electrons, the structure changes to octahedral. Explain this observation on the basis of Wade's rules.

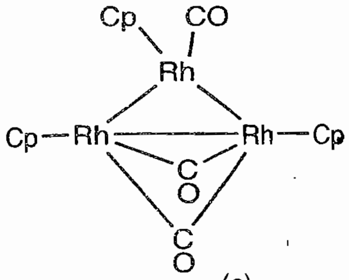
10.4. Derive the isolobal organic hydrocarbon fragment for the following molecules.



(a)

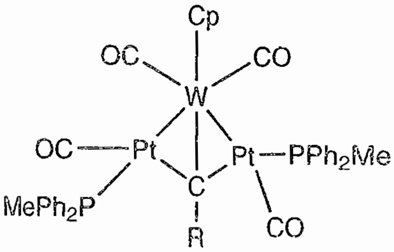


(b)

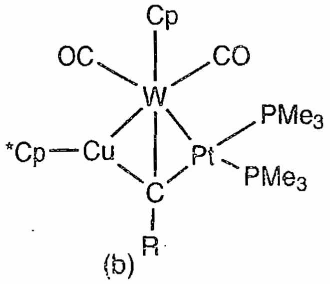


(c)

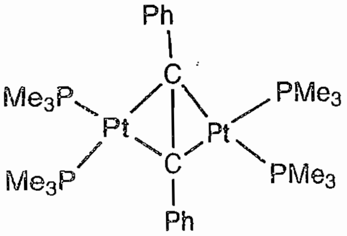
10.5. Are the following compounds composed of isolobal fragments? Verify.



(a)



(b)

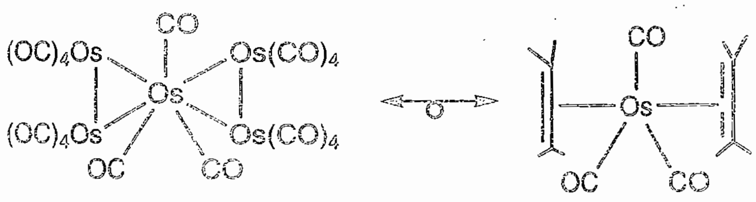


(c)

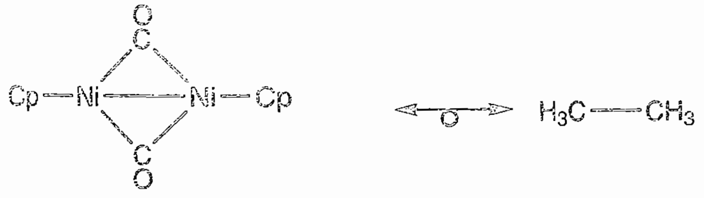
10.6. Rationalise the following in terms of isolobal analogy.

(a) $(OC)_4Fe{=}Fe(CO)_4 \quad \underset{o}{\longleftrightarrow} \quad (OC)CpRh{=}RhCp(CO)$

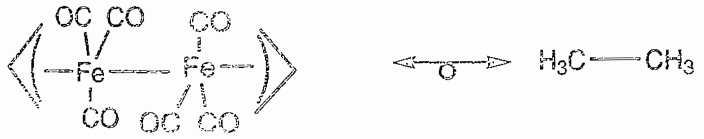
(b)



(c)

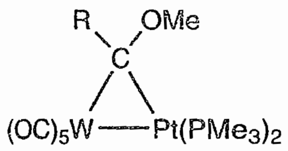


(d)

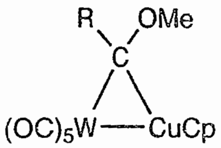


10.7. Determine if the following compounds are isolobal with each other or not.

(a)



(b)



10.8. From the following isolobal analogies, pick true or false in each series.

(a) $\mathrm{CH_2} \underset{o}{\longleftrightarrow} \mathrm{SiH_2} \underset{o}{\longleftrightarrow} \mathrm{Fe(CO)_4} \underset{o}{\longleftrightarrow} \mathrm{Ru(CO)_4}$

(b) $\mathrm{CH_3} \underset{o}{\longleftrightarrow} \mathrm{BH_3^-} \underset{o}{\longleftrightarrow} [\mathrm{Fe(CO)_5}]^+ \underset{o}{\longleftrightarrow} \mathrm{Mn(CO)_5}$

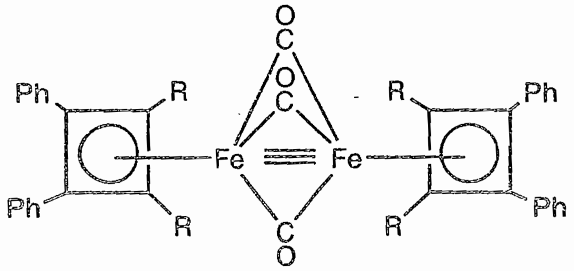
(c) $\mathrm{CH_3^+} \underset{o}{\longleftrightarrow} \mathrm{BH_3} \underset{o}{\longleftrightarrow} [\mathrm{Cr(CO)_5}]^- \underset{o}{\longleftrightarrow} \mathrm{Mn(CO)_5^+}$

(d) $\mathrm{CH^+} \underset{o}{\longleftrightarrow} \mathrm{Fe(CO)_3} \underset{o}{\longleftrightarrow} \mathrm{CpCo} \underset{o}{\longleftrightarrow} \mathrm{Ni(PR_3)_2}$

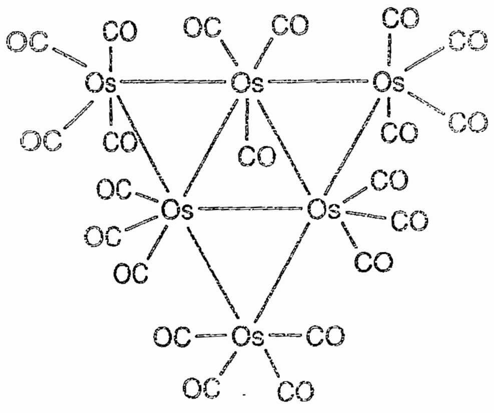
(e) $\mathrm{Ni(CO)_3} \underset{o}{\longleftrightarrow} \mathrm{CH_2} \underset{o}{\longleftrightarrow} \mathrm{CH_3^+} \underset{o}{\longleftrightarrow} \mathrm{CH^-}$

10.9. The osmium cluster $\mathrm{Os_6(CO)_{18}Py}$ has a total valence electron count of 86e. Wade's rule predicts an octahedral structure but its observed structure is an edge capped TBP. Using Mingos' rules, schematically show how this structure can be constructed.

10.10. The following compound looks very different from acetylene. But both are isolobal with each other. Justify the statement.



10.11. The observed structure of $\mathrm{Os_6(CO)_{21}}$ is as follows. Show three different ways to construct this structure starting with a smaller 3-atom polyhedral cluster (*J. Organometal. Chem.*, 1990, Vol. 394, 533).



Supplementary reading

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CHAPTER

11

HOMOGENEOUS CATALYSIS USING ORGANOMETALLIC COMPOUNDS

11.1 CATALYSIS

A thermodynamically favourable reaction may be very slow at moderate temperatures and may therefore not be of much value for synthesis. Increasing the temperature of the reaction may significantly accelerate its rate, but providing the energy to do so is expensive. High temperatures may also induce competing side reactions which will lead to the reduction in the yield of the desired product. A more attractive approach is to increase the rate of a reaction using a catalyst. Catalysts are widely used in nature, in industry and in the laboratory, and it is estimated that they contribute to one sixth of the value of all manufactured goods in industrialised countries. In industrial processes, a non-catalysed reaction often gives side products which have to be discarded and thus add on to the cost of production. In recent days, concerns about pollution have promoted the idea of 'atom economy' in chemical reactions, especially in industrial processes. An atom-economic reaction is one in which all the atoms of the reactants are used to form the product and no side products are formed. Many homogeneous catalysed reactions such as the industrial conversion of methanol to acetic acid are atom economic in nature.

The Arrhenius equation states that the rate constant, k, of a reaction is directly proportional to the frequency factor (A), inversely proportional to the activation energy E_a, and directly proportional to the temperature.

$$k = Ae^{-Ea/RT} \tag{11.1}$$

The negative exponent means that k is large when the value of E_a/RT is small (and vice versa). E_a/RT will be small when E_a is small or T is large (R is a constant). Thus, k is large when T is large or E_a is small. If a catalyst has to increase the reaction rate k, it should do so by two ways.

Catalyst: A substance that brings reactants together and accelerates their interactions but does not permanently get changed during a reaction. This function is aptly reflected in the Chinese term for catalyst, 'tsoo mei', which literally means 'marriage broker'.

- Increase the frequency factor *A*, (that is, in some way increase the rate of successful molecular collisions).
- Decrease the activation energy, E_a.

In general, a catalyst typically increases the reaction rates by lowering the activation energy by opening up pathways with lower Gibbs free energies of activation (*G*). A catalyst does not affect the Gibbs free energy of the overall reaction because *G* is a state function. (*G* depends only on the current state of the system and not on the path that leads to the state.) Thus, reactions which are thermodynamically unfavourable cannot be made favourable by a catalyst. The free energy profile of a catalysed reaction contains no high peaks and no deep troughs. An important point is that the stable catalytic intermediates (dotted curve in Fig. 11.1) should not occur in the cycle and the product must be released in a thermodynamically favourable step. If a stable product is formed with the catalyst, it would turn out to be the final product of the reaction and the catalytic cycle will not continue.

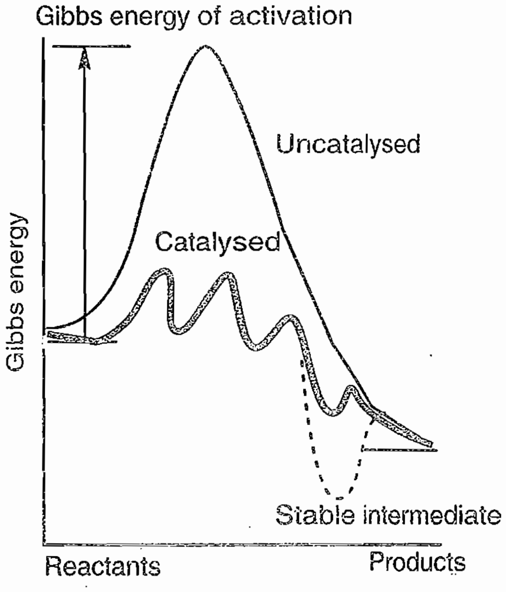


Fig. 11.1 Difference between catalysed and uncatalysed reactions

Catalysts are classified as homogeneous if they are soluble in the reaction medium (catalyst and reactants in the same phase) and heterogeneous if they are insoluble. Each class has its advantages and disadvantages (Table 11.1). Heterogeneous catalysts are easily separated from the reaction products but tend to require rather high temperature and pressure, and frequently lead to a mixture of products, that is, they have low selectivity. Homogeneous catalysts, as they mix with the products are difficult to separate from the products. However, they operate at relatively low temperature and pressure and usually give good selectivity. Homogeneous catalysis is also mechanistically better understood since solution reactions can be more easily monitored and modified compared to surface reactions.

Although a variety of new homogenous catalysts have come up in the last two decades, heterogeneous catalysts still dominate the chemical and petrochemical industries. Around 90% of all the chemical processes depend largely on heterogeneous

Table 11.1 Comparison of homogeneous and heterogeneous catalysts

Parameter	Heterogeneous	Homogeneous
Phase	Gas/solid	Usually liquid/ or solid soluble in the reactants
Required temperature	High	Low (less than 250°C)
Activity	Low	High
Diffusion	Very important	Facile
Heat transfer	Problematic	Facile
Product selectivity	Less (often mixtures)	More
Catalyst recycling	Simple and cost effective	Expensive and complex
Reaction mechanism	Poorly understood	Reasonably well understood
Product separation from catalyst	Easy	Elaborate and sometimes problematic
Fine tuning of catalyst	Difficult	Easy
Catalyst deactivation	Less sensitive	More sensitive

catalysts. Homogenous catalysts are often used when selectivity is critical and the problems associated with product–catalyst separation can be resolved. Table 11.2 lists some of the well known examples of homogeneous catalytic processes of industrial importance.

Many homogeneous catalysts can decompose to form heterogeneous catalysts, and some can be made insoluble by anchoring to a polymeric substrate. As heterogeneous catalysts can also remain as colloids, one should always be careful about making assumptions on what type of catalyst one is using in any new catalytic process. There are several general ways to test whether a catalyst is homogeneous or heterogeneous. For example, exposure to elemental mercury will generally poison a heterogeneous catalyst while exposure to polythiols can poison most homogeneous catalysts. Light scattering studies can be used to identify the presence of colloids and thereby the heterogeneous nature of catalysts.

11.2 TERMINOLOGY IN CATALYSIS

Some of the commonly used terms in catalytic processes are given below.

11.2.1 Turnover (TO)

Catalysis occurs in cycles where the active form of the catalyst gets regenerated. Turnover describes one loop through a catalyst cycle. Typically, one equivalent of reactant is converted to one equivalent of product (per equivalent of catalyst).

Table 11.2 Some industrially important homogenous catalysis reactions

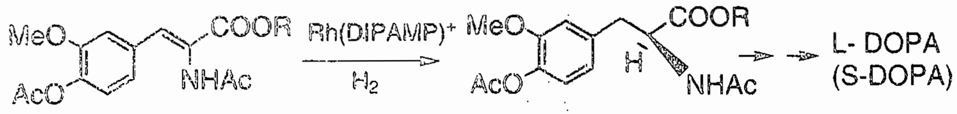
Process and reaction	Catalysts used and contributors associated with the process	Industrially important end products and processes
Hydrogenation of alkenes $RHC{=}CH_2 + H_2 \longrightarrow RCH_2CH_3$	$RhCl(PPh_3)_3$ (G Wilkinson) $[Rh(PPh_3)_2(COD)]^+$ (R R Schrock, J A Osborn) $[Ir(COD)(Py)(PCy_3]^+$ (R H Crabtree)	Hydrogenated oils
Asymmetric hydrogenation of prochiral alkemes 	$[Rh(DIPAMP)(S)_2]^+$ (W S Knowles) $[RuCl_2(R\text{-}BINAP)]$ (R Noyori)	L-DOPA, asparatame, L- menthol
Hydroformylation of alkenes $RCH{=}CH_2 + CO + H_2 \longrightarrow RCH_2CH_2CHO + RCH(CH_3)CHO$	$Co_2(CO)_8$, $Co_2(CO)_8/PR_3$ $HRh(CO)(PPh_3)_3$ (O Roeln, D S Breslow, R F Heck) Union Carbide	Dioctyl phthalate (DOP) 2-ethylhexanol 1,4-butanediol
Oxidation of alkenes (Wacker process) $CH_2{=}CH_2 + O_2 \longrightarrow CH_3CHO$ $H_2C{=}CH_2 + 1/2\ O_2 + CH_3COOH \longrightarrow H_2C{=}CHO(CO)CH_3$	$PdCl_4^{2-}$ Hoechst-Wacker	Acetaldehyde, vinyl chloride, vinyl acetate, terephthalic acid
Carbonylation of methanol to acetic acid $CH_3OH + CO \longrightarrow CH_3COOH$ $CH_3C(O)OCH_3 + CO \longrightarrow [CH_3C(O)]_2O$	$[Rh(CO)_2I_2]^-$ Monsanto (BASF), $[Ir(CO)_2I_2]^-$ Cativa (BP chemicals)	Acetic acid, acetic anhydride

Table 11.2 Continued

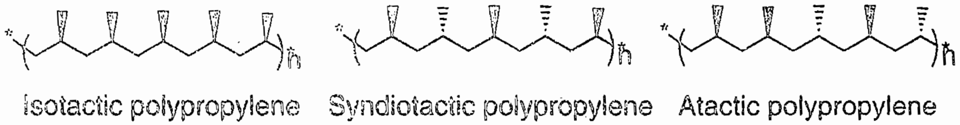
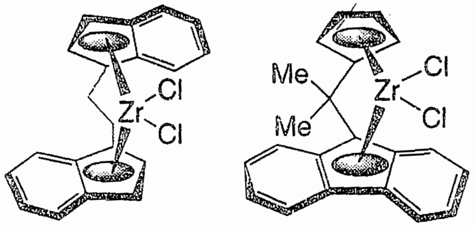
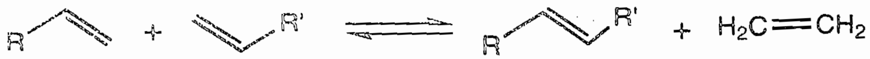
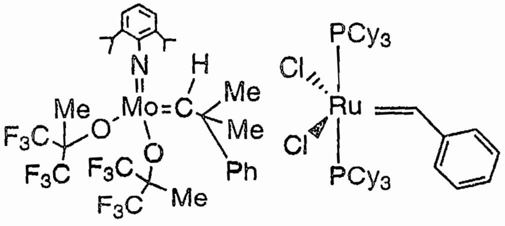
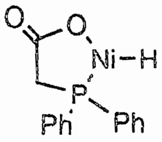
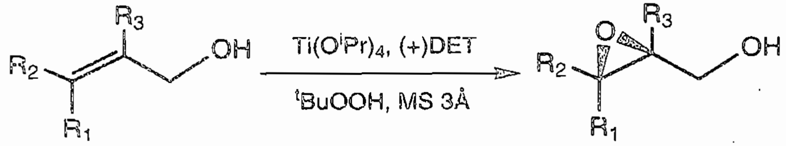
Process and reaction	Catalysts used and contributors associated with the process	Industrially important end products and processes
Polymerisation of alkenes  Isotactic polypropylene Syndiotactic polypropylene Atactic polypropylene	 (W Kaminsky, T Ziegler , M Brookhart)	Polyethylene (LLDPE, HDPE,UHMWPE polypropylene (isotactic, syndiotactic and atactic)
Olefin metathesis 	 Schrock's and Grubbs catalysts (R R Schrock, R Grubbs)	Linear olefins, polydicyclo pentadiene, OCT (olefin conversion technology) process
Oligomerisation of alkenes  C_4-C_8 40% C_{10}- C_{18} 40 % C_{20} & > 20 %	 Shell's SHOP process	Linear α olefins, dimersol (mix of propene / butene)
Hydrocyanation of alkenes $CH_2{=}CHCH{=}CH_2 + 2\,HCN \xrightarrow{NiL_4/\,L} NCCH_2CH_2CH_2CH_2CN$	$Ni[P(O\text{-}o\text{-}tolyl)_3]_4$ Dupont	Adiponitrile (nylon precursor)

Table 11.2 Continued

Process and reaction	Catalysts used and contributors associated with the process	Industrially important end products and processes
Hydrocarboxylation of acetylenes $HC\equiv CH + CO + H_2O \longrightarrow CH_2{=}CHCOOH$ $HC\equiv CH + CO + ROH \longrightarrow CH_2{=}CHCOOR$	$Ni(CO)_4/HX$ $HCo(CO)_4$ BASF, Röhm and Haas	Acrylic acid, acrylates (used in superabsorbent polymers and paint additives)
Carbonylation of alkenes to polyketones $n\ CH_2{=}CH_2 + n\ CO \longrightarrow *\!-\!\left[C(O)\ CH_2CH_2\right]_n\!-\!*$	$[Pd(dppp)](OAc)_2$/ TsOH Shell (Pd/ Phosphine)	Polyketones (Carilon, Shell)
C–C and C–N cross coupling reactions $RB(OH)_2 + R'X \xrightarrow[\text{base}]{L_nPd^0} R\text{-}R' + BX(OH)_2$ Suzuki $HC\equiv CR + R'X \xrightarrow[Et_3N]{PdL_n,\ CuI} R-C\equiv C-R'$ Sonogashira	$Pd(PPh_3)_4$, $Pd(OAc)_2/R_3P$ $PdCl_2(dppf)$ Suzuki, Heck, Sonogashira, Stille, Kumuda, Hiyama, Buchwald–Hartwig coupling reactions	Valsartan (anti hypertensive), Boscalid (fungicide)
Hydrosilylation reaction $Et_3SiH + PhC\equiv CPh \xrightarrow{[Pt]} Et_3Si(Ph)C{=}CHPh$ $Cl_3SiH + PhCH{=}CH_2 \xrightarrow{[Pt]} PhCH(SiCl_3)CH_3$	Speier's catalyst H_2PtCl_6 Lukevic's catalyst $(NBu_4)_2PtCl_6$ Karstedt's catalyst $\left[O(SiMe_2CH = CH_2)_2\right]_3Pt_2$	Vinyl silanes, silyl ethers, cross linking of silicone polymers, dendrimer synthesis
Asymmetric epoxidation  	$Ti(OiPr)_4$, (+)Diethyl tartarate, t-BuOOH , molecular sieves 3Å (K B Sharpless)	Chiral 2, 3-epoxy alcohols

11.2.2 Turnover Number (TON)

The absolute number of passes through the catalytic cycle before the catalyst becomes deactivated is called the turnover number. *TON is defined as the amount of reactant* (in moles) *divided by the amount of catalyst* (in moles) *times the percentage yield of product* (in decimals, that is, 65% is taken as 65/100). A large TON (such as 10^5–10^{10}) indicates a stable catalyst with a long life.

11.2.3 Turnover Frequency (TOF) or Turnover Rate

It is the number of passes through the catalytic cycle per unit time (often per hour). This number is usually determined by taking the number of moles of product produced, dividing that by the number of moles of catalyst used in the reaction, and then dividing that by the time to produce the given amount of product. Effectively this is dividing the TON by the time taken for the reaction. The unit for TOF is $time^{-1}$. Note that the rate of a catalytic reaction is fastest at the very beginning when the concentration of the reactant is the highest and generally slows down as the reaction proceeds and stops when all the reactant is used up. The TOF, therefore, will vary throughout the course of a batch reaction. The *initial TOF* is defined as the initial part of a catalytic reaction where the rate is the fastest and essentially linear. A large TOF indicates a very efficient catalyst.

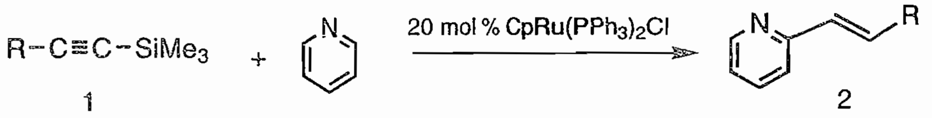
Academic chemists sometimes report only the TON when the catalyst is very slow. Industrial chemists are interested in both the TON and TOF. Calculation of TOF and TON therefore forms an integral part of any catalytic study. Authors report their results in many different ways. For example, if the catalyst is given in mole% of catalyst used, it refers to the percentage of catalyst relative to the moles or equivalents of one of the reactants present (for example, 0.01 mole% catalyst = (1/0.01)% = 10,000. This is to be multiplied by the percentage yield of product in decimals for TON). Sometimes, it is expressed directly as the substrate–catalyst ratio which needs to be multiplied by the percentage yield of product in decimals to get the TON. Also, the concentrations of catalyst and reactant are often given in different units but they should be expressed in moles. It is also possible that excess of ligand may be present, which should not affect the calculations.

It is also worth mentioning that unlike organometallic chemists, biochemists dealing with enzyme kinetics do not make a clear distinction between TON and TOF. In enzymology (Michaelis–Menten kinetics), the turnover number (also termed as k_{cat}), is defined as the maximum number of molecules of substrate that an enzyme can convert to product per catalytic site per unit time, which translates more or less to the TOF of homogeneous catalysis.

Examples 11.1 and 11.2 illustrate in detail how turnover number and turnover frequency are calculated with different kinds of experimental data.

Example 11.1

The following data was obtained for the alkenylation of pyridine with alkynyl silanes. Determine which substituent (R) gives the best TON and TOF for the compounds when the R groups are varied (data taken from Murakami M, Hori S, *J. Am. Chem. Soc.*, 2003, Vol. 125, 4720).



Entry	1 R=	Time(h)	Product	Yield(%)
1	Ph (1a)	7	2a	87
2	p-Me-C_6H_4 (1b)	9	2b	92
3	n-C_5H_{11} (1c)	6	2c	90
4	1-cyclohexenyl (1d)	11	2d	75

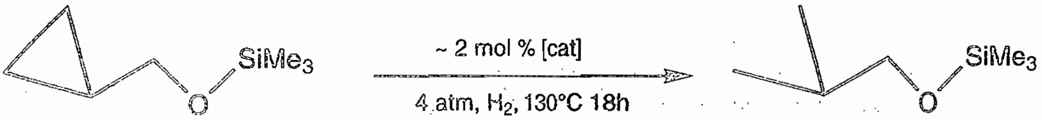
Solution

1. 20 mole% catalyst means 1 / (20/100) = 5
   TON = 5 × 0.87 = 4.35 TOF = 4.35/7 = 0.62 /h
2. TON = 5 × 0.92 = 4.6 TOF = 4.60/9 = 0.51/h
3. TON = 5 × 0.90 = 4.5 TOF = 4.50/6 = 0.75/ h
4. TON = 5 × 0.75 = 3.75 TOF = 3.75/11= 0.34/ h

The best TON is for entry 2 and the best TOF is for entry 3.

Example 11.2

The following data was obtained for catalytic hydrogenation of cyclopropyl substrates with a series of hydrogenation catalysts. Determine which among them gives the best turnover frequency (data taken from Bart S C, Chirik P J, *J. Am. Chem. Soc.*, 2003, Vol. 125, 886).



Entry	Catalyst[a]	% Product[b]
1	$(PPh_3)_4Pd$	37
2	$(PPh_3)_3RhCl$	35
3	$[(COE)_2IrCl]_2$	38
4	$[(COD)RhCl]_2$	50
5	$[(COD)IrCl]_2$	25
6	$(COD)PtCl_2$	20
7	$(PPh_3)_2Rh(CO)Cl$	9.4

[a] 2.75 mM catalyst and 0.138 M substrate in anhydrous toluene
[b] determined by GC at 18 hours; COE = cyclooctene

Solution

1. [0.138/0.00275] = 50.18
   TON = 50.18 × 0.37 = 18.56 TOF = 18.56/18 =1.03/h
2. TON = 50.18 × 0.35 = 17.56 TOF = 17.56/18 = 0.98/h
3. TON = 50.18 × 0.38 = 19.07 TOF = 19.07/18 = 1.06/h
4. TON = 25.09 TOF = 1.39/h
5. TON = 12.55 TOF = 0.69/h
6. TON = 10.04 TOF = 0.56/h
7. TON = 4.72 TOF = 0.26/h

The best TON and TOF are obtained for entry 4 of the table.

11.3 SEQUENCES INVOLVED IN A CATALYSED REACTION

The general steps involved in a homogeneous catalytic process and the sequence of events that occur in a catalysed reaction are shown in Fig. 11.2. The first step is the formation of a catalyst–substrate complex C:S. The binding between the catalyst and the substrate should not be too strong or too weak. If C:S is very stable, the activation energy required to reach the transition state C:TS′ will be similar to that of an uncatalysed reaction. If it is too weakly bound, the substrate will fail to get activated. The catalysed reaction proceeds by a multistep mechanism in which the metal stablises those intermediates that are stable only when bound to the metal (for example, the catalyst–intermediate complex, C:I^1 in Fig. 11.2). The product P will initially be formed as complex C:P which should also not be very stable. Of all the species bound to the catalyst, the product P must be the least strongly bound and if it is not, the substrate will not be able to displace the product from the catalyst and continue the catalytic cycle. This will lead to the catalyst getting deactivated (C:P″).

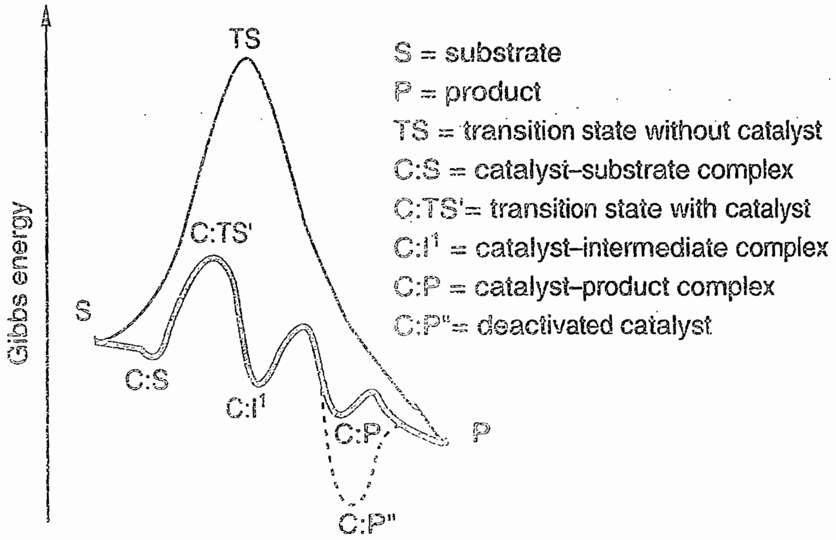


Fig. 11.2 Steps involved in a homogeneous catalytic process

Each time a complete catalytic cycle occurs, it is considered that a catalytic turnover has been completed. The slow step in a catalytic cycle is known as the turnover limiting ste

TOF can be increased by lowering the barrier for the turnover limiting step. It is observed that changes in other barriers do not affect the TOF. For realising a high TOF, it is necessary that none of the transition states are too high in energy and none of the substrate–catalyst intermediates be too strongly bound. Ideally, the whole reaction profile must not stray away from a narrow range of free energies, accessible at the reaction temperature.

11.4 OTHER IMPORTANT TERMINOLOGY USED IN CATALYSIS

Enantioselectivity (*ee*)

This defines the enantioselectivity of an asymmetric catalyst that produces more of one optically active enantiomer (*R* enantiomer, for example) than the other (*S* enantiomer). Enantiomeric excess (*ee*) is defined as:

$$ee = \frac{|R - S|}{R + S} \times 100\%$$

A catalyst that makes an equal amount of *R* and *S* enantiomers has 0% *ee* (a racemic mixture); 85% or higher is generally considered a good *ee*, although it depends on what the best known catalyst for a process does relative to that being reported.

Stereoselectivity

It is the preferential formation of one stereoisomer over another in a chemical reaction. When stereoisomers are enantiomers (non superimposable mirror images), the phenomenon is called *enantioselectivity* and is quantitatively expressed by *ee*; when they are diastereoisomers (a situation which usually arises when more than one chiral centre is present in the molecule), it is called *diastereoselectivity* and is quantitatively expressed by the diastereomeric excess. Diastereomers, unlike enantiomers generally have different chemical properties and different rates of reactivity to a particular reagent. The reactions are termed stereoselective (100%) if the discrimination is complete or partially stereoselective if one product predominates.

Chemoselectivity

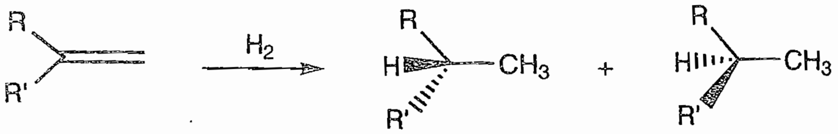
When a chemical reagent preferentially reacts with one of the two or more different functional groups present on it, it is referred to as *chemoselective*. A reagent has a high chemoselectivity if the reaction occurs with only a limited number of different functional groups. For example, $NaBH_4$ is a better chemoselective reducing agent than $LiAlH_4$. The term is also applied to reacting molecules or intermediates which exhibit selectivity towards chemically different reagents.

Regioselectivity

The preference of one direction of bond-making/breaking over all other possible directions is termed *regioselectivity*. Reactions are termed completely (100%) regioselective if the discrimination is complete, or partially regioselective if the product of reaction at one site predominates over the product of reaction at other sites. The discrimination may also semi-quantitatively be referred to as high or low regioselectivity. Originally, the term was restricted to addition reactions of unsymmetrical reagents to unsymmetrical alkenes.

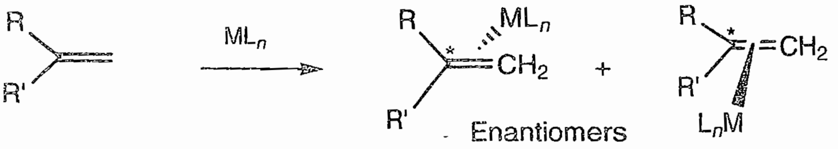
11.5 ASYMMETRIC SYNTHESIS USING A CATALYST

When an achiral alkene on hydrogenation can result in two enantiomers, the alkene is termed prochiral. Depending upon which face of the alkene the H_2 reacts (*si* or *re*), different enantiomers are obtained.

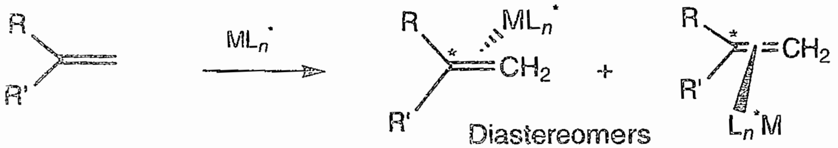


(11.2)

Generally, this will result in a 50:50 mixture but if by some method, the addition of H_2 to one particular face can be made preferential over the other, the ratio of enantiomers formed will not be equal and an asymmetric synthesis results. Similarly, when prochiral alkenes bind to a metal centre, two different isomers are obtained. If the metal complex ML_n is achiral we get a pair of enantiomers but when [‡]ML_n* is chiral, a pair of diastereomeric complexes will result. Since diasteromers have different rates of reactivity, reactions such as oxidative addition of H_2 on the two ML_n* bound diasteromers will form one of the chiral alkanes in excess. In other words, while both the diastereomers can lead to the product, one of them will react at a faster rate to form one of the isomers in excess. The advantage of this method is that by using a very small amount of a chiral catalyst with a prochiral precursor, a very large amount of chiral product can be prepared.



Enantiomers (11.3)



Diastereomers (11.4)

11.6 HETEROGENEOUS CATALYSIS

Before looking into the details of some industrially important homogeneous catalysed reactions, for the sake of comparison, it is of interest to look into the sequences involved in a well known heterogeneous catalysed reaction. A heterogeneous catalyst exists in a different phase from the reactant molecules—often as a solid in contact with either gaseous or liquid reactants. Many important industrial reactions are catalysed by the surfaces of special solid materials. Heterogeneous catalysts are often composed of metals or metal oxides. The greater the surface area of a heterogeneous catalyst, the more is the number of reaction sites. Thus, techniques are used to maximise the surface area while manufacturing heterogeneous catalysts (for example, by using highly porous structures).

[‡] A metal complex can be made chiral by having a ligand which has a single chiral centre bound to it or by using a bidentate ligand which has a helical symmetry (usually having a C_2 symmetry).

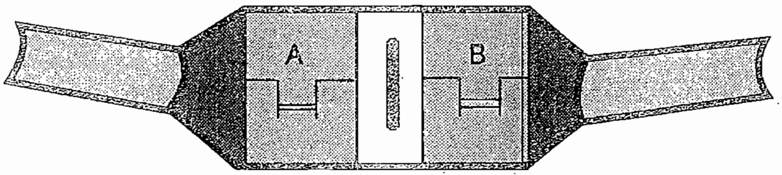
The initial step in heterogeneous catalysis is the adsorption of reactants onto the surface of a catalyst. The surfaces of metal catalysts are highly reactive in comparison to interior atoms. Interior atoms have fully satisfied bonding interactions with neighboring atoms but atoms on the surface lack a complete set of bonding partners, and thus can bind and react with other molecules in the environment.

11.6.1 Catalytic Converters in Automobiles

CO(*g*) and NO(*g*) are environmentally toxic gases produced by the incomplete combustion of hydrocarbons in a nitrogen containing atmosphere. Rh, Pt and Pd catalysts in an automobile exhaust can render these pollutants as less harmful gases at the necessary kinetic rate. A catalytic converter in an automobile exhaust system provides an environment for chemical reactions where unburnt hydrocarbons undergo complete combustion and poisonous gases that are formed get deactivated. The device is a prerequisite on most unleaded petrol engine passenger cars manufactured on and after 1 August 1992. A catalytic converter has three simultaneous tasks. These are:

- oxidation of carbon monoxide to carbon dioxide,
- reduction of nitrogen oxides to nitrogen, and
- oxidation of hydrocarbons (volatile organic compounds; VOCs) to carbon dioxide and water.

Most of the modern cars are equipped with three-way catalytic converters. 'Three-way' refers to three regulated emissions it helps to reduce, namely CO, VOCs and NO_x molecules. The converter uses two different types of catalysts, a reduction catalyst and an oxidation catalyst. Both types consist of a ceramic honeycomb like structure interspersed with a metal catalyst, usually Pt, Rh and/or Pd. The idea is to create a structure that exposes the maximum surface area of the catalyst to the exhaust stream, while also minimising the amount of catalyst required. The ceramic base is required to withstand high temperatures that are attained during the reaction.



A = reduction catalyst; B = oxidation catalyst.

The reduction catalyst is the first stage of the catalytic converter. It uses platinum and rhodium to help reduce the NO_x emissions. When an NO or NO_2 molecule contacts the catalyst, the catalyst rips the nitrogen atom out of the molecule and holds on to it, freeing the oxygen in the form of O_2. The nitrogen atoms bond with other nitrogen atoms that are also stuck to the catalyst, thus forming N_2. For example:

$$2NO \longrightarrow N_2 + O_2 \text{ or } 2NO_2 \longrightarrow N_2 + 2O_2 \qquad (11.5)$$

The oxidation catalyst is the second stage of the catalytic converter. It reduces the amount of unburnt hydrocarbons and CO by burning (oxidising) them over a Pt/Pd catalyst. This catalyst aids the reaction of CO and hydrocarbons with the remaining oxygen in the exhaust gas. For example:

$$2CO + O_2 \longrightarrow 2CO_2 \qquad (11.6)$$

There is also a control system that monitors the exhaust stream and uses this information to control the fuel injection system. There is an oxygen sensor mounted upstream of the catalytic converter. This sensor provides the computer in the engine with data about the amount of oxygen present in the exhaust. This computer can increase or decrease the amount of oxygen in the exhaust by adjusting the air-to-fuel ratio. This control scheme allows the computer to make sure that the engine is running close to the stoichiometric point, and also to make sure that there is enough oxygen in the exhaust to allow the oxidation catalyst to burn the unburned hydrocarbons and CO.

11.7 FEEDSTOCK FOR THE CHEMICAL INDUSTRY

Substances available in large quantities directly from natural resources or that involve only minimal treatment of naturally obtained mixture of resources are the starting materials or feedstock for the chemical industry. Over the past 40–45 years the heavy organic chemistry industry has come to rely almost entirely on feedstock derived from petroleum. The initial distillation of petroleum gives a volatile fraction below 400°C and a nonvolatile residual oil. The volatile fraction on redistillation gives (i) C1–C4 hydrocarbons, (ii) light gasoline, (iii) naphtha (heavy gasoline), (iv) kerosene and (v) light gas oil in order of their increasing boiling temperature.

In Europe, thermal as well as catalytic cracking of the naphtha fraction produces olefins and acetylene while processes in North America use cracking of natural gas to produce olefins. These olefins (ethylene, propylene, butene and others) along with methane, carbon monoxide and hydrogen constitute the principal building blocks for the heavy organic chemical industry. The task of the industry is to convert the available feedstock – mainly olefins, synthesis gas and arenes – to compounds possessing additional functional groups that confer desired properties and/or reactivity. The industrially important compounds include alcohols, aldehydes, acids and polymers. To achieve large scale preparation of these compounds by the most energy and cost efficient method, one has to depend almost totally on catalysis.

Carbon monoxide and hydrogen required for the chemical industry are conventionally obtained from water gas and synthesis gas (syn gas) according to the following equations.

$$\text{C (red hot coke)} + H_2O\ \text{(steam)} \longrightarrow CO + H_2\ \text{(Water gas)} \qquad (11.7)$$

$$CH_4 + H_2O \xrightarrow[700\text{–}1100°C]{40\ \text{atm}} CO + 3\,H_2\ \text{(Synthesis gas)} \qquad (11.8)$$

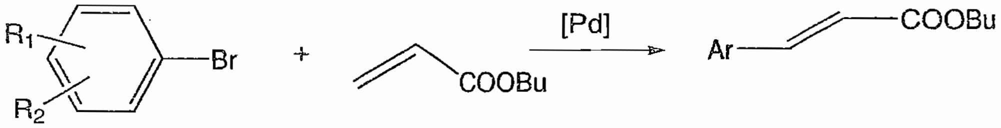
$$CO + H_2O \xrightarrow[190\text{–}350°C]{10\ \text{atm}} CO_2 + H_2\ \text{(Water gas shift reaction)} \qquad (11.9)$$

The water gas shift reaction is used for making more hydrogen from syn gas or water gas, and during the process, CO gets converted to CO_2.

Pressure swing adsorption (PSA) is a technology that is used to separate a mixture of gases at ambient temperature. An adsorptive material (such as zeolite) is used to preferentially adsorb the target gas species at high pressure. The process then swings to low pressure to desorb the pure adsorbent material. One of the primary applications of PSA is in the removal of carbon dioxide as the final step in the large scale commercial synthesis of H_2.

Problems and Exercises

11.1. Consider the following Heck olefination of aryl bromides with butyl acrylate and determine which entry gives the best TOF and TON (data taken from Feuerstein M, Doucet H, Santelli M, *J. Org. Chem.*, 2001, Vol. 66, 5923).



1. R_1 = 4-HCO, R_2 = H
2. R_1 = 4-PhCO, R_2 = H
3. R_1 = 4-NO_2, R_2 = H
4. R_1 = 3-CF_3, R_2 = 5-CF_3
5. 3-Bromoquinoline
6. Iodobenzene

Entry number	Aryl halide	Time (h)	Substrate–catalyst ratio	Product	Yield (%)
1	1	20	100,000	1a	99
2	1	72	1000,000	1a	46
3	2	20	1000,000	2a	97
4	2	72	10,000,000	2a	25
5	3	20	1000,000	3a	44
6	4	72	1000,000,000	4a	21
7	4	20	100,000,000	4a	100
8	5	48	100,000	5a	96
9	6	20	100,000,000	6a	99

11.2. Results of the catalytic hydrosilylation of cyclohexene and ketones using $[Re(H)_2(\eta^2\text{-}C_2H_4)(NO)(PR_3)_2]$ R= i-Pr (A) and R=Cy (B) are given in the following table. Determine the TOF in all the experiments conducted (data taken from Choualeb A, Maccaroni E, Blacque O, Schmalle H W, Berke H, *Organometallics*, 2008, Vol. 27, 3474).

Substrate	Catalyst	Cat/sub (mol%)	Temp (°C)	Time (h)	Conversion (%)
Cyclohexene/Et_3SiH	A	0.5	80	3	81
PhCOMe/Ph_3SiH	A	0.1	70	2	100
PhCOMe/Ph_3SiH	B	0.5	70	2	100
PhCOMe/Et_3SiH	A	0.5	70	0.25	100
PhCOMe/Et_3SiH	B	0.5	70	0.25	100

11.3. While considering any catalytic reaction, generally only a small amount of the catalyst is required for the purpose. How is it that a small amount of catalyst is sufficient to carry out the entire catalytic cycle of a large amount of substrate?

11.4. What are the prerequisites one looks for in a catalyst that is used to catalyse a thermodynamically favourable reaction? Why do most of the transition metal complexes fail to act as good catalysts?

11.5. Define the terms turnover frequency, selectivity, catalyst and catalytic cycle.

11.6. Consider the following catalytic processes and categorise each one as homogeneous or heterogeneous. Justify your answer.

(a) The rate of the following oxidation reaction increases in the presence of NO(*g*).

$$SO_2(g) + O_2(g) \longrightarrow SO_3(g)$$

(b) The hydrogenation of vegetable oil is carried out with finely divided Ni as a catalyst.

(c) D-Glucose is transformed to a D, L mixture and the reaction is catalysed by HCl(*aq*).

11.7. If the catalytic converter of an automobile is connected in the reverse manner (the oxidation catalyst in the first stage directly connected to the exhaust) will it affect the working of the converter? Explain.

Supplementary reading

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CATALYTIC HYDROGENATION OF ALKENES AND RELATED REACTIONS

CHAPTER 12

12.1 HYDROGENATION CATALYSTS

Although the reaction of hydrogen gas with ethylene is thermodynamically favourable ($\Delta G° = -101$ kJ mol^{-1}), it does not occur at room temperature and atmospheric pressure. Many heterogeneous catalysts were found to bring about hydrogenation of alkenes, alkynes and other unsaturated substrates but the first example of an effective and rapid homogeneous catalyst, active at room temperature and atmospheric pressure was the square planar 16 electron d^8 complex $(Ph_3P)_3RhCl$, well known as the Wilkinson's catalyst.[1] After the landmark discovery of this catalyst by G Wilkinson as well as separately by R Coffey at almost the same time (1964–65), many other homogenous catalysts which bring about catalytic hydrogenation have been discovered.[2]

There are three different ways by which one can activate H_2. These are oxidative addition (most common), hydrogenolysis using lanthanides, actinides and early transition metals with d^0 electron count: $L_nM\text{–}X + H_2 \longrightarrow L_nM\text{–}H + HX$ and base assisted heterolytic cleavage of hydrogen (mainly using Ru^{2+} compounds, $L_nM + H_2 + B \longrightarrow L_nM\text{–}H + H^+B$).

12.1.1 Classification of Hydrogenation Catalysts

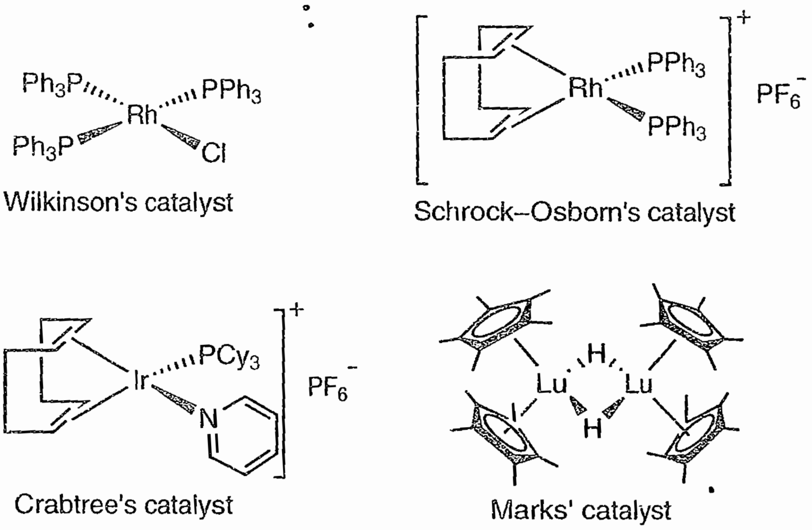
Hydrogenation catalysts can be broadly classified as:

(i) those without a metal–hydrogen bond where oxidative addition with molecular hydrogen is the first step,

(ii) those with a metal–hydrogen bond where hydrogenation is not initiated by molecular hydrogen, and

(iii) *f* block and some early transition metal hydrides where there is no oxidative addition step in the catalytic cycle.

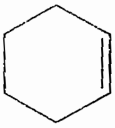
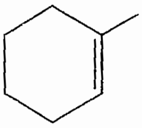
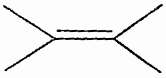
Some of the most well known examples of hydrogenation catalysts are given in Fig. 12.1; their relative turnover frequencies are given in Table 12.1.[3–6]



Wilkinson's catalyst
Schrock–Osborn's catalyst
Crabtree's catalyst
Marks' catalyst

Fig. 12.1 Well known examples of hydrogenation catalysts

Table 12.1 Turnover frequencies of some homogeneous hydrogenation catalysts

Catalyst **25°C, 1 atm H_2**	**Turnover frequency (TOF) in h^{-1} for hydrogenation of alkenes**			
				
Wilkinson's catalyst	650	700	13	NA
Schrock–Osborn's catalyst	4000	10	NA	NA
Crabtree's catalyst	6400	4500	3800	4000
Marks' catalyst	120,000	NA	NA	NA
$HRuCl(PPh_3)_3$	9000	7	NA	NA

NA = Data not available

Wilkinson's catalyst is the most well studied among these and it is prepared by a rather simple method as shown below.[7–8]

$$RhCl_3(H_2O)_3 + CH_3CH_2OH + 3\,PPh_3 \longrightarrow RhCl(PPh_3)_3 + CH_3CHO + 2HCl + 3H_2O \qquad (12.1)$$

Although ethylene is usually used to illustrate homogenous hydrogenation with Wilkinson's catalyst, the process does not proceed at an appreciable rate with this alkene. The explanation lies in the formation of a stable Rh–ethylene complex which does not undergo further reaction with hydrogen. A reaction involving a true catalyst is represented by a closed loop. Thus, the various equations can be combined into continuous cycles called catalytic loops. Wilkinson's catalyst has been successfully utilised for hydrogenation of a wide variety of alkenes including cyclic alkenes.

12.1.2 Catalytic Cycle of Wilkinson's Catalyst

The conventional hydrogenation catalytic cycle with Wilkinson's catalyst (Fig. 12.2) indicates that the first step of the catalytic cycle is the cleavage of a PPh_3 to generate the active form of the catalyst followed by oxidative addition of hydrogen. The evidence for this has been based on the fact that if triphenylphosphine is replaced by triethylphosphine, there is no catalytic activity. Separate kinetic studies have indicated that oxidative addition of H_2 on $ClRh(PPh_3)_2$ is 10^4 times faster than that on $ClRh(PPh_3)_3$. However, detailed studies carried out later have indicated the following findings:[9–11]

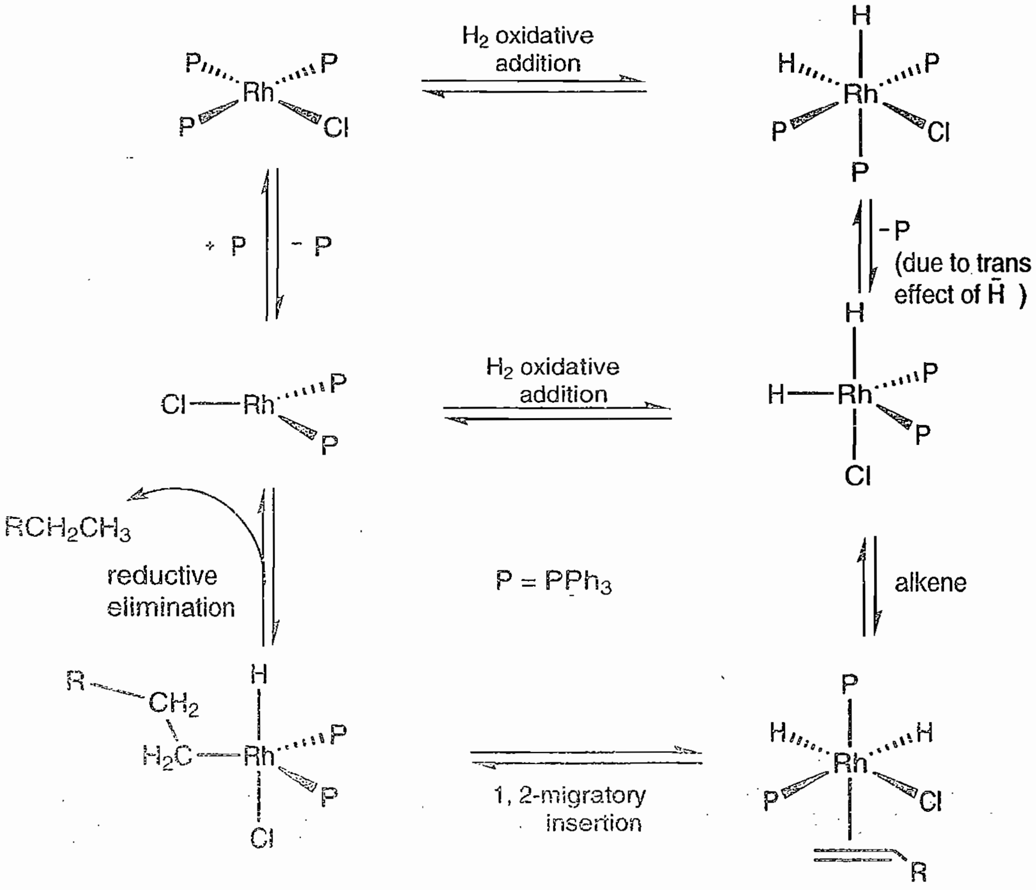


Fig. 12.2 Catalytic cycle for hydrogenation of alkenes using Wilkinson's catalyst

- kinetic studies have shown that the dissociation of PPh_3 from the distorted square planar complex $RhCl(PPh_3)_3$ in benzene occurs only to a very small extent ($k = 2.3 \times 10^{-7}$ M at 25°C), and
- under an atmosphere of H_2, a solution of $RhCl(PPh_3)_3$ becomes yellow as a result of the oxidative addition of H_2 to give *cis*-$H_2RhCl(PPh_3)_3$.[12, 13]

An outer catalytic cycle, in addition to the basic cycle, has therefore been suggested as a modification based on these observations (Fig. 12.2). One cannot rule out both the cycles operating at the same time or the generation of an active form of the catalyst from the outer cycle, which then continues the main catalytic process. The outer cycle suggests that the first step in this hydrogenation is the oxidative addition of H_2 to the Wilkinson's catalyst. This is immediately followed by the rapid dissociation of one PPh_3 which is *trans* to a hydride. The strong *trans* effect of H makes this phosphine more labile. The pentacoordinate molecule formed (or a hexacoordinate species with a weakly coordinated solvent) easily coordinates an alkene molecule and begins the catalytic cycle. It has also been observed from kinetic studies that when a chelating diphosphine is used, hydride transfer to the alkene (1, 2-migratory insertion) is faster suggesting that a *cis*-phosphine geometry is more active in the octahedral species.

Rhodium–PPh_3 hydrogenation catalysts are sensitive to the steric influence of the alkene substrate. The rate of hydrogenation decreases with increasing alkene substitution in the following sequence (Fig. 12.3).

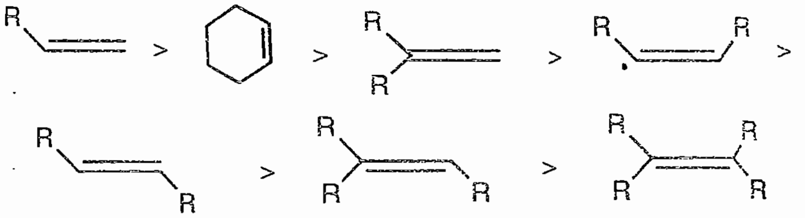


Fig. 12.3 Relative reactivity of alkenes for hydrogenation using Wilkinson's catalyst

It is also observed that

- terminal alkynes are hydrogenated more rapidly than terminal alkenes,
- conjugated dienes are reduced more slowly than isolated alkenes,
- internal and branched alkenes/alkynes undergo hydrogenation more slowly than terminal ones, and
- substrates containing polar functional groups are hydrogenated more rapidly than those having no such groups, because polar functional groups assist the olefin to coordinate better with the catalyst.

12.1.3 Catalytic Cycles of Iridium and Ruthenium Based Catalysts

In 1976, Schrock and Osborn discovered that the cationic rhodium complexes such as $[Rh(COD)(PPh_3)_2]^+$ were more active for hydrogenation compared to Wilkinson's catalyst.[3, 14] The cationic metal centre is relatively more electrophilic and thus favours alkene coordination. They also came up with a modified catalyst having dppe (a chelating biphosphine ligand replacing two PPh_3 units) which showed better activity. Then, Crabtree came up with a few cationic iridium based catalysts whose activity was even better than the Schrock–Osborn's catalyst.[4] (Incidentally, the iridium analogue of the Wilkinson's catalyst is inactive.) Crabtree's catalyst is cationic and similar to the Schrock–Osborn's catalyst and has a cyclooctadiene, COD, bound to the metal (Fig. 12.4).

The mode of activation of the COD substituted catalysts of Schrock–Osborn and Crabtree were similar since the active form of the catalyst is generated after the COD is hydrogenated to cyclooctane which then detaches from the metal. The two vacant sites thus generated are weakly coordinated by solvent molecules. The turnover frequencies of both these catalysts

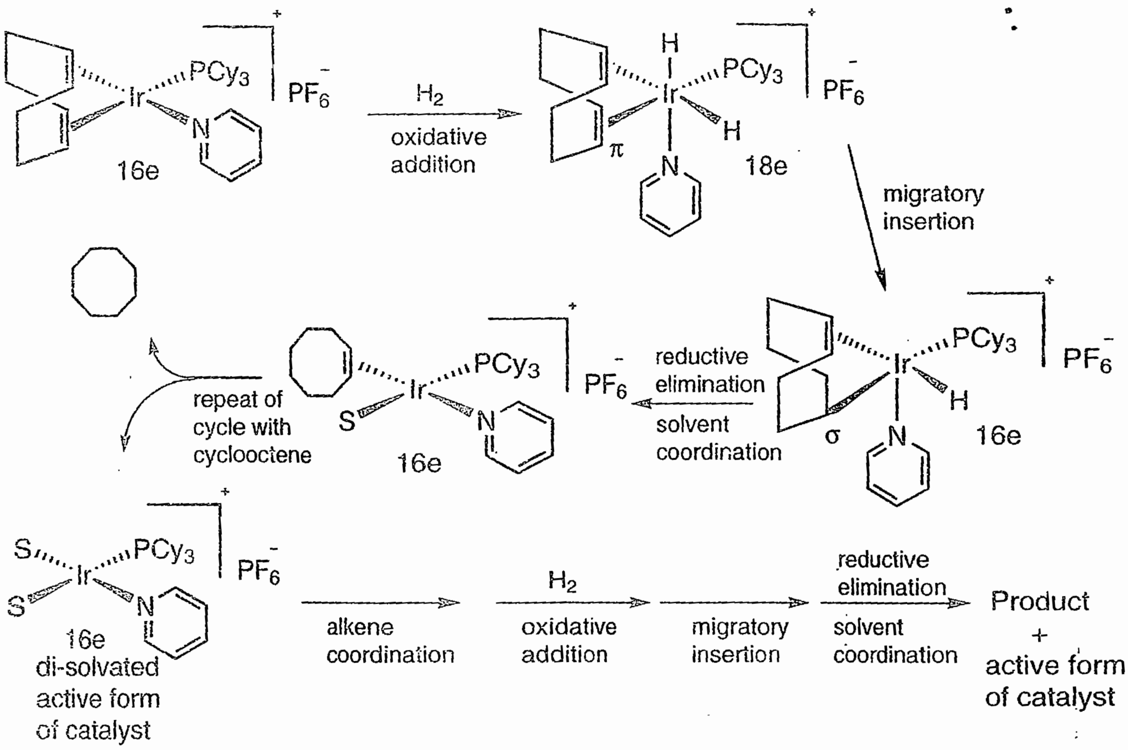


Fig. 12.4 Catalytic cycle for hydrogenation using Crabtree's catalyst

were significantly higher as expected from their cationic nature and less steric bulkiness on the metal. The di-solvated form of the active catalyst was identified from NMR studies. Replacing COD in the Schrock–Osborn's catalyst by norbornadiene results in a much more facile hydrogenation as norbornadiene undergoes hydrogenation faster than COD due to reduction of ring strain upon hydrogenation.

The proposed mechanism for the Schrock–Osborn's catalyst also proceeds in a similar manner with the generation of a di-solvated active catalyst. In contrast, the reaction involving RuH(Cl)(PPh_3)$_3$ as a catalyst is believed to proceed by following a hydrogenolysis mechanism (Fig. 12.5). The oxidation state of the metal remains the same (+2) during the process. Ru^{2+} has a strong tendency not to undergo oxidative addition reaction with H_2.[6]

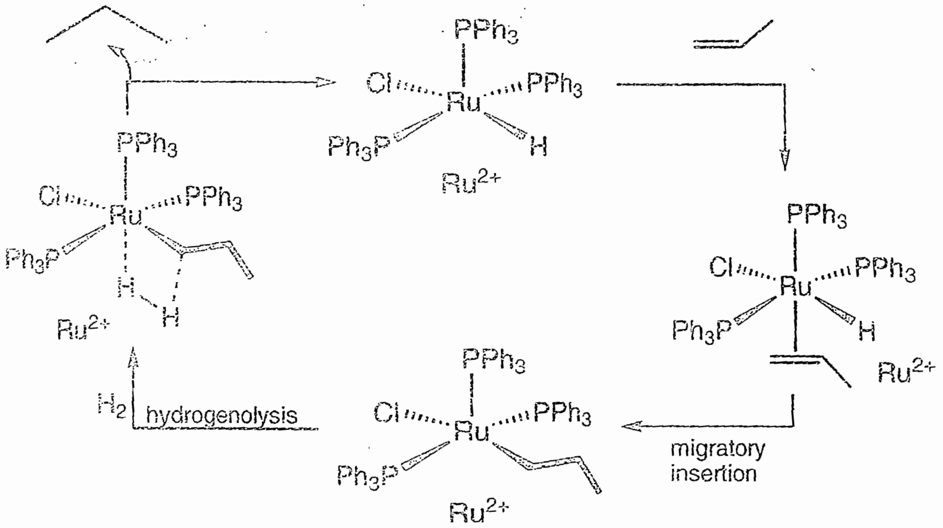
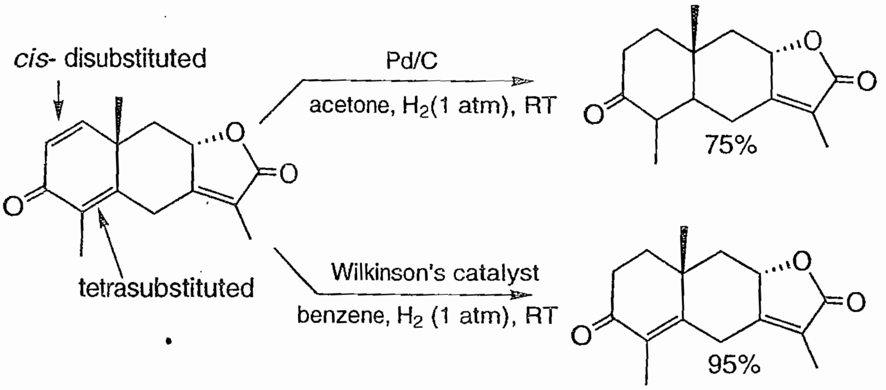


Fig. 12.5 Proposed catalytic cycle for hydrogenation using RuH(Cl)(PPh_3)$_3$

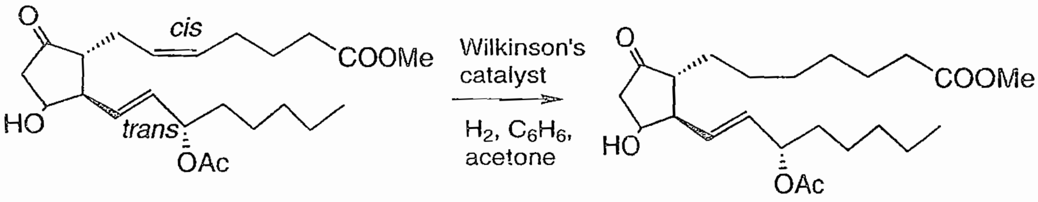
Unlike heterogeneous hydrogenation catalysts, homogeneous catalysts provide high site selectivity in hydrogenation. An example where Pd/C/H_2 is compared with Wilkinson's catalyst is given below.[15]



(12.2)

Cis versus *trans* disubstituted olefins

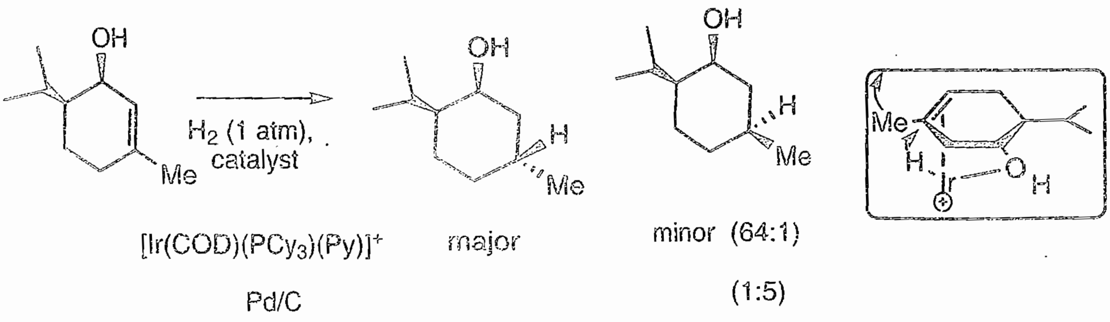
The following example shows that the *cis* isomer is preferentially hydrogenated compared to the *trans* in disubstituted olefinic complexes.[16]



(12.3)

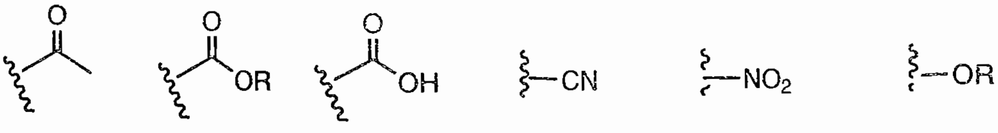
12.1.4 Directing Effects in Catalytic Hydrogenation

Functional groups on the alkene which are capable of coordination to a cationic metal ion, often direct the addition of H_2 to a specific side of the catalyst–alkene complex and thus increase the selectivity of a particular isomer. The following example demonstrates this. Note that the same effect is not observed for the heterogeneous Pd/C catalyst.[17]



(12.4)

Tolerance of the following functionalities is also observed in the hydrogenation of alkenes using Wilkinson's catalyst.



12.1.5 Hydrogenation by Lanthanide Organometallic Compounds

Many lanthanide and actinide based organometallic compounds have been found to act as catalysts and enable C-H activation as well. One of these compounds $(Cp^*_2 LuH)_2$ – discovered by T J Marks and coworkers – has shown extraordinary activity for alkene and alkyne hydrogenation. This catalyst brings about hydrogenation of 1-hexene with a TOF of 120,000/h at 1 atm H_2 and 25°C. As oxidative addition on this molecule is ruled out (since Lu is already in the +3 oxidation state) the proposed mechanism shows hydrogenolysis in the final step before the alkane is released from the catalytic cycle (Fig. 12.6).[5]

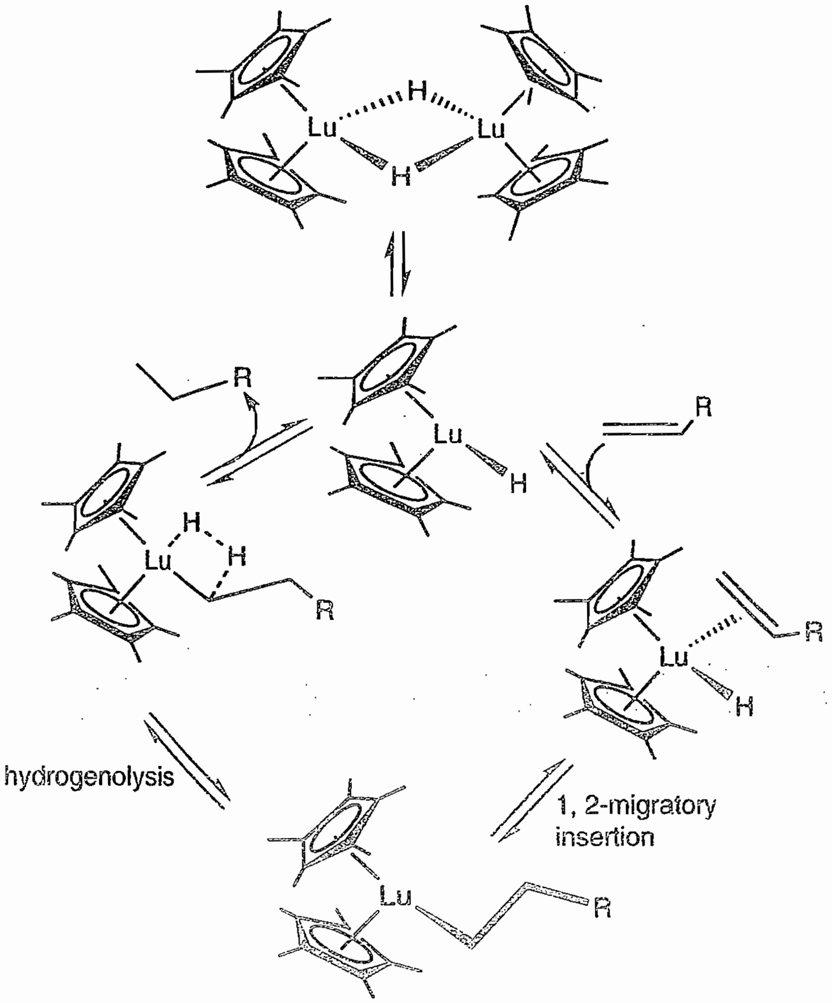


Fig. 12.6 Proposed catalytic cycle for hydrogenation using Marks' catalyst

Hydrogenation from the perspective of converting monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) to saturated fatty acids with better shelf life has been losing significance ever since it was discovered that saturated fatty acids (SATFA) are harmful for health and a healthy diet requires more of MUFA and PUFA. In addition, development of technology has helped in proper storage of unsaturated fatty acids. In this context, the emphasis on hydrogenation has changed mostly from simple hydrogenation to asymmetric hydrogenation of prochiral substrates. This provides scope for the preparation of many chiral drugs and organic compounds (using catalysts) in the optically pure form. The breakthrough in this chemistry came from the work of William S Knowles of Monsanto company and Ryoji Noyori of Nagoya University for which they received the 2001 Nobel Prize in Chemistry (along with Sharpless of Scripps Research Institute for research on catalytic asymmetric oxidation).

12.2 CATALYTIC ASYMMETRIC HYDROGENATION

It was not known in the early sixties whether catalytic asymmetric hydrogenation was feasible, that is, would it be possible to catalyse an asymmetric reaction to produce an excess of one of the enantiomers? The breakthrough came in 1968 when Knowles, working at the Monsanto Company discovered that it was possible to make a chiral catalyst by using rhodium metal and this catalyst could transfer chirality to a nonchiral substrate to get a chiral product. The reaction used was hydrogenation.

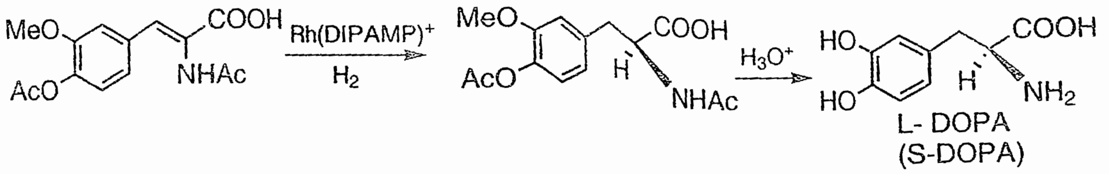
Knowles' experiments were based on two discoveries that had been made a few years earlier (i) synthesis of soluble, nonchiral rhodium catalysts by Wilkinson that made it possible to catalyse hydrogenation in solution and (ii) Horner's and Mislow's syntheses of chiral phosphines.[18]

Knowles' hypothesis was that it might be possible to produce a catalyst for asymmetric hydrogenation if the nonchiral PPh_3 ligand in Wilkinson's metal complex was replaced by one of the enantiomers of a chiral phosphine. The phosphine first used by Knowles, P(Ph)(Me)(*n*-Pr) was not enantiomerically pure, yet it produced a mixture of the hydrogenated product in which there was 15% more of one enantiomer (the first reaction yielded only 3%). In other words, the enantiomeric excess (*ee*) was 15%. Although this excess was modest and was hardly of any practical use, the result proved that it was, in fact, possible to achieve catalytic asymmetric hydrogenation. Other scientists achieved similar results and they all have contributed to opening the door to a new, exciting and important field for both academic and industrial research.

12.2.1 The First Industrial Catalytic Asymmetric Hydrogenation

Knowles' aim was to develop an industrial synthesis of the amino acid L-DOPA (or S-DOPA), which had proved useful in the treatment of Parkinson's disease. By testing enantiomers of phosphines with varied structures, Knowles and his colleagues (at Monsanto) quickly succeeded in producing usable catalysts that provided a high enantiomeric excess of the product, L-DOPA.[19, 20]

The ligand used in Monsanto's industrial synthesis of L-DOPA was the diphosphine ligand DIPAMP (Fig. 12.7). A cationic rhodium complex with this ligand afforded extraordinarily high levels of enantioselectivity in the hydrogenation of achiral enamides. This was the first demonstration that a chiral transition metal complex could effectively transfer chirality to a



(12.4)

nonchiral substrate with selectivities that even rival those given by enzymes. The synthesis gave a mixture of the enantiomers of DOPA in 100% yield with 97.5% of L-DOPA. Thus Knowles had, in a short time, succeeded in applying his own basic research and that of the others, to come up with an industrial synthesis of an important drug. This was the first catalytic asymmetric synthesis. A variety of chiral diphosphines are nowadays used and many of them are found to give very good *ee* (even 100%) in hydrogenation reactions. These phosphines can be broadly classified as follows.[21, 22]

- Diphosphines having chiral phosphorus atoms (DIPAMP),
- Diphosphines having a chiral backbone (DIOP),
- Ligands having atropisomerism (BINAP),
- Those carrying chiral substituents on the phosphorus site (DuPhos),
- Ligands having a planar chirality (Josiphos).

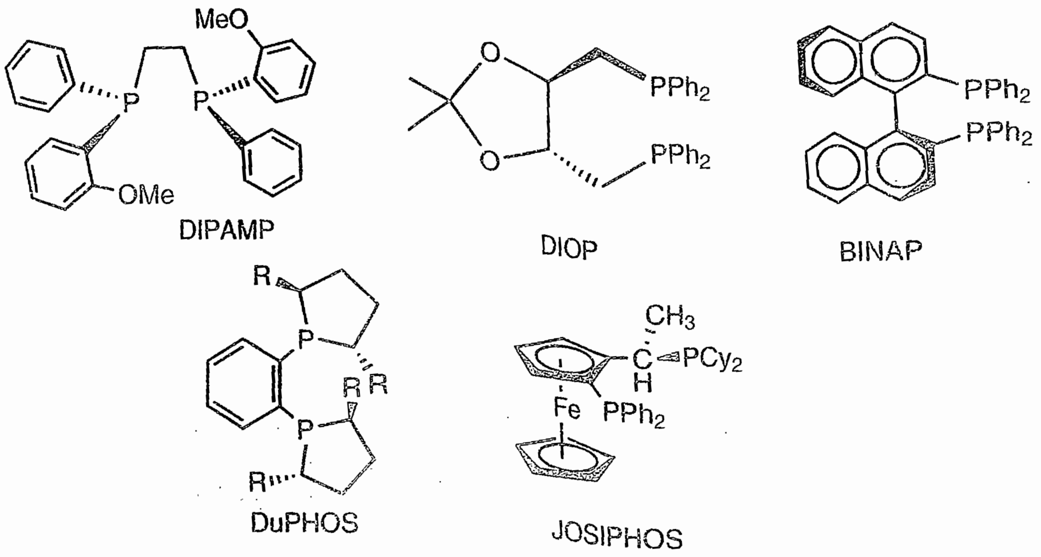


Fig. 12.7 Chiral diphosphines used in asymmetric hydrogenations

12.2.2 The Mechanism of Asymmetric Hydrogenation Using a Chiral Catalyst

A transition metal, say rhodium, when bound to the chiral diphosphine, has the ability to simultaneously bind both H_2 and the substrate. The complex obtained then undergoes a migratory insertion and H_2 is added to the double bond in the substrate. This is the vital stage during hydrogenation when a new chiral complex is formed; the chiral product is released from this complex. Thus, using a substrate that is prochiral, the chirality has been transferred from the chiral catalyst to the product. This product contains more of one enantiomer than the other, that is, the synthesis is asymmetric.[23–25]

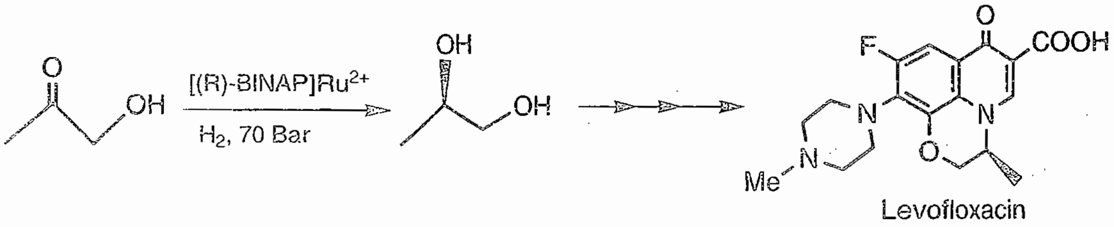
The reason for the enantiomeric excess lies in the hydrogenation stage, as hydrogen can add in two ways that give different enantiomers at different rates. These two pathways utilise different transition state complexes which are diastereomers and therefore have different energies. Details of the mechanism are given in Scheme 12.2. Hydrogenation takes place more rapidly via the complex with the lowest energy, thus producing an excess of one of the enantiomers.

To develop better asymmetric hydrogenation catalysts, it is important to increase the energy difference between the transition state complexes in order to obtain better enantiomeric excess. This is of vital interest in industrial applications in which the aim is to achieve economy in the process as well as to use environmentally acceptable methods, that is, the process with as few waste products as possible. This development has been led by Noyori.

12.2.3 Asymmetric Hydrogenation of Ketones and Isomerisation

In 1980, Noyori and coworkers synthesised both enantiomers of the diphosphine ligand BINAP. The ruthenium complexes containing this ligand catalyse the synthesis of certain amino acids with an enantiomeric excess of up to 100%.[22]

Noyori also saw the need for more general catalysts with broader applications. For example, exchanging Rh(I) with Ru(II) proved to be very successful. The Ru(II)–BINAP complex hydrogenates many molecules having other types of functional groups. A well known example is the hydrogenation of ketones and aldehydes. Although relatively high pressures are required, the enantioselectivity is very good and the reaction can be scaled up for industrial use. Noyori's Ru–BINAP is used as a catalyst in the production of (R)-1,2-propanediol for the industrial synthesis of an antibiotic, levofloxacin. Similar reactions are used for the synthesis of other antibiotics.



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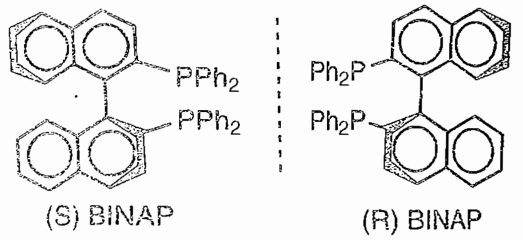
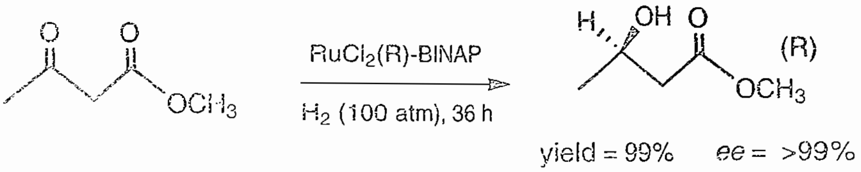
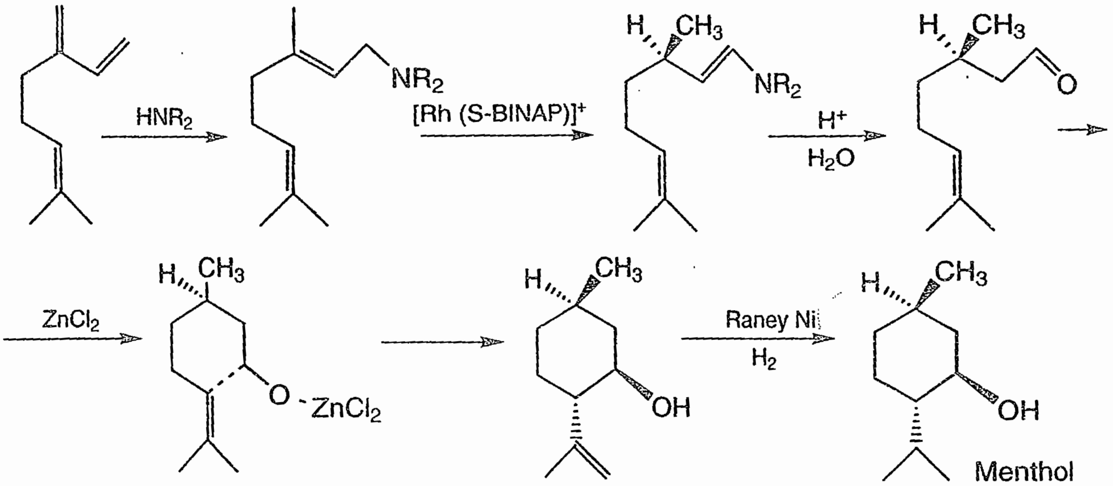




(12.7)

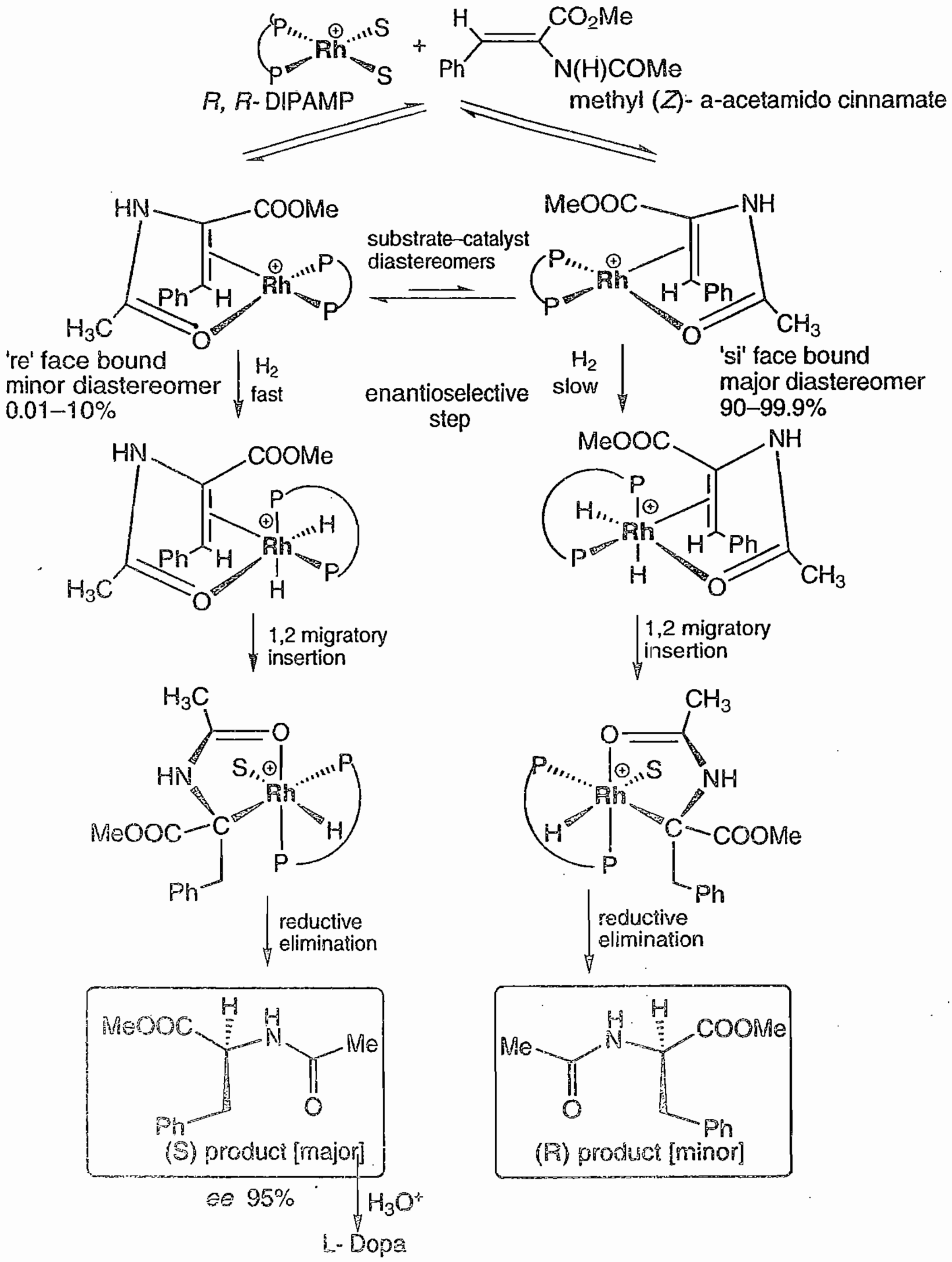
The Takasago International Company has been using BINAP in the industrial synthesis of a chiral aromatic compound, menthol, since the early 1980s. The key reaction in this process is the enantioselective isomerisation of an allylamine to an asymmetric enamine. The enamine is then hydrolysed followed by a Lewis acid ($ZnCl_2$) catalysed ring closure reaction that gives the menthol skeleton. In the final step, the isopropenyl group is hydrogenated over Raney nickel to get (–)menthol (Scheme 12.1).



Scheme 12.1 Takasago process for the preparation of (–)menthol

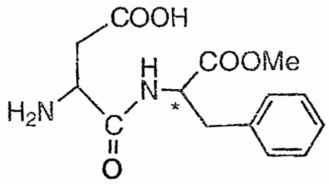
Let us see how the asymmetric synthesis with metal catalysts works. Scheme 12.2 shows the asymmetric hydrogenation of methyl (Z)-α-acetamidocinnamate, a compound quite similar to the starting material used for the synthesis of L-DOPA. The rhodium catalyst used is bound to a chiral diphosphine R,R-DIPAMP. The metal can bind the alkene in two ways—through the *re* or the *si* face. [The prochiral alkene carbon and the three atoms including the other carbon attached to it define a plane. The metal can bind from either side of the plane. One side of the alkene is called the *re* face and the other side is called the *si* face. *Re* stands for rectus and *si* for sinister. To distinguish between the *re* and the *si* faces, the three groups attached to the prochiral carbon are assigned priorities using the Cahn–Ingold–Prelog system of assigning priorities. The *re* face is the one closest to the observer when decreasing priorities (1 > 2 > 3) are in a clockwise direction and the *si* face is the one opposite or the one closest to the observer when decreasing priorities are in a counter clockwise direction.)] Thus, two diastereomers are formed which have different energies. One of them is the major isomer and the other is the minor.

The enantioselective step is the oxidative addition of H_2 to the square planar diastereomeric substrate complexes that are in rapid dissociation equilibrium. The major enantiomer of the product arises from the minor substrate–catalyst diastereomer. It was shown from kinetic studies that the minor diastereomer was 580 fold more reactive towards H_2 (it is the rate determining step at room temperature). Therefore, the minor isomer is in low concentration in solution. Consequently at the end of the reaction, the (*S*) isomer which came from the minor diastereomer is obtained as the major product.[21, 24, 25]

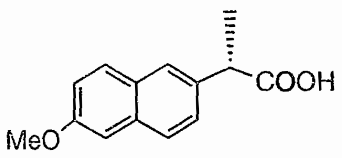


Scheme 12.2 Steps involved in the asymmetric hydrogenation of methyl (*Z*)-α-acetamidocinnamate

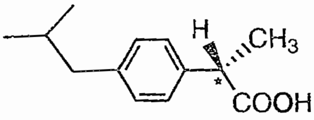
Some of the other compounds of industrial importance, prepared by homogeneous asymmetric hydrogenation, are aspartame, naproxen and ibuprofen.



Aspartame
(artificial sweetner)



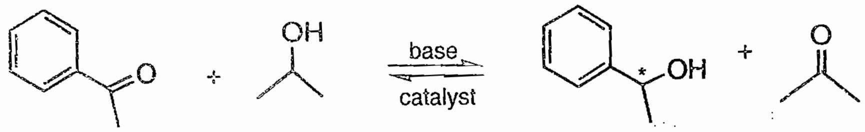
(*S*) Naproxen
a drug used as NSAID
(*R*) Naproxen is a liver toxin



Ibuprofen

12.2.4 Asymmetric Hydrogen Transfer

For hydrogenation reactions and catalytic processes where the use of hydrogen gas is not favoured due to various reasons, alternative methods exist which include transfer of hydrogen from another organic molecule or from a metal hydride. However, from the industrial perspective, the metal hydride reaction is not an economically viable alternative. There is an alternate method which makes use of aluminum isopropoxide and is especially useful for the preparation of alcohols from ketones. This is well known as the Meerwein-Pondorff–Verley reaction. A catalytic version of this reaction using metal complexes of Ir, Rh and Ru with nitrogen based ligands has been known for some time with very high TONs. In 1996, Noyori came up with a novel ruthenium catalyst having a chiral substituted amine and a η^6-ligand (such as mesitylene/cymene) for preparing chiral alcohols using the catalysed version of the reaction. The product is an equilibrium mixture and the reaction requires an excess of isopropanol to drive the reaction forward. Instead of the alcohol, a mixture of formic acid and triethylamine has also been used as the hydrogen source which makes the thermodynamics of the reaction more favourable with the release of CO_2 gas.[26–28]



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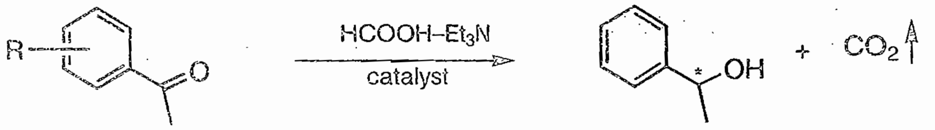
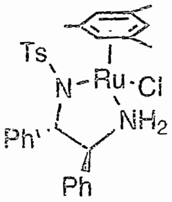
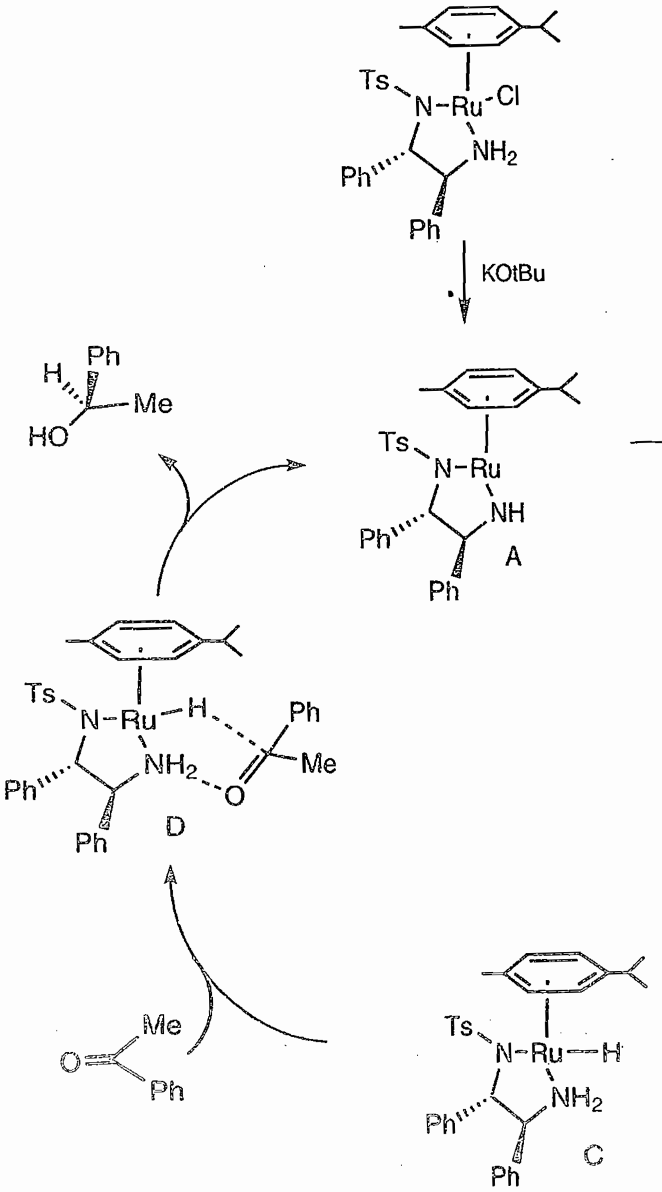


(12.9)

catalyst =



The concerted mechanism for this reaction has been proposed by Noyori (Scheme 12.3). The driving force for the formation of intermediate B is the hydrogen bond between the proton of the alcohol and the nitrogen atom of the amide. The interesting feature of this mechanism is that the ketone substrate does not coordinate to the metal but binds through the ruthenium–hydride bond (D). Commercial application of this method is not yet known but many new processes are in the development stage.



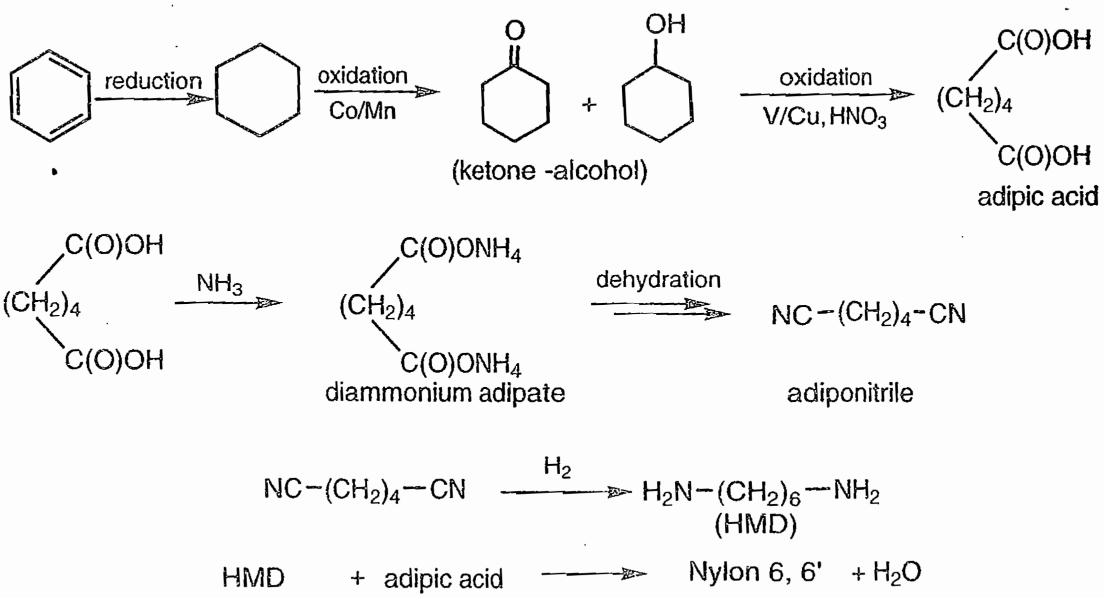
Scheme 12.3 Proposed mechanism for asymmetric hydrogen transfer

Two homogeneous catalytic processes closely related in mechanism to hydrogenation as well as of high practical importance are hydrocyanation and hydrosilylation. Salient aspects of these two processes are described in Sections 12.3 and 12.4.

12.3 HYDROCYANATION OF ALKENES

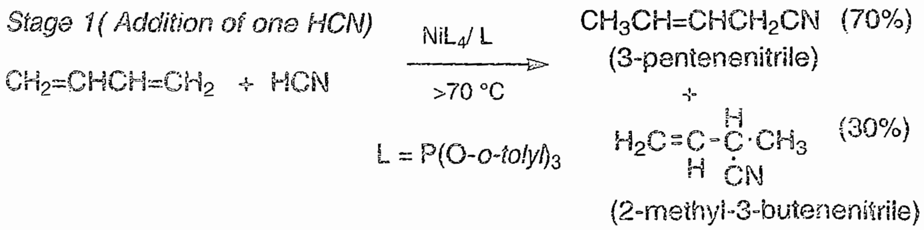
Hydrocyanation is a process by which H^+ and CN^- ions are added to a molecular substrate. Usually the substrate is an alkene and the product is a nitrile. Since cyanide is both a good σ donor and a π acceptor ligand, its presence accelerates the rate of substitution of the ligand *trans* to it by the *trans* effect. A key step in hydrocyanation is the oxidative addition of hydrogen cyanide to low valent metal complexes. The most important industrial application of hydrocyanation is in the production of Nylon-6,6′.[29]

Condensation polymerisation of hexamethylenediamine (HMD) and adipic acid is the common route to obtain Nylon-6,6′. Traditionally, this was prepared by using benzene as a starting material. This method of production involved a complex set of steps (Scheme 12.4).



Scheme 12.4 Conventional synthesis of nylon-6,6′

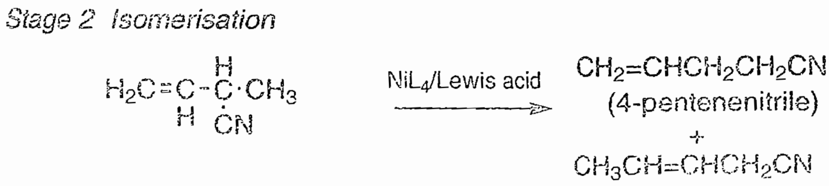
Two alternative procedures using homogeneous catalysis and 1,3-butadiene as precursor have been developed. BASF demonstrated selective dicarbonylation of butadiene to give adipic acid and Dupont developed double anti-Markownikov addition of HCN to butadiene using Nickel–phosphite catalysts to make adiponitrile. The process for adiponitrile developed during 1960 and commercialised in 1971 operates in three stages as shown in Eqs 12.10–12.12. Today, more than 75% of adiponitrile prepared annually is by catalytic hydrocyanation.[30, 31]



Stage 1 (Addition of one HCN)

$$CH_2{=}CHCH{=}CH_2 + HCN \xrightarrow[>70\ ^{\circ}C]{NiL_4/\ L} \underset{\text{(3-pentenenitrile)}}{CH_3CH{=}CHCH_2CN\ (70\%)} + \underset{\text{(2-methyl-3-butenenitrile)}}{H_2C{=}\underset{H}{C}-\underset{CN}{\overset{H}{C}}-CH_3\ (30\%)} \qquad (12.10)$$

$L = P(O\text{-}o\text{-}tolyl)_3$



Stage 2 Isomerisation

$$H_2C{=}\underset{H}{C}-\underset{CN}{\overset{H}{C}}-CH_3 \xrightarrow{NiL_4/\text{Lewis acid}} \underset{\text{(4-pentenenitrile)}}{CH_2{=}CHCH_2CH_2CN} + CH_3CH{=}CHCH_2CN \qquad (12.11)$$

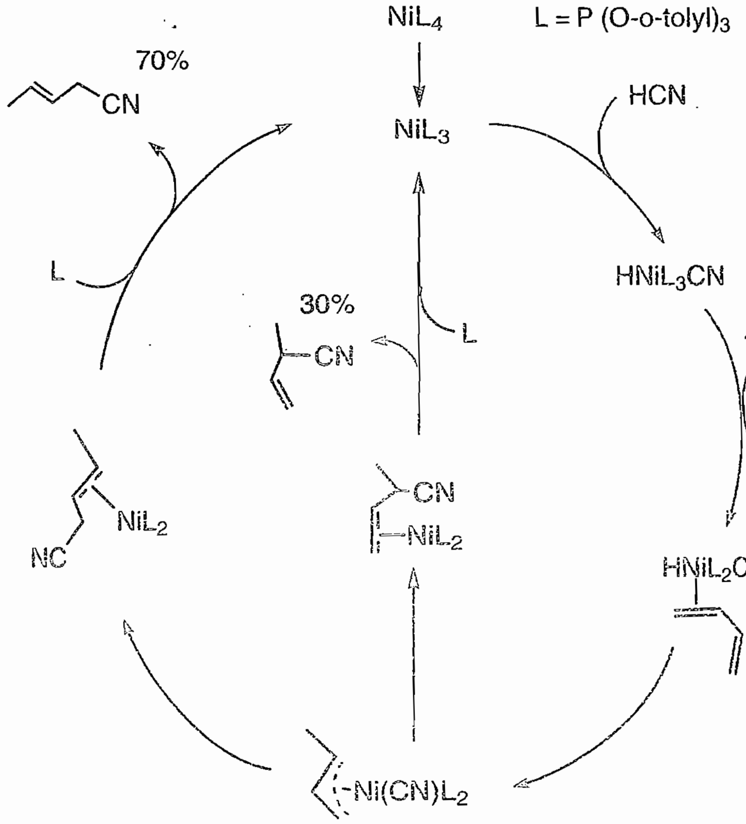
Stage 3 Isomerisation and HCN addition

$$\begin{array}{c}\mathrm{CH_2{=}CHCH_2CH_2CN} \\ + \\ \mathrm{CH_3CH{=}CHCH_2CN}\end{array} \xrightarrow[\text{Lewis acid}]{\mathrm{NiL_4/\,L}} \mathrm{NCCH_2CH_2CH_2CH_2CN} \qquad (12.12)$$

The nature of the phosphorus ligand is significant in these reactions and only phosphites produce catalysts of sustained activity. If instead of phosphite, an alkyl or aryl phosphine is used, the oxidation of Ni(0) to Ni(II) will occur with the formation of complexes of the type $L_2Ni(CN)_2$ which lead to catalyst deactivation. Aryl phosphites maintain nickel in the zero valent state during the key stages of the catalytic cycle. It is also observed from kinetic studies that tris(*o*-tolyl)phosphite gives the highest activity and also helps in the formation of the active form of the catalyst NiL_3.[32]

The mechanism of hydrocyanation of butadiene to give 3-pentenonitrile and 2-methyl-3-butenenitrile is given in Scheme 12.5. Catalytic addition of HCN to acetone to form the cyanohydrin is also an important route to methylmethacrylate. The cyano group can then be converted to the amine, carboxylic acid or amide group.

One of the first enantioselective hydrocyanation reactions was developed by T V Rajan Babu who utilised a diarylphosphite ligand derived from (D)-glucose. He observed that an enantiomeric excess of up to 75% could be obtained in the hydrocyanation of



Scheme 12.5 Catalytic cycle for the hydrocyanation of butadiene

aromatic vinyl compounds.[33] Naproxen, an anti-inflammatory drug, utilises an asymmetric enantioselective hydrocyanation of vinylnaphthalene from a phosphinite (OPR_2) ligand. The enantioselectivity of this reaction is important because only the *S* enantiomer is medicinally desirable, whereas the *R* enantiomer produces harmful health effects. This reaction can produce the *S* enantiomer with a selectivity > 90%.

12.4 HYDROSILYLATION OF ALKENES

Hydrosilylation is a reaction which is widely used in cross linking of silicon based polymers, in the synthesis of silicon based dendrimers and for making silyl derivatives that have a wide range of applications. These include modification of the surface of glass, stone, fabrics, making supported catalysts as well as conservation of archeologically important materials. In addition to C=C bonds, C=O, N=O, N=N and C=N bonds have been subjected to hydrosilylation. In heteroatomic cases, during hydrosilylation, the silyl group gets attached to the more electronegative element of the double bond. Terminal alkenes preferentially undergo hydrosilylation compared to internal alkenes. Hydrosilylation has also been applied to alkynes and nitriles. Hydrosilylation of C–O bonds leads to silyl ethers which on hydrolysis give alcohols.[34]

Hydrosilylation is catalytically carried out by suitable platinum based catalysts. The general reaction can be given as

$$HSiR_3 + RCH_2{=}CH_2 \xrightarrow{PtL_n} RCH_2CH_2SiR_3 \qquad (12.13)$$

where PtL_n is the platinum based catalyst.

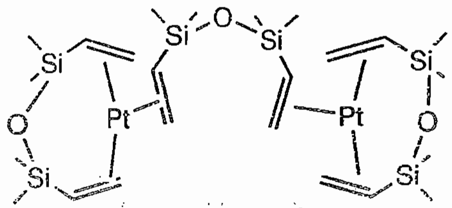
The three well known platinum based catalysts used for hydrosilylation are Spier's catalyst, Lukevic's catalyst and Karstedt's catalyst.[35–38]

H_2PtCl_6

Spier's catalyst

$(NBu_4)_2PtCl_6$

Lukevic's catalyst

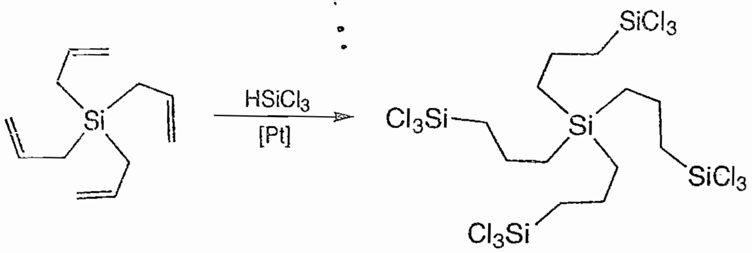


Karstedt's catalyst

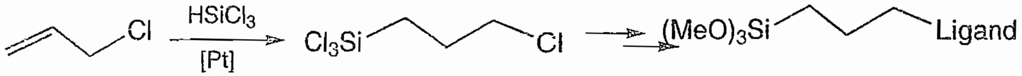
Alkene hydrosilylation is highly exothermic; its heat of reaction is close to that of hydrogenation of alkenes. The reaction needs to be controlled often as a highly exothermic reaction sets in when the catalyst is added to the mixture of alkene and $HSiCl_3$. Industrial hydrosilylation using Speier's catalyst has been found to give turnover numbers close to a million.

Silicon dendrimers up to the sixth generation can be prepared by a combination of hydrosilylation with $HSiCl_3$ and coupling of allyl Grignard reagents. The first step of this reaction is shown in Eq. 12.14.[39]

Anchoring of a catalyst to a silica/glass surface is often carried out by making a tether having a ligand which can bind to a metal at one end and a $(MeO)_3Si$ group at the other. The hydrosilylation of allyl chloride with $HSiCl_3$ results in $Cl(CH_2)_3SiCl_3$. The chlorines of this molecule are suitably substituted to make such molecules (Eq. 12.15).[40]

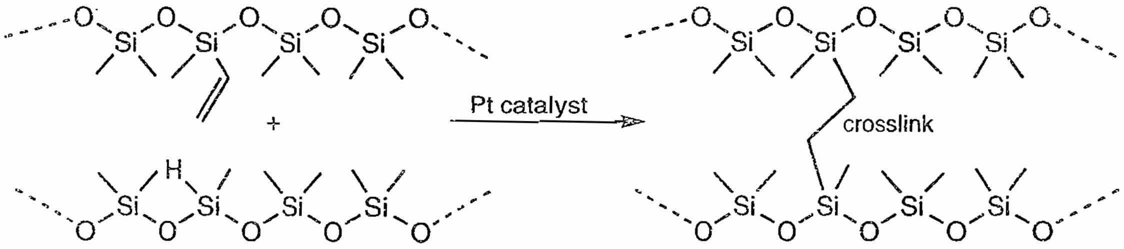


(12.14)



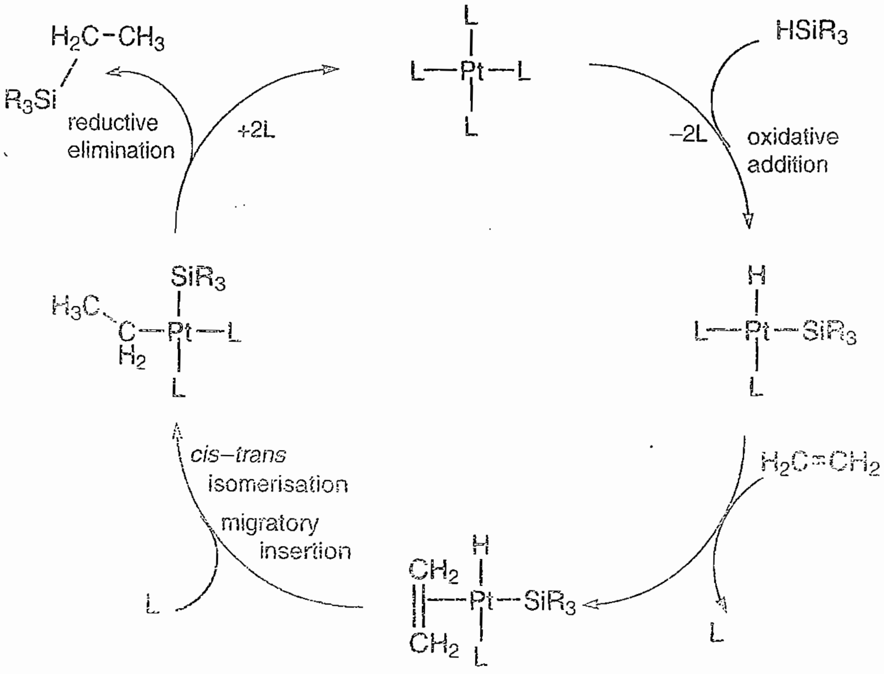
(12.15)

Cross linking of silicone polymers by hydrosilylation is carried out by introducing Si–vinyl groups and Si–H groups on the polymer chain in a very limited amount. Treatment with a platinum based hydrosilylation catalyst results in cross linking of the chains. Vinyl groups themselves are introduced on the chain by partial hydrosilylation of the Si–H groups with acetylene.



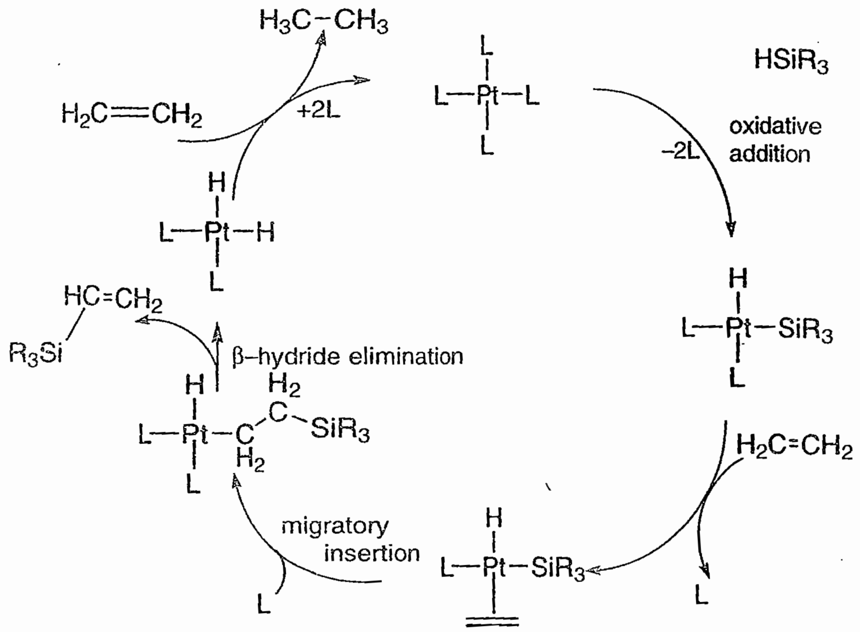
(12.16)

The mechanism of hydrosilylation, well known as the Chalk–Harrod mechanism is shown in Scheme 12.6.[41]



Scheme 12.6 The Chalk–Harrod mechanism of hydrosilylation

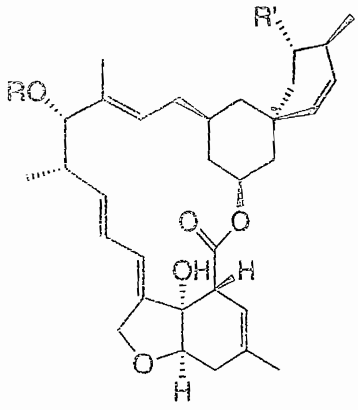
A side reaction also often occurs during the hydrosilylation reaction resulting in the formation of a vinyl–silyl compound along with the hydrogenated alkene precursor in a 1:1 molar ratio (Scheme 12.7). The vinyl product is formed as a result of insertion of the alkene into the metal–silicon bond followed by β-hydride elimination. Alkene hydrogenation happens consequently by the action of the hydrogens present on the catalyst.



Scheme 12.7 Mechanism showing the formation of the vinyl–silyl side product during hydrosilylation

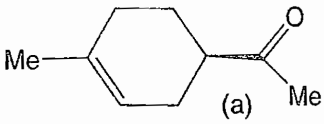
Problems and Exercises

12.1. Only one double bond is hydrogenated in the given compound, ivermecetin, on reaction with H_2 (RT, 1 atm) in the presence of Wilkinson's catalyst. Draw the structure of the product.

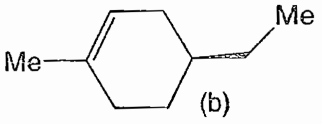


Ivermecetin

12.2. Draw the structure(s) of the preferred products (if any) for the following compounds when these are hydrogenated using Crabtree's catalyst (H_2, RT, 1atm).

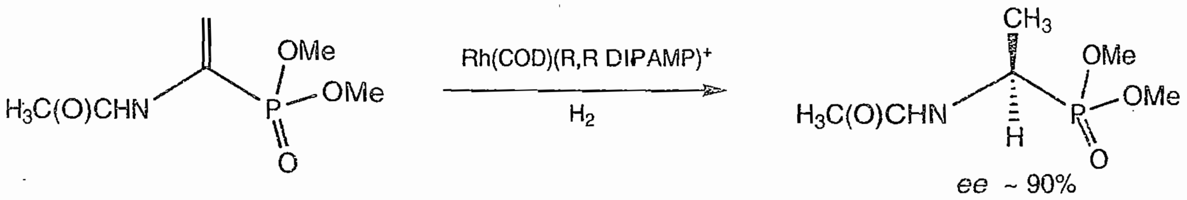


(a)

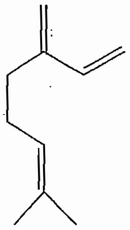


(b)

12.3. Knowles' asymmetric hydrogenation catalyst for the given reaction gives the major product as shown. The *re* face bound diastereomer was the minor diastereomer in the reaction. Draw the steps leading to the formation of the major product.

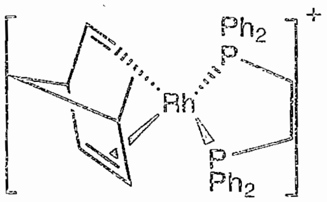


12.4. The hydrogenation behaviour of myrcene (see figure) using $RhH(CO)(PPh_3)_3$ in cyclohexane was found to be similar to Wilkinson's catalyst resulting in only one double bond getting saturated. Out of the three double bonds, one remained unaffected by the reaction. Predict the major (A) and minor (B) products of hydrogenation.

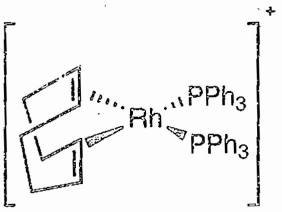


Two products resulting from the isomerisation of A and B were also obtained from this reaction and these were thermodynamically more stable than A and B. Predict their structures as well.

12.5. Arrange the given hydrogenation catalysts of rhodium in the increasing order of catalytic activity. Justify your answer with respect to the position allotted to each one in your arrangement.



(a)



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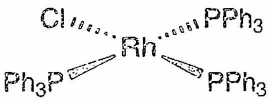
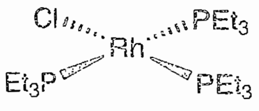
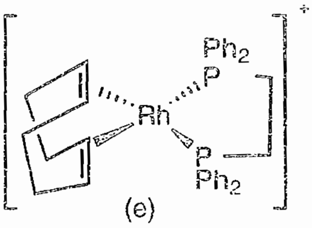


(c)



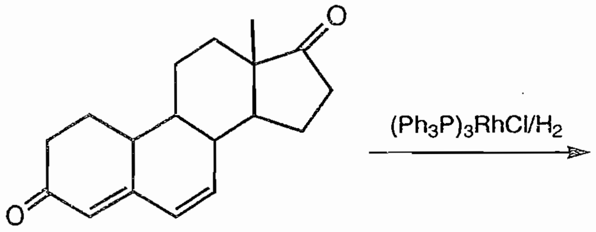
(d)



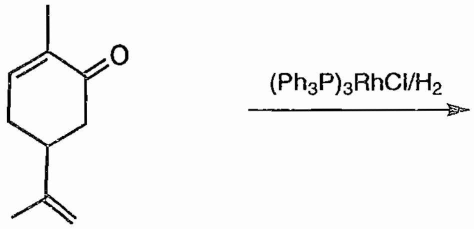
(e)

12.6. Predict the products in the following hydrogenation reactions using Wilkinson's catalyst.

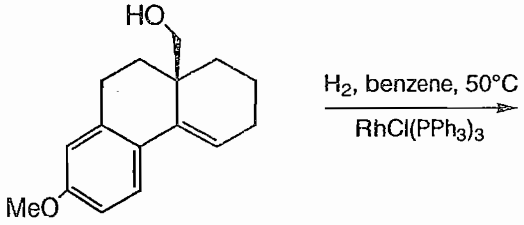
(a)



(b)



12.7. Predict the product stereochemistry in the given hydrogenation reaction. Explain how the stereochemistry is achieved.

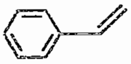


12.8. Among the given pairs of compounds, indicate which one will be more easily hydrogenated by Wilkinson's catalyst.

(a) 

and 

(b) 

and 

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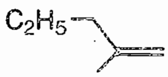
and 

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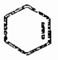
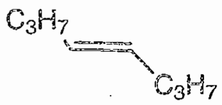
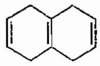
and 

(e) 

and 

12.9. Isomerisation is a minor pathway in the hydrogenation catalysis. The hydrogenation of triene  in the presence of Pd/C forms fully saturated decalin and some amount of the isomerised product tetralin. Write the products formed (both hydrogenated and isomerised product if any) when the same reaction is carried out in the presence of Wilkinson's catalyst.

12.10. Indicate what features and the sequence of steps differ in the hydrogenation reaction using Wilkinson's catalyst and the chiral catalyst $[Rh(DIPAMP)(S)_2]^+$.

12.11. Hydrogen cyanide does not add to unactivated olefins but the addition is catalysed by low valent transition metal complexes. The given reaction is catalysed by the nickel complex $(C_2H_4)Ni[P(O\text{-}o\text{-}tolyl)_3]$. Draw the catalytic cycle for the mechanism of this reaction.

$$C_2H_4 + HCN \xrightarrow[\text{Ni catalyst}]{} C_2H_5CN$$

Supplementary reading

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CHAPTER 13

HYDROFORMYLATION

Hydroformylation – often called the *oxo process* – is used to describe the addition of H_2 and CO to an olefinic double bond resulting in the formation of an aldehyde which has one carbon atom more than the olefin. In simple terms, the equation can be written as

$$RCH{=}CH_2 + CO + H_2 \longrightarrow RCH_2CH_2CHO + RCH(CH_3)CHO \tag{13.1}$$

13.1 IMPORTANCE OF HYDROFORMYLATION

The reaction was first discovered by Otto Roeln in 1938 at the Ruhrchemie industry in Germany while studying recycling of olefins.[1] Since then, the reaction has been developed by industry and accounts for more than 7 × 10^6 tons/year of aldehydes. It is the largest homogeneous catalytic process worldwide. Actually, aldehydes are not the end products, they get further reduced to alcohols; sometimes in the same plant or by other heterogeneous catalysts. The short chain alcohols thus obtained are extensively used as solvents in the lacquer industry for making plasticisers and the long chain alcohols are used in the manufacture of synthetic detergents.[2]

As the alkene also has equal propensity to react with H_2, it is interesting to study the thermodynamics involving both hydrogenation and hydroformylation reactions. The changes in entropy and free energy of these two reactions for propene under standard conditions are given below.

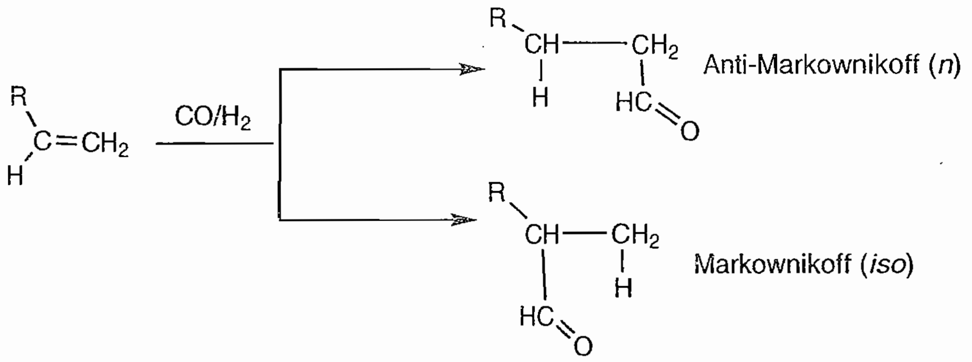
$$CH_3CH{=}CH_2 + CO + H_2 \longrightarrow CH_3CH_2CH_2CHO$$

$$\Delta H = -150 \text{ kJ/mol}; \Delta G = -42 \text{ kJ/mol}$$

$$CH_3CH{=}CH_2 + H_2 \longrightarrow CH_3CH_2CH_3$$

$$\Delta H = -126 \text{ kJ/mol}; \Delta G = -88 \text{ kJ/mol}$$

It becomes evident that the alkane is the thermodynamically favoured product and not the aldehyde. Since the aldehyde is the major product, it shows that the reaction is kinetically controlled. At higher temperatures, the entropy loss is more important and ΔG becomes less negative. Also, the reaction is exothermic and if conducted under adiabatic conditions, the temperature rises and ΔG becomes close to zero.



Over the years, four catalytic processes have come into prominence for hydroformylation reactions. These are:

- the $Co_2(CO)_8$ catalysed process,
- the $Co_2(CO)_8/PR_3$ catalysed process,
- the $HRh(CO)(PPh_3)_3$ catalysed process, and
- the biphasic $HRh(CO)(PR_3)_3$ process ($R = m\text{-}C_6H_4SO_3Na$)

The major differences between these processes are in (i) the operating temperatures and pressures, (ii) the ratio of the product formed, *n*-aldehyde to *iso*-aldehyde (*n*/*iso* ratio), (iii) the rate of reaction and the control of side reactions such as hydrogenation and (iv) ease of recovery of catalyst.[3,4]

Currently C_3 to C_{15} aldehydes are produced by the oxo process and these are subsequently converted into amines, carboxylic acids and most importantly to primary alcohols. Some of the major industrially important end products are butanol, 1,4-butanediol (for THF synthesis), vitamin A and 2-ethylhexanol. 2-Ethylhexanol is used in making diethylhexyl phthalate (DEHP), also known as dioctyl phthalate (DOP) which is the most widely used plasticiser in the world.

13.2 COBALT CATALYSTS FOR HYDROFORMYLATION

Cobalt catalysts dominated the hydroformylation industry till the early 1970s after which the triarylphosphine rhodium based catalysts took over. The latter are especially good with C_8 or lower alkenes when a higher selectivity of the linear aldehyde is required. Under H_2/CO pressure, cobalt salts produce $HCo(CO)_4$ as the active catalytic species. Heck and Breslow in 1960–61 proposed the now accepted catalytic cycle based on cobalt. Kinetic studies support a general rate expression as given below.[5,6]

$$d[\text{aldehyde}]/dt = k[\text{alkene}][\text{Co}][pH_2][pCO]^{-1}$$

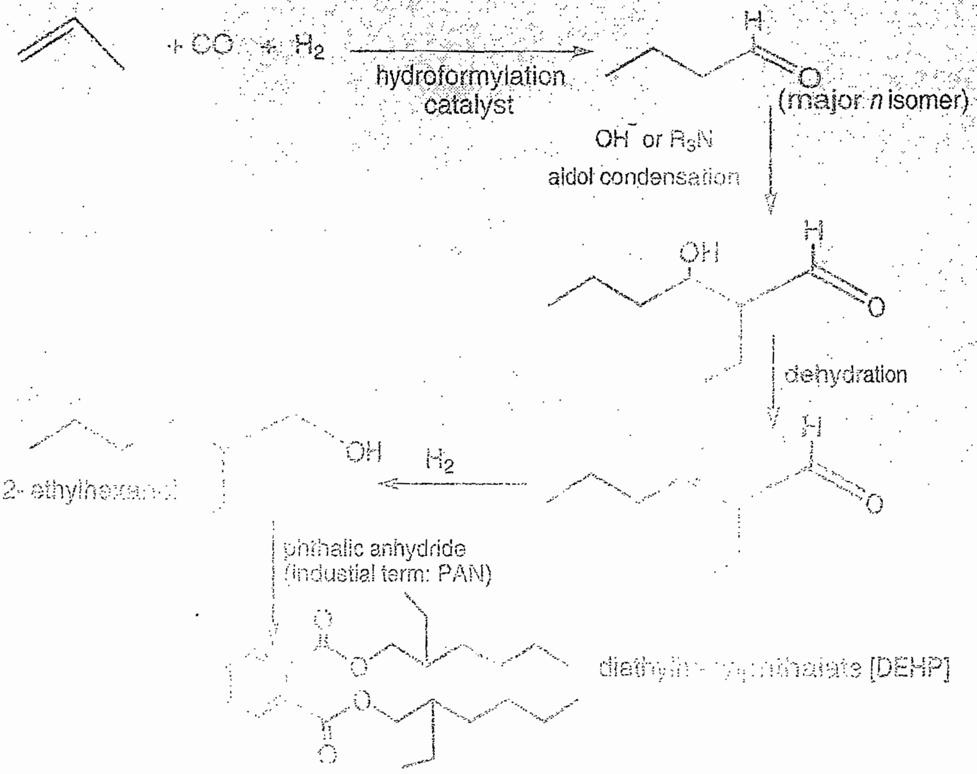
The inverse dependence on the concentration of CO agrees with the mechanistic requirement of CO dissociation from the 18 electron species, $HCo(CO)_4$. However, if the CO partial pressure is not kept high enough, metallic cobalt gets deposited due to the thermal

Plasticisers and industry

A plasticiser is a substance which when added to a material – usually a hard plastic such as PVC – makes it flexible, resilient and easier to handle. Early examples of plasticisers include water to soften clay and oils to plasticise pitch used for waterproofing ancient boats. Modern plasticisers are manmade organic chemicals, the majority of which are esters such as adipates and phthalates. PVC is often softened by using plasticisers such as phthalates, adipates, trimellitates and citrates; 95% of plasticiser production is for PVC end use.

Plasticisers are used in a wide range of applications, from toys and baby care items, life-saving medical devices and cling wrap to flooring, wall coverings, electrical cables, automotive parts, packaging, stationery, coatings, and the manufacture of clothing and footwear. Small quantities of plasticisers are also used in paints, rubber products, adhesives and some cosmetics. Importantly, they are not just additives (like pigments or fillers) but are major components that determine the physical properties of polymer products. They are colourless, odourless liquids produced by a simple chemical reaction. There are more than 300 different types of plasticisers of which 50–100 are in commercial use.

In Western Europe alone, about one million tons of phthalates are produced each year, of which approximately 900,000 tons are used to plasticise PVC. The most common plasticisers are diethylhexyl phthalate (DEHP: mp −50°C, bp 384°C) and diisononyl phthalate (DINP). As the most universal plasticiser, diethylhexyl phthalate occupies 75% of the world plasticiser market and is widely employed for a variety of applications, mainly for plasticising PVC and other polymers. Synthetic procedure for the preparation of DEHP from propene is shown below.



[illegible]stability of HCo[illegible] [illegible]sing the CO partial pressure [illegible]creases the reaction rate of hydroformylation an[illegible] [illegible] the extent of alkene isomer[illegible] [illegible] reaction. The detailed [illegible]

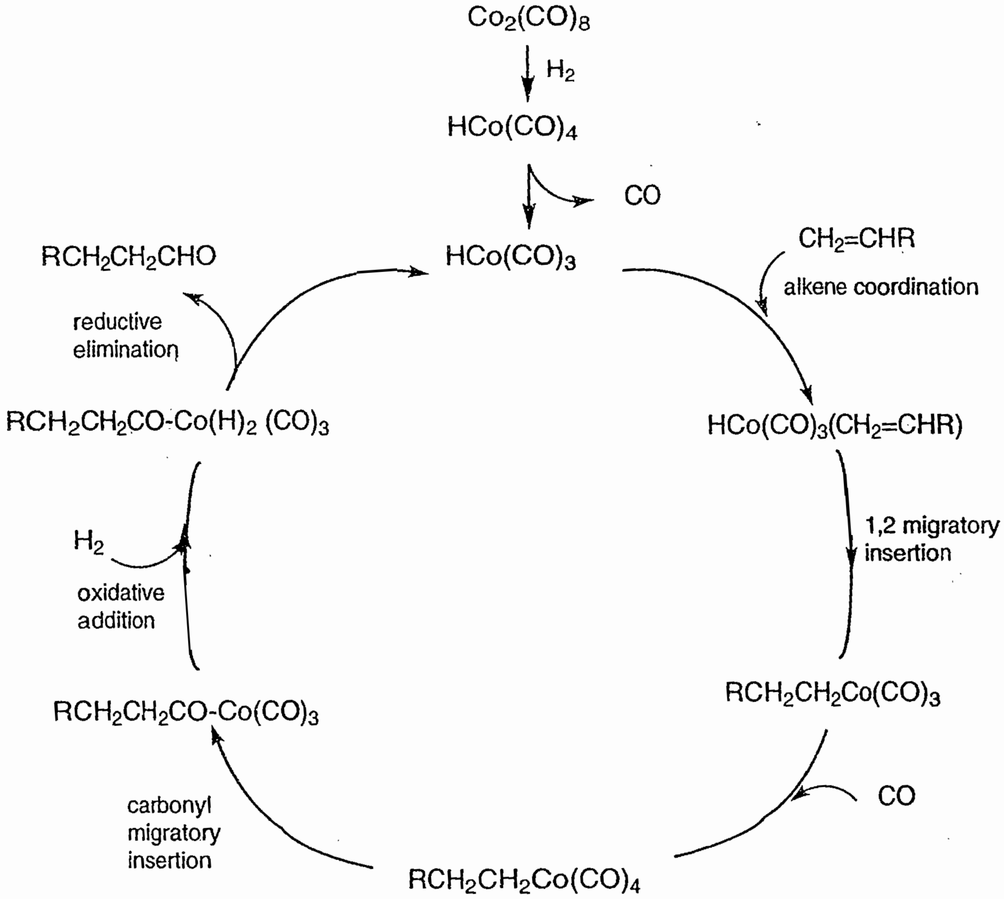
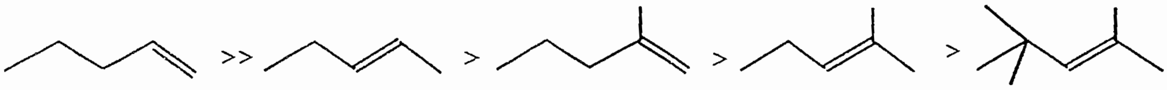


Fig. 13.1 Catalytic cycle for hydroformylation using $HCo(CO)_4$

The general relative reactivity of alkenes for hydroformylation is as follows.



13.3 PHOSPHINE MODIFIED COBALT CATALYSTS

The addition of trialkyl phosphine ligands to the cobalt carbonyl catalyst brought about a dramatic change in the rate of the reaction and its selectivity. When a CO is substituted by the electron donating PR_3 group, the back bonding from the metal to the rest of the CO groups increases, thereby increasing the thermal stability of the catalyst against decomposition. The CO partial pressure required to stabilise the catalyst comes down considerably from 200–300 to 50–100 bars. Also, the hydridic nature of H increases is there is more electron density on the metal. The catalyst can even convert the aldehyde formed to alcohol by hydrogenation, but the presence of less electron donating phosphines like PPh_3 on the catalyst checks this process and produces less of the alcohol.[7]

A highly active catalyst has an additional drawback since it also hydrogenates the lkene and some alkene is wasted in the formation of unwanted products. Higher stability f the catalyst also means lesser activity.

13.4 RHODIUM–PHOSPHINE CATALYSTS

In 1965, Osborn, Wilkinson and others reported that Rh(I) catalysts with PPh_3 affect not only hydrogenation but also hydroformylation with high regioselectivity near ambient conditions. As halides were found to be inhibitors for hydroformylation, the original Wilkinson's catalyst was modified to contain no halides. $HRh(CO)(PPh_3)_3$ and $Rh(acac)(CO)_2$ are two commonly used catalyst precursors for hydroformylation. The catalytic cycle (Fig. 13.2) shows that the steps are analogous to Heck's mechanism for hydroformylation using $HCo(CO)_4$. Kinetic studies on the rhodium catalyst showed that unlike the cobalt catalyst, there is no inverse dependence of the rate on CO concentration.[8-11]

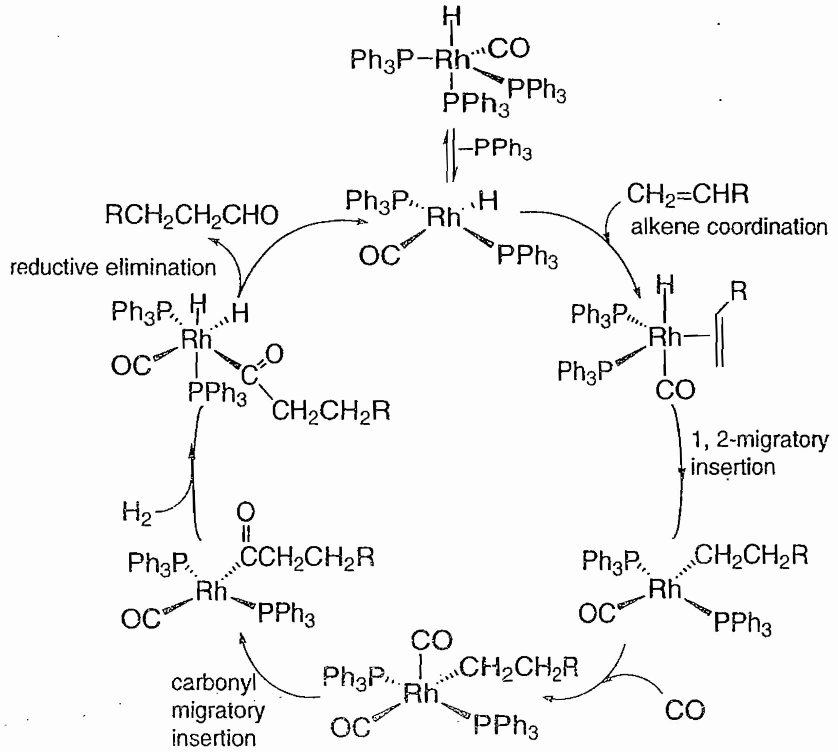


Fig. 13.2 Catalytic cycle for hydroformylation using rhodium catalyst

$$\text{Rate } \alpha \ [\text{propylene}][\text{Rh}][\text{pH}_2]$$

The main drawback of the rhodium-PPh_3 catalyst is a problem related to the industrial process. Since a high temperature is required for separation of the long chain aldehyde products, the catalyst decomposes at that temperature. So the application has been limited to C_3 and C_4 alkenes. This problem was solved by using a water soluble phosphine along with the catalyst and also by resorting to biphasic catalysis. Tables 13.1 and 13.2 summarise the reaction parameters of four catalysts and their advantages and drawbacks.[12]

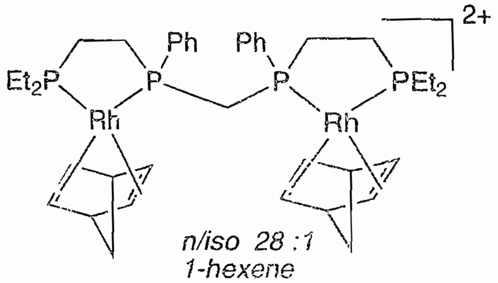
Table 13.1 Reaction parameters and *n/iso* ratio obtained with different catalysts

Catalyst (active form)	Reaction parameters	*(n/iso)* ratio maximum
$Co_2(CO)_8$ $[HCo(CO)_4]$	Pressure 200–300 bar Temp. 110–160°C Cat. concentration* 0.1–1.0	3:1
$Co_2(CO)_8/PR_3$ R = *n*-Bu and similar groups	Pressure 50–100 bar Temp. 160–200°C Cat. concentration* 0.6	7:1
$HRh(CO)(PPh_3)_3$	Pressure 15–25 bar Temp. 80–120°C Cat. concentration* 0.01–0.05	16 :1
$HRh(CO)(PR_3)_3$ R = $mC_6H_4SO_3Na$	Pressure 40–60 bar Temp. 110–130°C Cat. concentration* 0.001–1	19:1

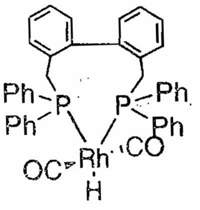
*percentage of metal/olefin

13.5 FACTORS AFFECTING THE *n/iso* RATIO OF HYDROFORMYLATION PRODUCTS

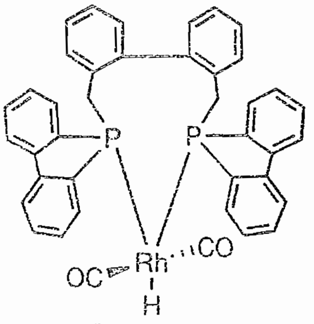
One of the directions of recent research in hydroformylation reactions has been to improve the *n/iso* ratio of aldehyde products. The first major development was the discovery of a chelating biphosphine BISBI developed by Eastman Kodak. For example, Rh with BISBI as ligand gave an *n/iso* ratio of 96:4 under mild conditions. Studies on related biphosphines led to an even better *n/iso* ratio; for example, when PPh_2 groups in BISBI were replaced with dibenzophosphole units, it resulted in an *n/iso* ratio of 99.4:0.6. However, there was a problem with the catalyst stability. Piet van Leeuwen and coworkers carried out systematic studies on a series of biphosphines by varying their bite angle. They observed that larger natural bite angles in the vicinity of 120° favoured a higher *n/iso* ratio of hydroformylation products (see Chapter 4).[13, 14]



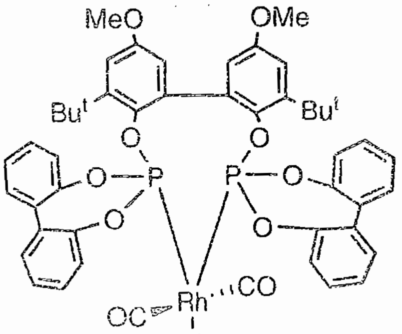
n/iso 28 :1
1-hexene



BISBI *n/iso* 96:4
propylene



n/iso 99.4 :0.6
propylene



n/iso 96:4
2-butene

Table 13.2 Advantages and disadvantages of various hydroformylation catalysts

Catalyst	Advantages	Disadvantages
$HCo(CO)_4$	Relatively less alkene hydrogenation (< 2%).	Thermal instability and volatility of $HCo(CO)_4$ leads to the deposition of Co or its oxide on the reactor. High pressure of CO (200–300 bar) required to prevent this brings in operational difficulties. Rate of reaction is inversely proportional to [CO]. So, increase in CO pressure reduces rate. Low *n/iso* ratio.
$Co_2(CO)_8/PR_3$ R = *n*-Bu and other similar groups	Catalyst decomposition reduced due to increased thermal stability of catalyst. Better *n/iso* selectivity due to increased hydridic character of H.	Pressures and temperatures still on the higher side. Lower reaction rate (at 180°C, the rate is only 20% of the rate of $HCo(CO)_4$, operating at 145°C). Increased hydrogenation of alkenes (up to 15% loss of alkene). Good for production of 2-ethylhexanol from propylene (up to 85% yield in a single reactor).
$HRh(CO)(PPh_3)_3$	Low pressure (15–25 bar) and low temperature. High *n/iso* selectivity (94%).	Applicable only to C_3 and C_4 olefins as catalyst is thermally unstable at the high temperatures required for the removal of products by distillation. High cost of Rh in comparison to Co.
$HRh(CO)(PR_3)_3$ R = $mC_6H_4SO_3Na$ (water soluble), biphasic catalysis	Easy catalyst recovery and less loss, low catalyst concentration required. Less olefin hydrogenation (< 2%). Applicable to long chain olefins as well.	Low rate of reaction due to reduced miscibility of higher alkenes with the aqueous phase of catalyst. Pressure required is on the higher side in comparison to $HRh(CO)(PPh_3)_3$.

The use of phosphites as ligands instead of phosphines also led to a higher *n/iso* ratio. The percentage of linearity obtained for PPh_3 and $P(OPh)_3$ is very similar at low ligand concentrations. However, at higher ligand concentrations, phosphites give a better *n/iso* ratio of products.[15] The electronic and steric effects of the substituents on the phosphites play a significant role in deciding the rate and selectivity of the reactions. One major finding from a comparative study is that higher the χ value of the phosphine/phosphite, higher the selectivity towards linear products. Table 13.3 gives some examples indicating this observation.

Based on these two findings, a series of biphosphite ligands having large bite angles were prepared and found to be useful for realising a high *n/iso* ratio of hydroformylation products.

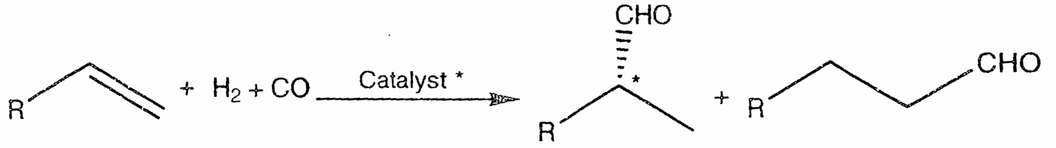
Table 13.3 Product selectivity in hydroformylation with rhodium phosphite and phosphine catalysts for 1-heptene at 90° and 7 bar of CO/H_2

R_3P: R =	χ value	Linearity of product (%)
Ph	13	82
PhO	29	86
n-Bu	4	71
*n*BuO	20	81
4-Cl-C_6H_4O	33	93
CF_3CH_2O	39	96

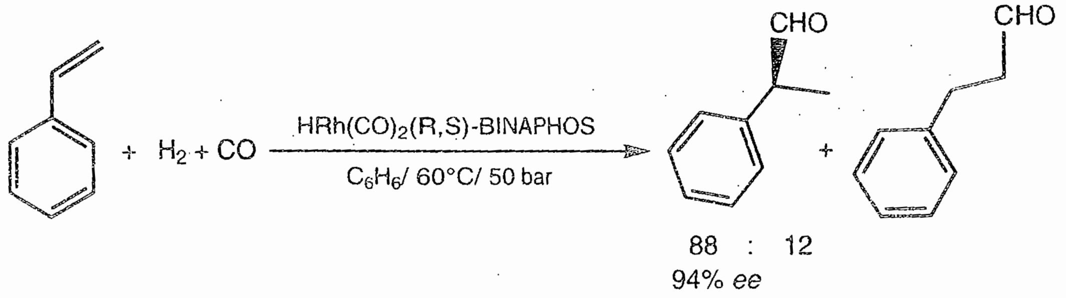
13.6 ENANTIOSELECTIVE HYDROFORMYLATION

Enantioselective hydroformylation is a relatively recent development in hydroformylation reactions. It is interesting to note that chiral aldehydes will be formed only when the addition of H_2/CO to the alkene occurs in the Markownikoff manner. In contrast to normal hydroformylation, a better *iso/n* ratio is preferred in enantioselective hydroformylation as the *n* isomer will be nonchiral. Initially, platinum based catalysts were tried; however, these gave a poor *iso/n* ratio and were plagued by hydrogenation. The isomerisation of the alkene also occurred. It is interesting to note that hydroformylation in the Markownikoff sense will form only the chiral aldehydes.[16]

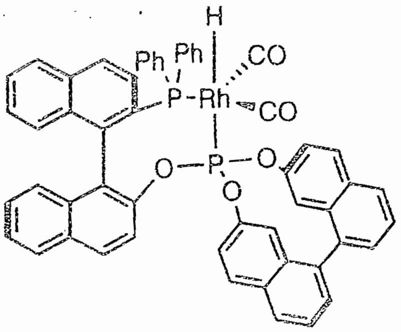
Rhodium based chiral catalysts such as HRh(CO)$_2$(R,S)-BINAPHOS have been developed which give high *iso/n* ratio as well as good enantiomeric excess.



(13.2)



(13.3)

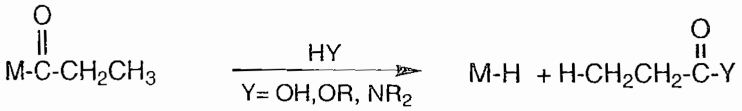


HRh(CO)2(R,S)-BINAPHOS

13.7 Carboalkoxylation of Olefins

If a hydrogen donor is used in place of H_2 in the hydroformylation of olefins, carboxylic acids and their derivatives can be prepared. This process which generates the -C(O)O- moiety allows the conversion of olefins, CO and alcohols directly into esters of carboxylic acids.

Carboxylic acids and their derivatives can be prepared from catalytic reactions between CO and an olefin in the presence of water, alcohol or an amine. These reactions are catalysed by many transition metal complexes and form the basis of several industrial processes. One such process is called carboalkoxylation. This process involves the solvolysis of the intermediate acyl complex [M(CO)R] formed during the reaction of the alkene and CO with the metal catalyst. The reaction resembles the hydroformylation reaction except that the acyl complex reacts preferentially with nucleophiles such as water, alcohol and amine rather than with H_2 as in the hydroformylation. Thus, when ethylene is used, propanoic acid or its derivatives may be produced. The reaction with ethylene probably proceeds via steps M–H → M–Et → M–COEt which then undergoes nucleophilic attack to form the product. After the attack by the nucleophile, the M–H species is regenerated to carry out the catalytic cycle.[17]



$$\text{M-}\overset{\overset{\displaystyle O}{\|}}{\text{C}}\text{-CH}_2\text{CH}_3 \xrightarrow[\text{Y= OH,OR, NR}_2]{\text{HY}} \text{M-H} + \text{H-CH}_2\text{CH}_2\text{-}\overset{\overset{\displaystyle O}{\|}}{\text{C}}\text{-Y} \qquad (13.4)$$

An alternative mechanism may also exist in which the nucleophile, water, alcohol or amine may attack the coordinated carbonyl group to give the corresponding carboxylic derivative. Commercial carboalkoxylation processes are used to prepare fatty acid esters from linear olefins. In this case too, as in the case of hydroformylation, selectivity for linear versus branched products is an issue. Another problem associated with this reaction is the occurrence of the water gas shift reaction. The hydrogen so produced can lead to hydrogenation or hydroformylation reaction products which can be unwanted side reactions.

The commercial olefin carboalkoxylation process uses $Co_2(CO)_8$ as an effective catalyst. The typical conditions are 140–170°C and 100–200 atm of CO in methanol. A small amount of H_2 is also present. The ester product formed has an *n/iso* ratio of 70:30. The addition of pyridine to the reaction increases the rate of reaction as well the formation of linear alkyl ester. The catalytic cycle given in Fig. 13.3 has been proposed.[18]

Pd catalysts are gaining importance since these are very effective even under milder conditions. Different mechanisms have been proposed depending upon which class of catalyst is used. Carboalkoxylation of 1-propene under acidic conditions with $PdCl_2(PPh_3)_2$ as catalyst predominantly forms the branched ester product (Eq. 13.5). It is proposed that it does not involve a Pd hydride–olefin insertion but instead an alkoxycarbonyl intermediate (A) is formed which then adds to the olefin. The regioselectivity of this reaction is achieved via the formation of intermediate (B). HCl cleaves the Pd–C bond to generate the catalyst and isobutyrate product.

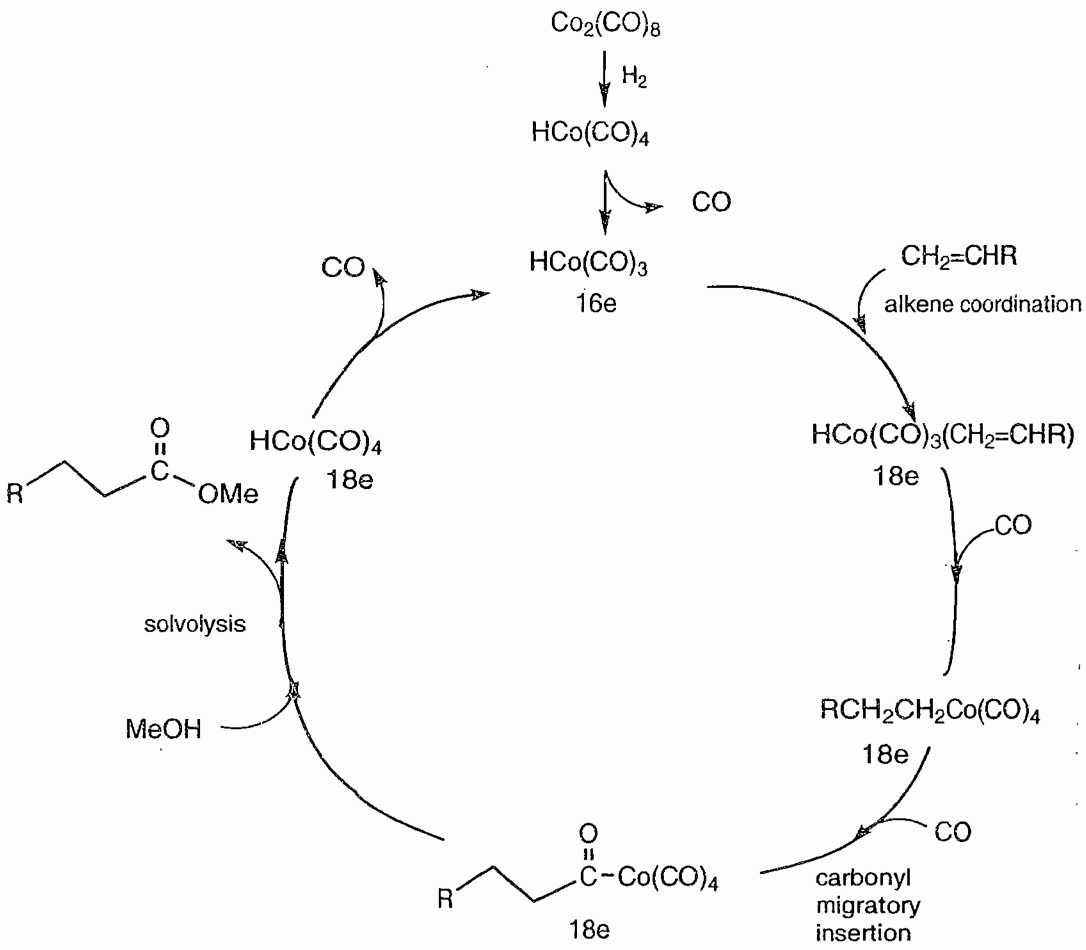
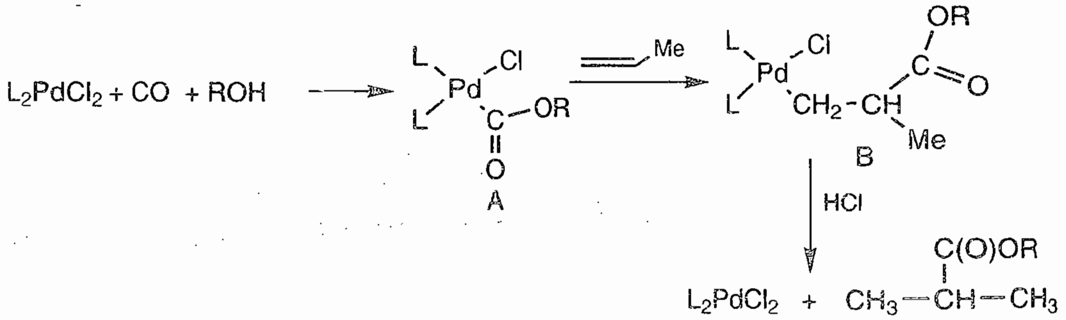


Fig. 13.3 Catalytic cycle for carboalkoxylation of olefins



(13.5)

When acetylene is used instead of the alkene, the alkoxycarbonylation reaction catalysed by nickel carbonyl forms acrylic acid and/or its ester. This process has been used in the industry for the production of acrylic acid and acrylates. Dicarbonylation of acetylene affords succinic acid.[19]

$$HC{\equiv}CH + CO + H_2O \xrightarrow{Ni(CO)_4,\ 180°C,\ 35\ atm} H_2C{=}CHCOOH \tag{13.6}$$

$$HC{\equiv}CH + CO + H_2O \xrightarrow{Co_2(CO)_8,\ 140°C,\ 170\ atm} HOOCCH_2CH_2COOH \tag{13.7}$$

Problems and Exercises

13.1. The mechanism of the hydroformylation of alkenes in the presence of $RhH(CO)(PPh_3)_3$ as catalyst has been well studied. Answer the following briefly.

(a) What is the active catalyst in this reaction?

(b) Why is the catalytic activity drastically inhibited when the concentration of CO is in excess over that of H_2?

(c) Which one is the probable rate determining step in the catalytic cycle?

13.2. Hydroformylation of formaldehyde to glycoaldehyde $CHOCH_2OH$, occurs in the presence of $HRh(CO)_2(PPh_3)$ as a catalyst. Write the probable steps in the catalytic cycle.

13.3. $CH_2{=}CHR$, on hydroformylation, forms RCH_2CH_2CHO. The reaction occurs at 120°C and the catalyst used is $Co_2(CO)_8$. However, when the temperature is raised to 185°C $RCH_2CH_2CH_2OH$ is formed as a major product from a competing reaction. Write the steps involved in the reduction of the aldehyde to the alcohol. [Note: The actual catalyst in this process is $HCo(CO)_3$].

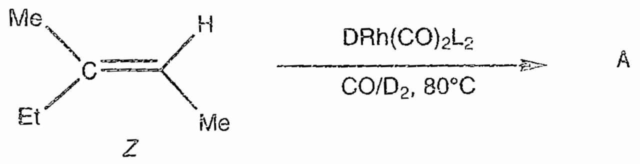
13.4. The hydroformylation of 1-pentene is catalysed by the cobalt catalyst $Co_2(CO)_8$. It is observed that an increase in partial pressure of CO above a certain threshold decreases the rate of the reaction. Account for this observation.

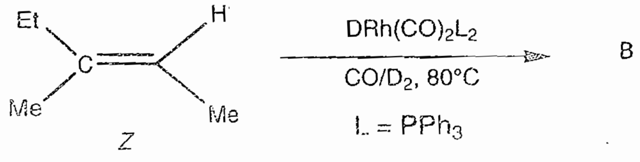
13.5. The hydroformylation of 1-butene in the presence of the catalyst $Co_2(CO)_8$, forms 1-pentanal as the end product. The infrared spectrum shows the presence of $CH_3CH_2CH_2CH_2\,C(O)Co(CO)_4$ (A) in the reaction mixture. When the same reaction was carried out in the presence of added Bu_3P, it did not form (A) or any analogous phosphine substituted complex. Based on these observations, what is the rate limiting reaction in the presence or absence of Bu_3P?

13.6. $HRh(CO)(PPh_3)_3$ is a useful catalyst for the hydroformylation reaction. What influence will it have on the rate of the reaction if an excess of PPh_3 is added to the reaction mixture?

13.7. Four different alkenes can give $CH_3CH_2CH(Me)CHO$ upon hydroformylation using $HRh(CO)(PPh_3)_3$. Identify these alkenes and predict their relative reactivity.

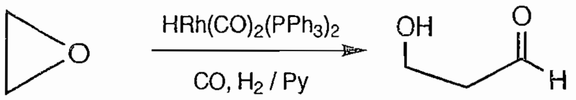
13.8. The hydroformylation of the *E* and *Z* isomers of 3-methyl-2-pentene is carried out under the following conditions. Write the products with proper stereochemistry in each case.





13.9. The hydroformylation of propene when carried out in the presence of the active catalyst $HCo(CO)_3$, can form both the *n* and *iso* products. What changes on the cobalt catalyst can you make so that the major product formed is the normal aldehyde? Consider only the steric factors around cobalt.

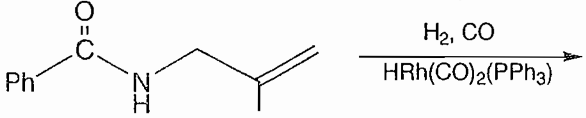
13.10. The hydroformylation of ethylene oxide to 3-hydroxypropane aldehyde is catalysed by $HRh(CO)_2(PPh_3)_2$. The reaction works best when the solvent is basic. Propose the mechanism for this transformation.

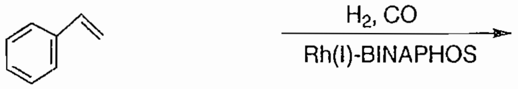


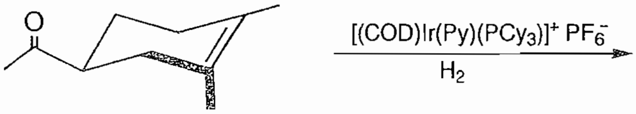
13.11. Write the possible major organic products in the following reactions.

(a)

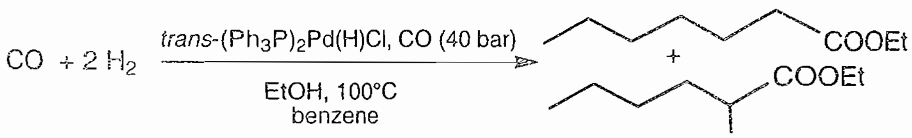

(b) $H_2C{=}CHMe \xrightarrow[HCo(CO)_4]{H_2,\ CO}$

(c)


(d)


(e)


13.12. The following hydroesterification reaction of a terminal alkene is mechanistically related to the hydroformylation reaction. However, the final step involves a nucleophilic attack on the palladium acyl complex releasing the ester. Draw a catalytic cycle for the formation of the *n*-isomer of the reaction.



13.13. Unlike the $HCo(CO)_4$ based hydroformylation (*n*:*iso* = 3:1), the PBu_3 added catalyst $HCo(CO)_3PBu_3$, provides a better *n*:*iso* ratio of products (7:1). Explain this observation on the basis of steric and electronic changes on the catalyst.

Supplementary reading

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METHANOL CARBONYLATION AND OLEFIN OXIDATION: MONSANTO, CATIVA AND WACKER PROCESSES

CHAPTER

14

Methanol can be produced commercially from synthesis gas and one of the great successes of homogeneous catalysis is the conversion of methanol to acetic acid. This is the second largest homogeneous catalytic industrial process worldwide. Over 8 million tonnes of acetic acid is produced all over the world annually of which 80% is made using methanol to acetic acid conversion technology.[1]

$$CO + 2H_2 \xrightarrow[50\text{–}100\text{ atm, }250°C]{Cu/ZnO/Al_2O_3} CH_3OH \tag{14.1}$$

14.1 HISTORY OF METHANOL CARBONYLATION

$$CO + CH_3OH \xrightarrow[I^-]{[Co]/[Rh]/[Ir]} CH_3C(O)OH \tag{14.2}$$

Three different industrial processes are known for this catalysis depending upon whether cobalt, rhodium or iridium is used as the metal. The metal forms a carbonyl iodo species which acts as the active form of the catalyst.

BASF introduced the first commercial homogeneous methanol to acetic acid process in 1960 using a cobalt catalyst and iodide as cocatalyst operating at 200°C and 700 atm. About 90% of the methanol was getting converted into acetic acid by this process along with the formation of side products such as acetaldehyde and ethanol.[2, 3]

In 1966, Monsanto established that a rhodium based catalyst with iodide as the cocatalyst could give 99% conversion of methanol to acetic acid and the reaction could be carried out at milder reaction conditions of 180°C and 30 atm (Fig. 14.1).[4]

Later in 1986, this process was taken over by British Petroleum (BP) but was still called the Monsanto process. Until 1996 this was the main process for acetic acid production around the world and the mechanism for this reaction was carefully studied.[5]

In 1996, BP announced their successful development of a new commercial process, named the Cativa process. A key feature of the Cativa process was the use of an iridium complex along with metal based iodide promoters. For example, the addition of a ruthenium based promoter compound could cause a three-fold increase in the rate of the iridium catalysed reaction. Since its inception in 1996, this process has become very popular and is currently replacing the Monsanto process in many plants across the world.

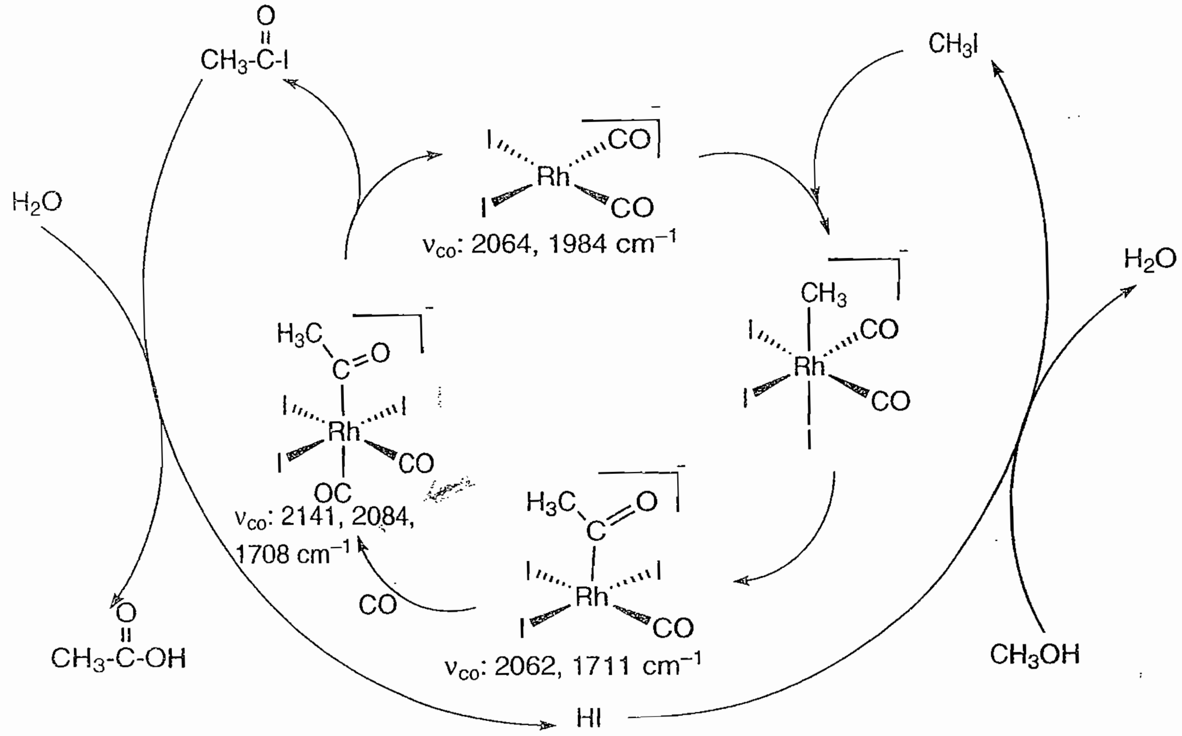

Fig. 14.1 Catalytic cycle for Monsanto acetic acid process

Acetic acid: Uses

In the industry, the major end products of acetic acid are vinyl acetate as a monomer (VAM) and related polymers (~50%), acetate esters as organic solvents (~15%), acetic anhydride and cellulose acetate (10%). Acetic acid by itself is used as a solvent in the industrial synthesis of purified terephthalic acid (PTA) (10%) by the oxidation of *p*-xylene. It is also used in food processing and pharmaceutical applications.

Vinyl acetate is a high volume chemical with the production exceeding 1 million pounds annually in the US alone. It is used in the manufacture of a wide variety of industrial and consumer products, for example, polyvinyl acetate is used for producing paints, adhesives and coatings for flexible substrates; polyvinyl alcohol is used to produce adhesives, coatings and water soluble packaging films; polyvinyl acetal is used to produce insulation for magnetic wire, interlayers for safety glass, wash primers and coatings; ethylene vinyl acetate copolymers are used to produce flexible films, coatings, adhesives, mouldings and insulation. Vinyl acetate monomer is the key raw material used in the manufacture of adhesives such as fevicol, in pulp and paper manufacture (impregnation agent) and in the rubber industry as a softener.

Nearly all purified terephthalic acid (PTA) is consumed in polyester production including polyester fibre, polyethylene terephthalate (PET) bottle resin and polyester film.

14.2 THE MONSANTO PROCESS

The industry standard was the Monsanto process and the kinetics of the reactions involved had been explored in detail mainly by in situ infrared spectroscopic measurements. The oxidative addition of MeI to $Rh(CO)_2I_2^-$ is the slower and rate determining step in the reaction. The CO migratory insertion step is faster than the oxidative addition (Fig. 14.2).[4,6,7]

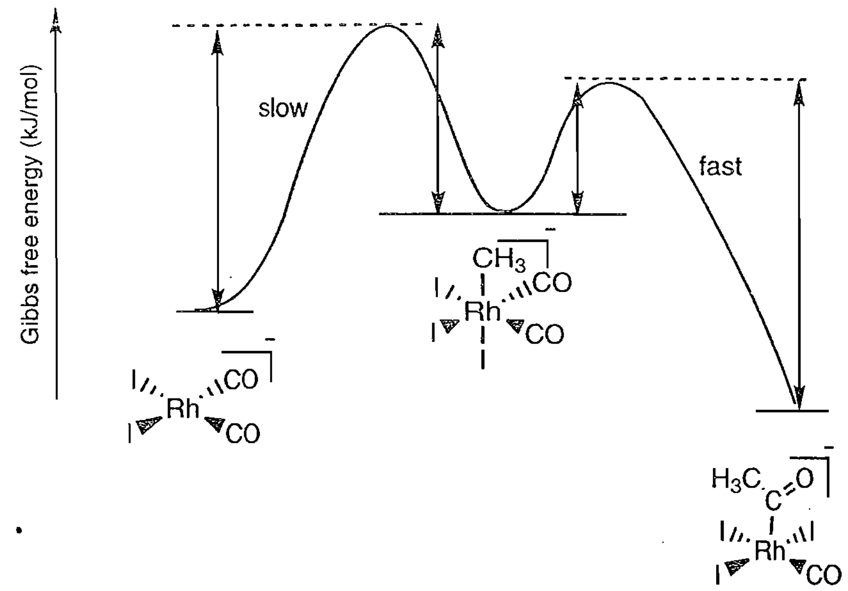

Fig. 14.2 Kinetic aspects of the Monsanto process

14.2.1 Problems with the Monsanto Process

As can be seen from the catalytic cycle (Fig. 14.1), water is an important ingredient for the catalytic process and the system requires a minimum of about 8–10 wt% of water for effective functioning. This is required for maintaining catalytic activity, catalytic stability and to achieve economically viable production rates. However, this brings about a dent in the process economics as separation of acetic acid from water (or making concentrated acid) requires a high input of energy.[8]

Another problem associated with the Monsanto process is the instability of the catalyst in the CO deficient areas of the reactor. The competitive oxidative addition of HI to $[Rh(CO)_2I_2]^-$ also occurs. Although this is of minor importance, it can lead to the formation of inactive species such as $[Rh(CO)_2I_4]^-$ and eventually the precipitation of Rh as inactive and insoluble RhI_3 occurs. The precipitation of RhI_3 is further enhanced if the concentration of water is reduced.

These drawbacks place a limit on plant productivity and increase the operation costs since distillation has to be carried out to remove all the water from the product (acetic acid).

14.3 CELANESE PROCESS USING LiI MODIFIED RHODIUM CATALYST

In the early 1980s, Hoechst Celanese (*Celanese* is incidentally the trademark name of the first commercial cellulose acetate filament spun in the United States in 1924) modified the Monsanto technology by introducing LiI as an inorganic iodide promoter to reduce the amount of water and HI in the catalysis. This enabled the development of a low water variant of the original Monsanto process. The promoter helped, to some extent, to optimise the concentration of $[Rh(CO)_2I_2]^-$ at low water concentrations and also to act as an additional promoter for catalytic activity. It has been proposed that a five coordinate dianionic species $[Rh(CO)_2I_2(CH_3COO)]^{2-}$ which is more active towards oxidative addition of MeI, is the active species responsible for the promoter activity.

14.4 TENNESSEE EASTMAN ACETIC ANHYDRIDE PROCESS

The process was first used in a plant, built on the site of a coal mine, to convert synthesis gas to acetic anhydride. The latter is an important chemical used in many acetylation reactions in the pharmaceutical industry.[9]

The Tennessee Eastman process actually begins from coal which is gassified to get synthesis gas.

$$\text{Coal} \longrightarrow CO/H_2 \longrightarrow \text{methanol} \longrightarrow \text{methyl acetate} \longrightarrow \text{acetic anhydride}$$

The catalytic cycle for the reactions has many similarities to the Monsanto and Celanese processes. The initial reactant has changed; methanol is replaced by methyl acetate, and acetate is the leaving group instead of the hydroxyl group. Note that in the catalytic cycle, LiI replaces HI (as water cannot be present in the synthesis of acetic anhydride) which reacts with methyl acetate to yield methyl iodide.

After acquiring the Monsanto process, British Petroleum (BP) chemicals has also started coproduction of acetic acid and acetic anhydride from 1988. The process makes both these chemicals and generates methyl acetate within the process (Fig. 14.3).

Acetic anhydride: Uses

The primary use of acetic anhydride is in the manufacture of cellulose acetate for photographic films and plastic goods; about 75 percent of the acetic anhydride produced annually in the United States is used for this purpose. Approximately 1.5% of the annual acetic anhydride production is used in the synthesis of aspirin. Other uses include the manufacture of industrial chemicals, pharmaceuticals, perfumes, plastics, synthetic fibres, explosives and weed killers. It is also a restricted chemical in many countries as it is used clandestinely for the purification of banned drugs.

14.5 BRITISH PETROLEUM'S CATIVA PROCESS

A more cost effective and efficient process called the Cativa process for the production of acetic acid came up from BP in 1996.[10] This process uses iridium instead of rhodium [the approximate cost of rhodium is US\$ 5200 per troy oz while that of iridium is US\$ 300 per troy oz (1 troy oz = 31.1 g)]. The catalyst is more robust at extremely low water concentrations, 0.5 wt% as against 8–10 wt% required for the Rh catalyst. The iridium catalyst is found to remain stable under a wide range of conditions that would cause the Rh complex to decompose to inactive Rh salts. Iridium compounds are more soluble in the reaction medium and thus provide higher catalyst concentration. The process uses metal

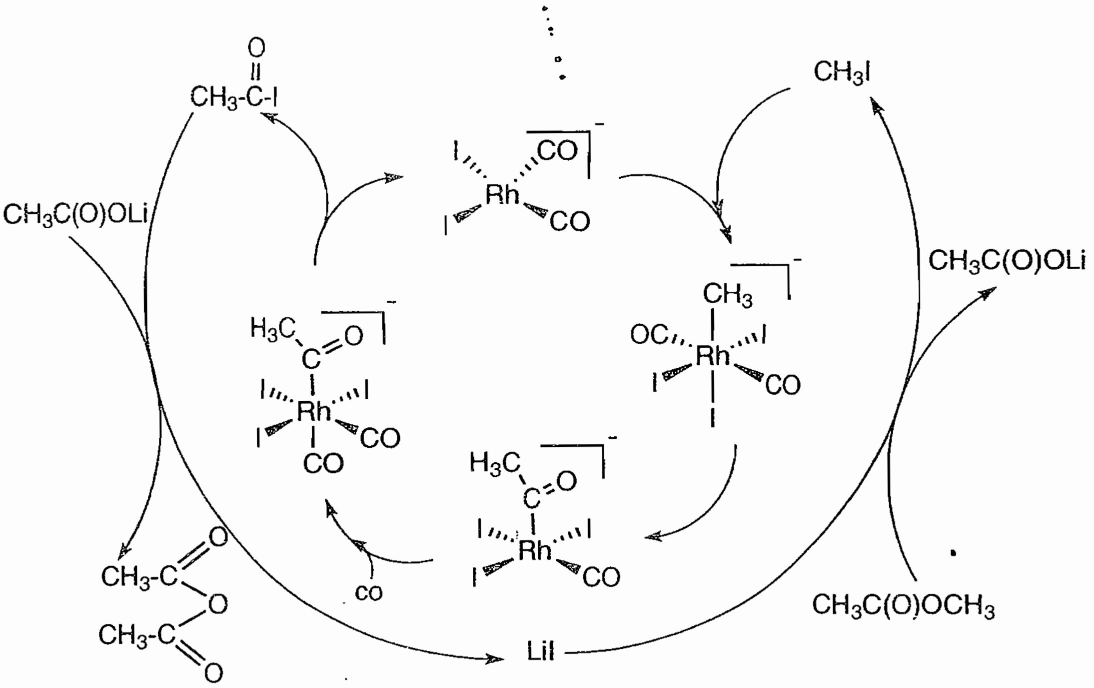

Fig. 14.3 Catalytic cycle for Tennessee Eastman acetic anhydride process

promoters such as InI_3 and $[Ru(CO)_3I_2]_2$. The mechanism of the Cativa process is shown in Fig. 14.4.

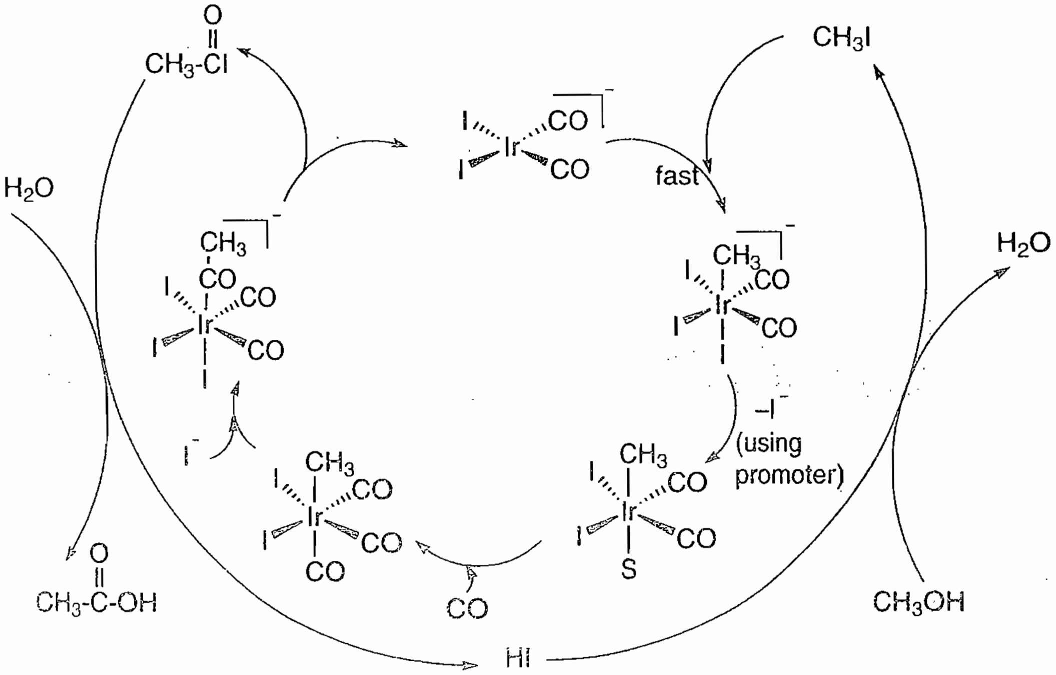

Fig. 14.4 Catalytic cycle for BP's Cativa process

The following steps possibly occur in the presence of a promoter. An iodide ligand is transferred from the anionic iridium complex to the promoter. This creates a free site on the catalyst so that a third molecule of CO can bind to the catalyst. This species has been identified by infrared spectral studies. It has also been seen that the migratory insertion of CO occurs much more readily in the neutral complex than in the anionic precursor. Once this happens, an iodide can be transferred back to the iridium followed by reductive elimination. The promoter reduces the standing concentration of the I^- ion thus facilitating the loss of I^- from the catalyst in the second step (second and third steps shown in the cycle). This is a slow step compared to the oxidative addition. (The addition of iodomethane to iridium, step 1 is about 150 times faster than the addition to rhodium). The promoter thus intervenes to speed up the slower step of the cycle.[11, 12]

Like the Monsanto process, the reaction is theoretically 100% atom efficient. The use of iridium/iodide as a catalyst has numerous benefits compared to rhodium/iodide as given below.

- The cost of iridium is much less compared to that of rhodium.
- The process is faster and more effective, requiring a smaller amount of catalyst.
- The iridium catalyst provides a much higher turnover number (TON) thereby reducing the frequency of catalyst replacement.
- Iridium is even more selective for methanol, increases the overall yield and reduces byproducts, resulting in lower purification costs and reduced waste.
- Iridium complexes are more soluble in the reaction mixture than rhodium complexes. This means that the catalyst is not lost by precipitation and does not need replacing so frequently. The water content in the reaction vessel can be reduced (up to 0.5 wt%), speeding up the process and reducing the energy needed at the distillation and purification stages.
- The existing plant can be modified to run the Cativa process at half the cost of building a new plant. This is referred to as retrofitting.
- Cativa plants have a higher output—a single plant can produce up to 75% more acetic acid than what was previously possible using the Monsanto process.

14.6. THE WACKER PROCESS

In the 1950s, Wacker Chemie discovered that ethylene could be oxidised with high efficiency to acetaldehyde or to vinyl acetate in the presence of acetic acid. [13-15]

$$CH_2{=}CH_2 + \tfrac{1}{2}\, O_2 \longrightarrow CH_3CHO \longrightarrow CH_3COOH \qquad (14.3)$$

$$CH_2{=}CH_2 + \tfrac{1}{2}\, O_2 + CH_3COOH \longrightarrow CH_2{=}CHOC(O)CH_3 \qquad (14.4)$$

Stoichiometric oxidation of ethylene to acetaldehyde by aqueous $PdCl_4^{2-}$ along with the deposition of metallic palladium has been known even before the beginning of twentieth century. In 1959, J Smidt and W Hafner of Wacker Chemie, discovered that the reaction could be made catalytic in Pd by using a cocatalyst $CuCl_2$ which could re-oxidise Pd(0) back to Pd(II). The reaction can be written in three steps. The first step is the oxidation of ethylene to acetaldehyde whereby Pd metal is obtained. The second step uses cupric chloride to oxidise Pd back to the soluble $PdCl_4^{2-}$ form. The cuprous chloride formed is re-oxidised back to the cupric form by oxygen in the third step.

$$[PdCl_4]^{2-} + C_2H_4 + H_2O \longrightarrow CH_3CHO + Pd + 2HCl + 2\,Cl^- \tag{14.5}$$

$$Pd + 2CuCl_2 + 2\,Cl^- \longrightarrow [PdCl_4]^{2-} + 2CuCl \tag{14.6}$$

$$2CuCl + 1/2\,O_2 + 2HCl \longrightarrow 2CuCl_2 + H_2O \tag{14.7}$$

$$C_2H_4 + 1/2\,O_2 \longrightarrow CH_3CHO \tag{14.8}$$

In reality, commercial processes operate by two methods—one involving two stages and the other a single stage. In the two stage method, ethylene is oxidised to acetaldehyde in a dilute HCl solution containing $PdCl_2$ and $CuCl_2$ (10 bar, 100–110°C). Heat produced in the reaction is used to separate the volatile acetaldehyde by fractionation without the decomposition of the catalyst. Once the catalyst activity is lost, the solution is circulated through a second reactor where air is used to regenerate $CuCl_2$ and the $CuCl_2$ regenerates the $PdCl_4^{2-}$. After this, the solution is sent back to the first stage for reaction with ethylene.[16, 17]

In the single stage process, the O_2/C_2H_4 mixture is fed to an aqueous solution containing $PdCl_2$ and $CuCl_2$ (3 bar, 100–120°C). The catalyst is regenerated in situ. Mechanistic studies for the Wacker process gave the following rate equation.

$$\text{Rate} = k\frac{[PdCl_4^{2-}][C_2H_4]}{[Cl^-]^2[H^+]}$$

The rate equation implies that during the process, $PdCl_4^{2-}$ has to gain an ethylene unit and lose two chloride ions and a proton. The various steps thought to be involved in the mechanism are shown in the catalytic cycle (Fig. 14.5). The first step involves the coordination of the alkene as a π complex. In the next step, a solvent water molecule converts this alkene to a β-hydroxy ethyl σ complex of palladium. This can be envisaged to occur by coordination of a water molecule to the metal which loses a proton resulting in an OH group bound to the metal followed by a migratory insertion of the hydroxyl group on the alkene. This proposal was later found to disagree with the detailed mechanistic studies carried out using deuterium labelled alkenes. The presently accepted mechanism shows that the metal coordinated alkene is attacked by a free water molecule from the solvent, converting it to a β-hydroxy ethyl σ complex. In the next step, a β hydrogen transfer occurs converting the σ complex to a vinyl alcohol π complex. This coordinated vinyl alcohol, by multiple insertion elimination steps, rearranges to give the stable aldehyde. In the case of solvents other than water, the final step does not occur and the complex dissociates to give

$$[PdCl_4]^{2-} + C_2H_4 + 2\,CH_3COONa \longrightarrow \begin{array}{l} CH_2{=}CHOC(O)CH_3 + Pd + \\ CH_3COOH + 2NaCl + 2\,Cl^- \end{array} \tag{14.9}$$

the vinyl product. For example, by using acetic acid as solvent, one can get vinyl acetate as the product.[18, 19]

Combining with the Cu based cocatalyst redox system, the net reaction can be written as follows.

$$C_2H_4 + 1/2\,O_2 + CH_3COOH \longrightarrow CH_2{=}CHOC(O)CH_3 + H_2O \qquad (14.10)$$

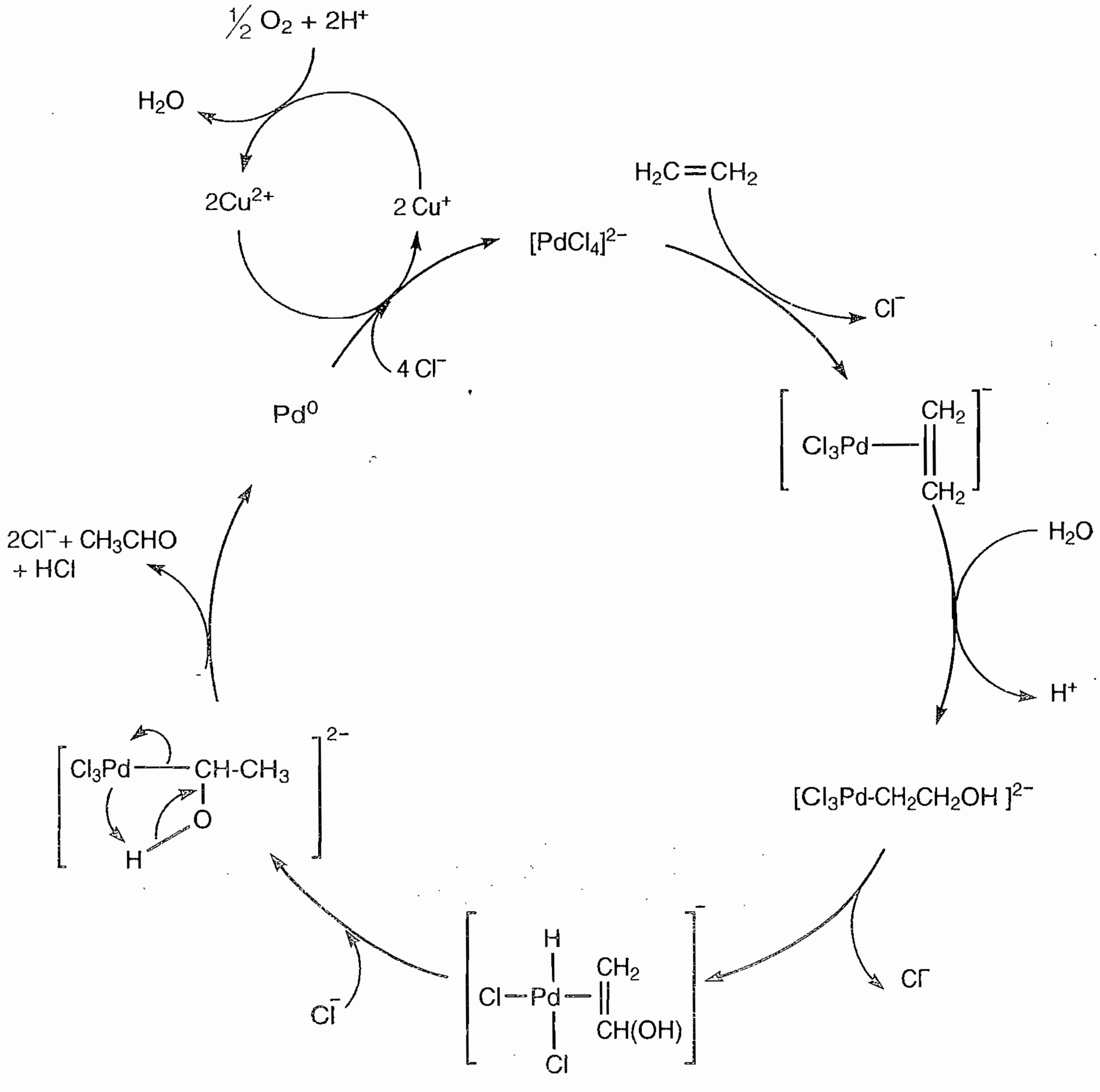

Fig. 14.5 Catalytic cycle for Wacker oxidation

The importance of Wacker oxidation for the industrial preparation of acetaldehyde has been decreasing over the years as the subsequent oxidation product of acetaldehyde, namely acetic acid, is prepared more efficiently using the single step methanol to acetic acid processes (Monsanto and Cativa). However, the direct synthesis of vinyl acetate still has considerable commercial importance.

Problems and Exercises

14.1. $[Rh(CO)_2I_2]^-$ and $Rh(CO)_3I$ are both square planar complexes with rhodium in the +1 oxidation state. Both can act as active catalysts in the conversion of methanol to acetic acid. However, the reaction rate is much lower when $Rh(CO)_3I$ is used in the Monsanto process. Give reasons for the same.

14.2. Write the structure of the active catalyst used in the Cativa process for the manufacture of acetic acid.

14.3. What are the advantages of using the iridium complex over the rhodium complex in the methanol to acetic acid process?

14.4. Write the steps involved in the following reaction.

$$RHC{=}CH_2 + CO + MeOH \xrightarrow{\text{catalyst}} RCH_2CH_2C(O)OMe$$

The catalyst used is $Co_2(CO)_8$ at 140–170°C/100–200 atm. A small amount of H_2 is also present in this reaction.

14.5. When the Wacker reaction was carried out on ethylene in D_2O instead of H_2O, it was observed that no deuterium was incorporated into the acetaldehyde formed.

(a) Modify the given mechanism using D_2O instead of H_2O at step 2 and indicate why deuterium is not incorporated in the product.

(b) As vinyl alcohol can also tautomerise to the acetaldehyde under normal conditions, does the above statement support a situation where the π coordinated vinyl alcohol falls off from the metal centre and rearranges by itself to the aldehyde? Explain.

14.6. What will the expected product from the Wacker process be if the reaction is carried out in (a) methanol medium and (b) a hydrocarbon medium.

14.7. Which of the following compounds are likely to act as promoters in the Cativa Process? Justify your answer.

GaI_3, $[Ru(CO)_3I_3]^-$, $[Ru(CO)_2I_4]^{2-}$, ZnI_2, LiI, SiI_4.

14.8. In the Tennessee Eastman catalytic cycle for the production of acetic anhydride, one of the steps is the oxidative addition of CH_3I to $[RhI_2(CO)_2]^-$ but CH_3I is not a initial reactant in this process. How is this generated in situ? Give appropriate equations.

14.9. Water is an essential reaction component in the production of acetic acid by the Monsanto process. The Eastman Tennessee process for the production of acetic anhydride has some similarity to the Monsanto process but does not use water as a reactant. How have they tackled this difficulty and how is the product formed?

14.10. The Wacker process is used for the synthesis of aldehydes and ketones from alkenes using a palladium catalyst in aqueous medium. How would you prepare acetone from 1-propene? Write a suitable mechanism.

Supplementary reading

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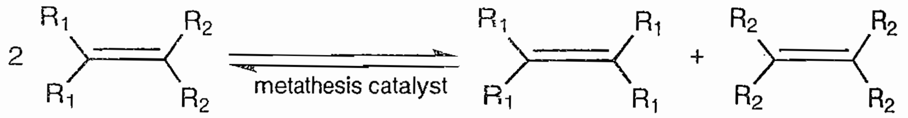
OLEFIN METATHESIS

CHAPTER 15

Olefin metathesis is a reaction in which all the carbon–carbon double bonds in an olefin (alkene) are cut, and then rearranged in a statistical fashion in the presence of certain transition metal compounds, mainly the metal carbenes.



If one of the alkene products is volatile (such as ethylene) which can be easily removed, then the reaction can be driven completely to the right. The reaction was called disproportionation in the beginning, but by 1967 a group of scientists led by Calderon at Goodyear Tyre and Rubber Company, USA, figured out that the unexpected products were formed by cleavage and reformation of the olefin's double bonds.[1] *One carbon of the double bond of one olefin, along with all the groups attached to it, exchanges place with one carbon of the double bond of the other olefin, along with all the groups attached to it.* They named the reaction *olefin metathesis.*[2]

15.1 OLEFIN METATHESIS AS A SYNTHETIC TOOL

Olefin metathesis is a powerful reaction that transforms the carbon–carbon double bond and with some metathesis catalysts, new carbon–carbon double bonds are formed at or near room temperature even in aqueous media from substrates that bear a variety of functional groups. In the chemical industry, olefin metathesis finds use in the SHOP (Shell's higher olefin process—ethylene conversion to linear α olefins) and OCT (olefin conversion technology—making propylene from 2-butene and ethylene) processes. The main types of olefin metathesis reactions using a homogeneous catalyst are the following:

- straight exchange of groups between two acyclic olefins (cross metathesis, CM),
- closure of large rings (ring closing metathesis, RCM),
- formation of dienes from cyclic and acyclic olefins (ring opening metathesis, ROM),

- polymerisation of cyclic olefins (ring opening metathesis polymerisation, ROMP),
- polymerisation of acyclic dienes (acyclic diene metathesis polymerisation, ADMET), and
- metathesis of an alkene and an alkyne (enyne metathesis, EM).

The use of olefin metathesis in organic synthesis has been directly related to the discovery and use of metal carbenes. The chemists well known for developing metal carbene complexes for olefin metathesis are Robert H Grubbs and Richard R Schrock. They, along with Yves Chauvin received the Nobel Prize for chemistry in 2005.[3,4] The so-called Grubbs and Schrock catalysts were developed through focussed research programs going back to the 1970s. Schrock came up with highly reactive imido carbene catalysts, based initially on tungsten and then molybdenum by 1990. Grubbs' catalysts based on ruthenium carbenes were first reported in 1992. These were less reactive than Schrock's catalyst and therefore more selective in reacting with olefins rather than with other functional groups. According to Amir H Hoveyda, another well known scientist involved in olefin metathesis, the ruthenium catalysts are used more often than the molybdenum catalysts because they are easier to handle. He says, '*When we need high reactivity, we go with molybdenum. When we can run reactions under mild conditions, we use ruthenium. They are the two wings of the same angel. The angel can't fly if you clip either one*'. Table 15.1 lists the landmarks in the development of olefin metathesis catalysts.[5]

15.2 WELL KNOWN OLEFIN METATHESIS CATALYSTS AND THEIR PROPERTIES

Some of the well known and commercially available olefin metathesis catalysts with their unique features are given in Tables 15.2 and 15.3.

Although Schrock's molybdenum catalysts were known since 1990, many people credit Grubbs' ruthenium catalysts for placing olefin metathesis in the forefront of organic synthesis. The molybdenum catalyst has high activity which allows it to react with both internal and terminal olefins and also bring about ring opening of low strain cyclic olefins. However, its limitations are high oxophilicity and sensitivity to oxygen and moisture; thus the process requires inert atmosphere and degassed dry solvents. It also has a relatively poor functional group tolerance (incompatible with acids, aldehydes and alcohols). Ruthenium compounds on the other hand, have comparatively lesser activity, high preference for carbon-carbon double bonds and are indifferent to alcohols, amides, aldehydes and carboxylic acids.[6] More importantly, their use does not require stringent air and moisture free conditions and organic chemists can use it by applying standard techniques. Vacuum lines and dry boxes, that are required when working with Schrock's catalysts, are not necessary in this case. The basic difference lies in the fact that ruthenium has increased reactivity for olefins while for molybdenum, reactivity with acids, alcohols and aldehydes is more than that towards olefins (Table 15.4).

15.3 SYNTHESIS OF GRUBBS' AND SCHROCK CATALYSTS

Grubbs' ruthenium catalyst (B in Scheme 15.1) was prepared in 1992.[7] It had good functional group tolerance but limited activity. Further refinements led to the catalyst

Table 15.1 Landmarks in the development of olefin metathesis catalysts

Year	Landmarks in olefin metathesis catalysts	Person/ Company
1950	Propylene feed after polymerisation showed mixture of ethylene and 1-butene along with propylene. It was called disproportionation.	Eleuterio, Dupont
1960–64	Propylene with MoO_3/alumina or $Mo(CO)_6$ yields ethylene and butane.	Peters and Everig of Standard Oil Co. and Banks and Bailey of Phillips Petroleum
1967	First called the reaction 'olefin metathesis' after observing cleavage and reformation of double bonds with butene and deuterated 2-butane.	Calderon of Goodyear Tyre and Rubber Company
1968–1972	Metal cyclobutane, tetramethylene complex and metallacyclopentane intermediates in the mechanism proposed. All of them were proved wrong later.	Calderon, Pettit, Grubbs
1971	Metal carbene was proposed as the olefin initiator and was proved true later.	Chauvin and Herisson, French Petroleum Institute
1974	$Ph_2C{=}W(CO)_5$ reacts with isobutene to give 1,1-diphenylethene.	Casey and Burkhardt
1975–76	First use of a metal carbene, $Ph_2C{=}W(CO)_5$ to initiate metathesis of alkenes.	T J Katz
1990	Synthesis of the Schrock's catalyst Mo(NAr)(CHR)$(OR')_2$ and its metathesis reaction.	R R Schrock
1992	Grubbs prepares the first ruthenium catalyst (without much functional group tolerance).	R H Grubbs
1996	Synthesis of the Grubbs' first generation catalyst.	R H Grubbs
1998	First Mo based chiral catalyst for metathesis.	R R Schrock, A S Hoveyda
1999–2000	Synthesis of Grubbs' second generation catalyst and Hoveyda's ruthenium based recyclable catalyst.	R H Grubbs, A S Hoveyda
2001	First ruthenium based chiral catalyst for metathesis.	R H Grubbs
2002	Discovery of fast initiating Grubbs III, Blechert and Grela catalysts.	R H Grubbs, S Blechert and K Grela
2003	Ruthenium based recyclable chiral catalyst.	A S Hoveyda
2004	Rapid initiating catalysts without ligand loss.	W Piers
2005	Nobel Prize in chemistry for olefin metathesis.	Chauvin, Schrock and Grubbs

Table 15.2 Advantages and disadvantages of Schrock's molybdenum catalyst and Grubbs' first generation catalyst [8, 9]

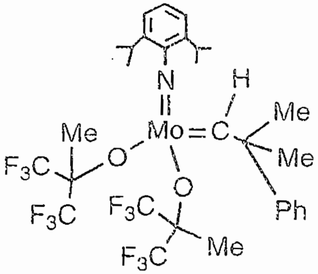
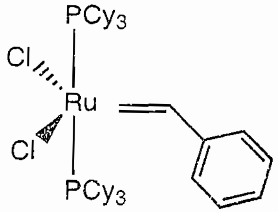
	
Schrock catalyst (1)	**Grubbs' first-generation catalyst (2)**
Advantages High activity. Applicable to both terminal and internal olefins. Low strain cyclic olefins also undergo ring opening. Olefins with sterically demanding and electron poor substituents also undergo ring closing metathesis. Metathesis effective even in the presence of phosphines, thioethers and amines.	**Advantages** Low activity (compared to Schrock catalyst). Easy handling of catalyst as it is stable to air and moisture. Good functional group tolerance to aldehydes, alcohols and acids. Fast initiation of the reaction.
Disadvantages Poor functional group tolerance even to aldehydes, acids and alcohols. Catalyst highly sensitivive to O_2 and moisture. Inert atmosphere and dry degassed solvents required for handling catalyst and for conducting reactions.	**Disadvantages** Ring opening polymerisation is limited to strained rings. Not feasible on reactions to make tri and tetrasubstituted olefins. Not applicable to deactivated olefins. No catalyst recyclability. Catalyst contamination of products observed often even after chromatographic purification. Catalyst is not effective in presence of primary amines.

Table 15.3 Advantages and disadvantages of Grubb's second generation catalyst and Hoveyda–Grubbs' catalyst[10, 11, 12]

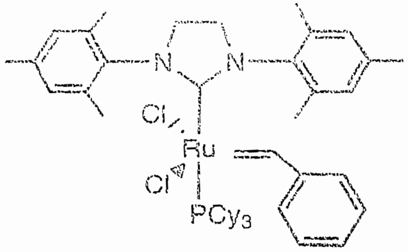
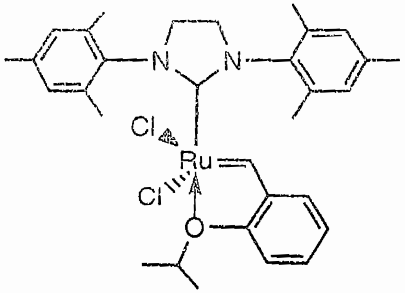
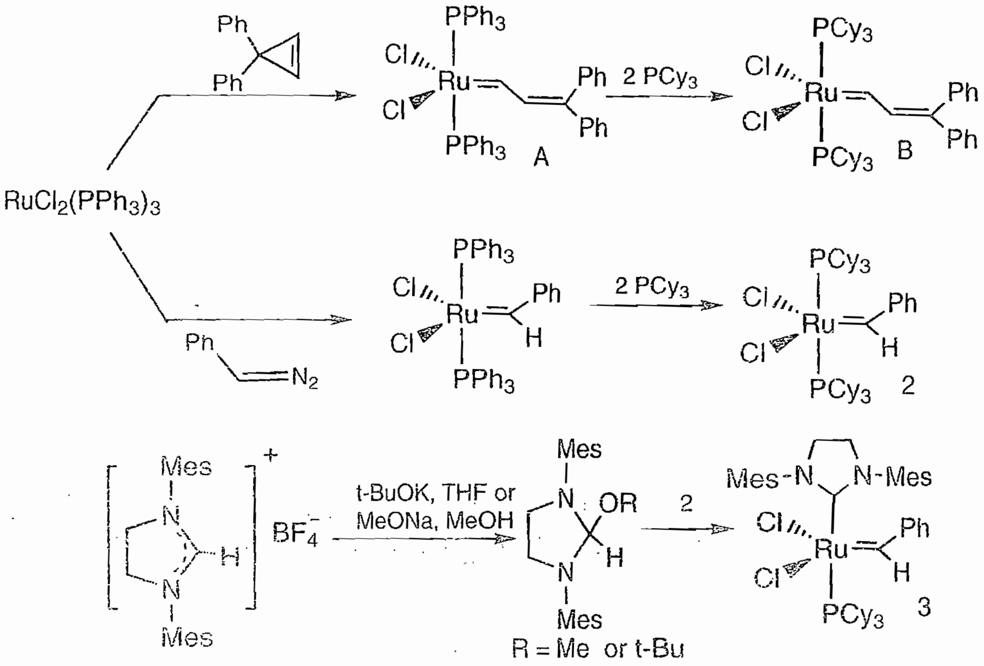
 **Grubbs' second-generation catalyst (3)**	 **Hoveyda-Grubbs' Catalyst II (4)**
Advantages	**Advantages**
Higher activity than Grubbs first generation catalyst.	Easy handling.
Good functional group tolerance to aldehdyes, alcohols and acids.	Good functional group tolerance.
Handling of catalyst in air and moisture possible.	Stable to air and moisture.
High rates of ring opening metathesis polymerisation possible on low strain substrates and even hindered trisubstituted olefins.	Catalyst is recoverable, reusable and even immobilisable on a polymer matrix.
Ring closing metathesis of sterically bulky dienes and deactivated olefins possible.	Improved activity than Grubbs II to electron deficient olefins such as acrylonitrile and fluoroalkenes.
Reactions work even with very low quantity of catalyst.	Active for trisubstituted alkene synthesis.
Disadvantages	**Disadvantages**
No catalyst recyclabilty.	Slower initiating than Grubbs second generation catalyst.
Catalyst contamination of products observed.	
Slow initiating.	
Poor tolerance of amines, thioethers and phosphines.	

Table 15.4 Decreasing order of reactivity of olefin metathesis catalysts towards functional groups

Ruthenium	Molybdenum	Tungsten
Olefins	Acids	Acids
Acids	Alcohols/water	Alcohols/water
Alcohols/water	Aldehydes	Aldehydes
Aldehydes	Olefins	Ketones
Ketones	Ketones	Olefins
Esters/ amides	Esters/ amides	Esters/ amides

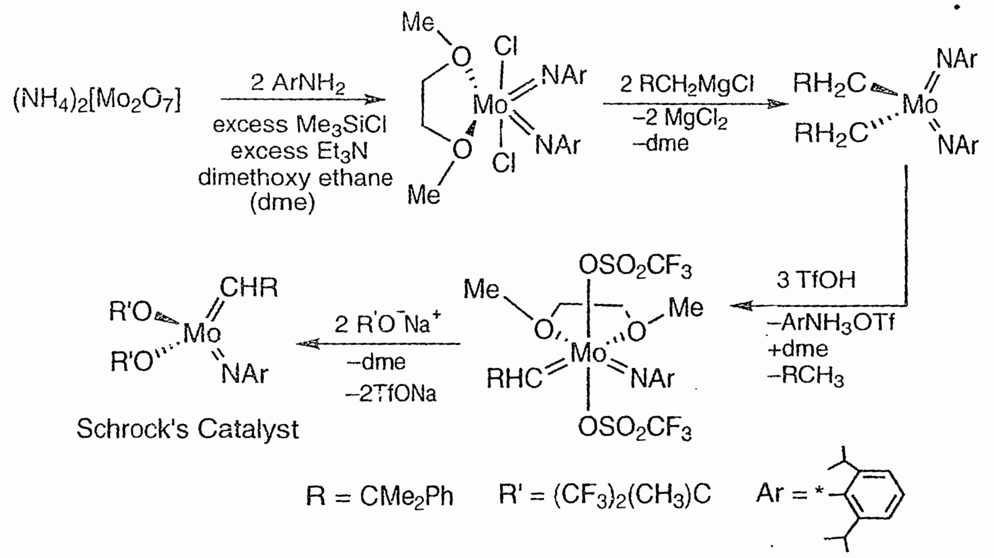
$(PCy_3)_2Cl_2Ru{=}CHC_6H_5$ (2) in 1996, which is now widely known as the Grubbs' first generation catalyst. Three years later, Grubbs introduced an even better ruthenium catalyst, the so-called Grubbs' second generation catalyst (3). Here, one of the PCy_3 group in the Grubbs' catalyst (2) is replaced with an N-heterocyclic carbene ligand. The synthesis of these catalysts is given in Scheme 15.1. Synthesis of Schrock's Mo based catalyst is given in Scheme 15.2.[10]



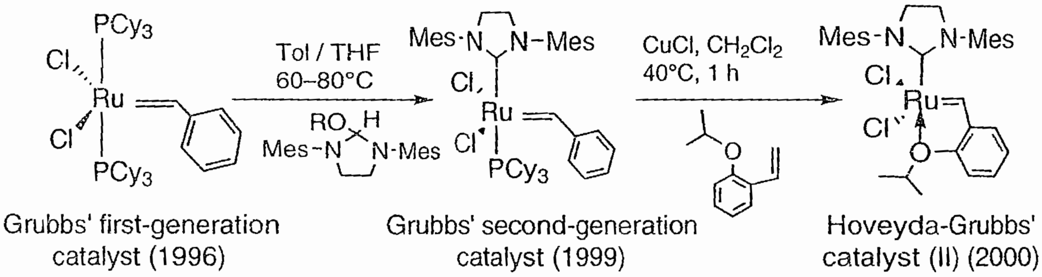
Scheme 15.1 Synthesis of Grubbs' olefin metathesis catalysts

Ever since the Grubbs' first generation catalyst was introduced in 1996, it has found many uses in organic synthesis. Chemists use the commercially available Schrock's molybdenum catalyst, Grubbs' first and second generation catalysts as well as the Grubbs–Hoveyda catalyst II (Tables 15.2 and 15.3) in the preparation of a variety of natural products and novel polymers.[13,14]

A major obstacle identified and addressed in the post Hoveyda–Grubbs catalysts is the relatively slow initiation of the metathesis reaction of ruthenium catalysts which partly results due to the presence of the NHC group. Blechert addressed this issue by using steric effects to destabilise the five membered ruthenacycle of the Hoveyda catalyst.[15] Grubbs' third

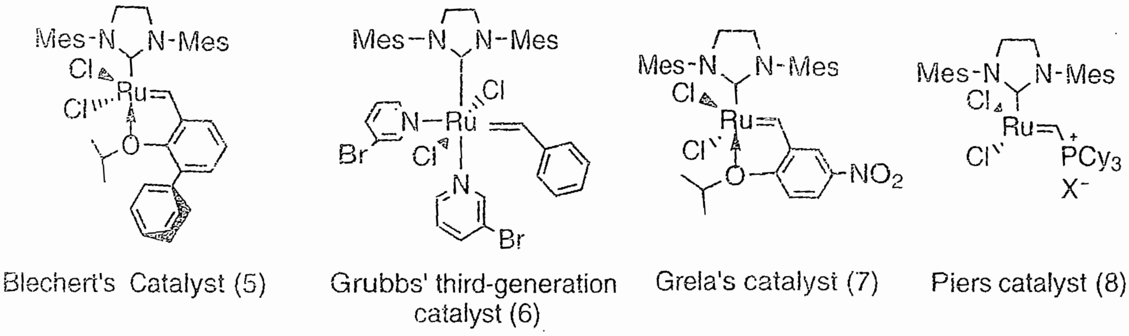


Scheme 15.2 Synthesis of Schrock's olefin metathesis catalyst



Scheme 15.3 Conversion of Grubbs' first generation olefin metathesis catalyst to higher analogues

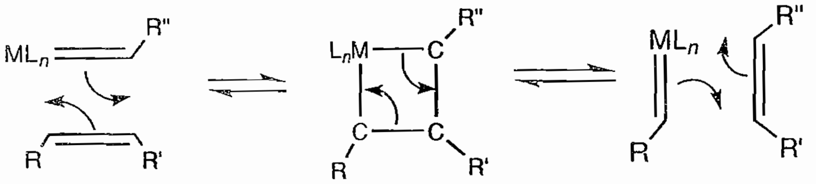
generation catalyst has two weakly bound 3-bromopyridyl groups (throwaway ligand) on the metal whose lability provides an initiation rate around six orders of magnitude higher than the Grubbs second generation catalyst.[16] Grela introduced an electron withdrawing NO_2 group on the aryl ring of the Grubbs–Hoveyda catalyst for faster initiation and enhanced activity.[17] Warren Piers later reported a rapid initiating catalyst which itself was a 14 electron species and did not require any ligand loss for activation (Scheme 15.4).[18]



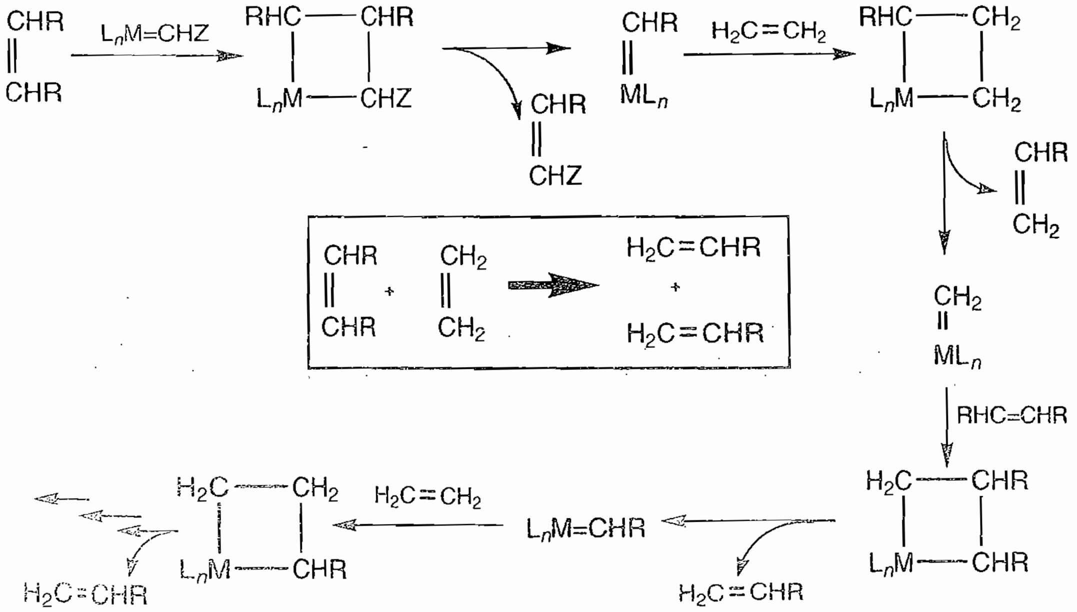
Scheme 15.4 Fast to rapid initiating olefin metathesis catalysts [15–18]

15.4 MECHANISM OF OLEFIN METATHESIS

As early as 1971, two chemists at the French Petroleum Institute, Chauvin and his student Hérisson, suggested that olefin metathesis is initiated by a metal carbene. Their commonly accepted mechanism involves a [2+2] cycloaddition reaction between a transition metal alkylidene complex and the olefin to form an intermediate metallacyclobutane.[19–21]

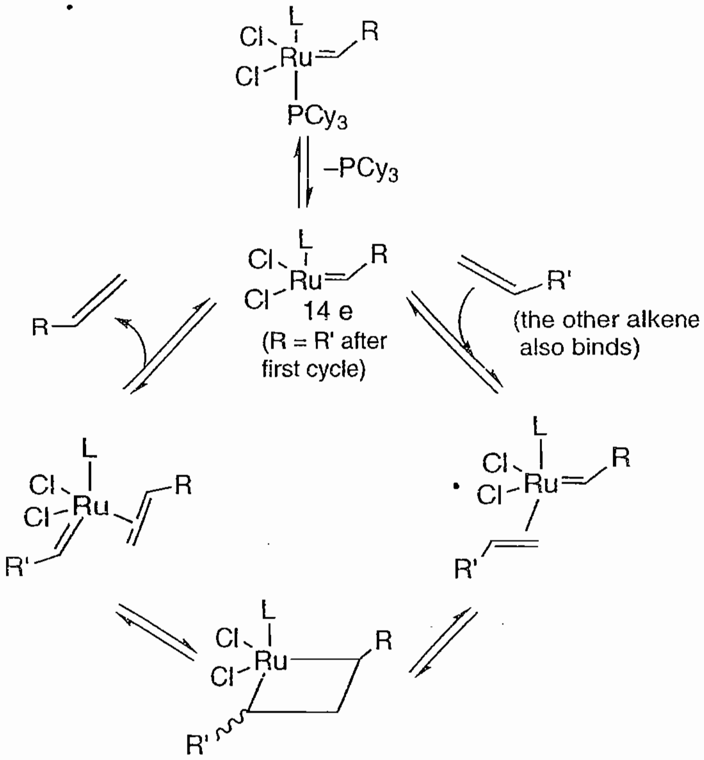


This metallacycle then breaks up in the opposite fashion to afford a new carbene and a new olefin. If this process is repeated enough number of times, eventually an equilibrium mixture of olefins will be obtained. If the groups on the acyclic olefin are sufficiently different, one metal carbene product will be favoured over the other, and only one olefinic product will be formed, the same one as predicted by the conventional mechanism (Scheme 15.5). If the groups are not sufficiently different, then olefin metathesis gives three products: one that is predicted by the conventional mechanism and the other two are cross products.



Scheme 15.5 General mechanism of olefin metathesis reactions

Cycloaddition reaction between two alkenes to give cyclobutanes is symmetry forbidden and occurs only photochemically. However, the presence of *d* orbitals on the metal alkylidene fragment breaks this symmetry and the reaction becomes facile. The specific mechanism proposed by Grubbs for his catalysts shows that the reaction proceeds by



Scheme 15.6 Formation of the metallacycle in the mechanism of olefin metathesis

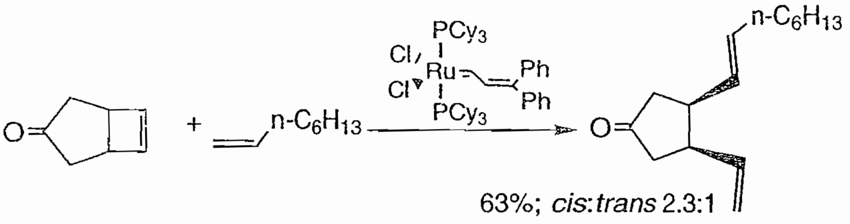
the loss of one phosphine to produce a 14e species (Scheme 15.6). The coordination of the alkene forms an intermediate which then undergoes a metallacyclobutane formation. This is followed by cleavage of the metallacyclobutane in the other direction to release the metathesis product—the alkene. The dissociation of phosphine in the first step has been supported by many studies such as kinetic data, phosphine substitution and isolation of intermediates with one phosphine cleaved. Less bulky phosphines coordinate too strongly to the metal and are not susceptible to dissociation whereas the phosphines with cone angles larger than PCy_3 are too labile to produce a stable complex. For the Grubbs'-Hoveyda catalysts, there is an opening up of the ether coordination to accommodate bonding of the alkene followed by formation of the metallacycle ring. However, for the Schrock's molybdenum catalyst (14e complex), there is no ligand opening up or cleavage and the alkene directly binds forming the metallacycle.

Evidence for the metallacycle formation in ruthenium catalysts was also reported in 2005. The first direct observation and characterisation of the active 14e ruthenacyclobutane metallacycle, relevant to the Grubbs' mechanism, was made by Piers. This was achieved by monitoring the reaction below –50°C using NMR spectroscopy.[22]

The most common and well studied types of olefin metathesis processes are given below.

15.4.1 Ring Opening Metathesis (ROM)

Cyclic olefins that have strained rings often undergo ROM in the presence of another olefin and catalyst (Scheme 15.7). The driving force for this reaction is the release in

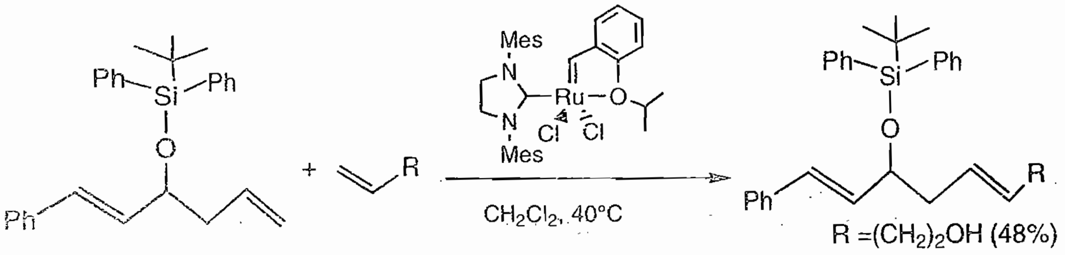


Scheme 15.7 Ring opening metathesis reaction

strain upon ring opening. However, in the absence of another olefin, the ring will often undergo ring opening metathesis polymerisation (ROMP). Ring opening metathesis of larger strain-free rings is possible with more active catalysts such as the Grubbs' second generation catalyst.[23]

15.4.2 Cross Metathesis (CM)

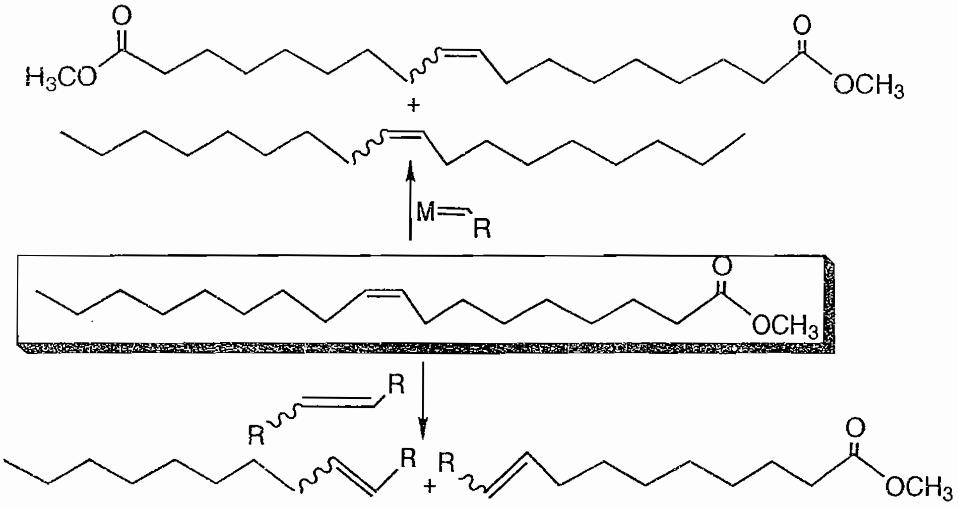
The transalkylidenation of two terminal alkenes under release of ethane is termed as cross metathesis (Scheme 15.8). Statistically, the reaction can lead to three possible pairs of geometric isomers, that is, *E/Z* pairs for two homocouplings and one cross-coupling product (R–CH=CH–R, R'–CH=CH–R' and R–CH=CH–R')—a total of six products. The selectivity of this reaction has been subject to further study, but various examples exist in which two alkenes with different reactivity give the cross-coupled product with excellent yields and excellent selectivity.[24]



Scheme 15.8 Cross metathesis reaction

Cross metathesis has been used in oleochemistry and also in transforming natural fatty acids (Scheme 15.9). The metathesis of natural oils and fats and their derivatives is a clean catalytic reaction. Cross metathesis can be used to shorten unsaturated fatty acid esters or to extend their length or to make terminal diesters from monoesters. Using this reaction, oleochemical feedstock can be converted into valuable chemical products, directly or in a few steps.[25]

The industrial production of olefins is based on cross metathesis using heterogeneous catalysts. From 1966–1972, Phillips Petroleum was making ethylene and 2-butene from propylene, a process known as the Phillips triolefin process. Because olefin metathesis is a reversible reaction, propylene can be produced from ethylene and 2-butene. As the global

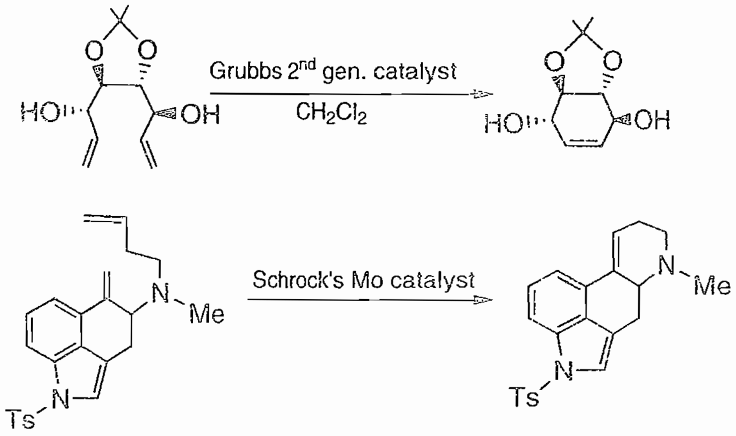


Scheme 15.9 Cross metathesis reaction for oleochemical synthesis

demand for propylene is high, the process known as olefins conversion technology (OCT) is currently used by many petrochemical companies. 1-Hexene and neohexene (3,3-dimethyl-1-butene) are also made by cross metathesis.

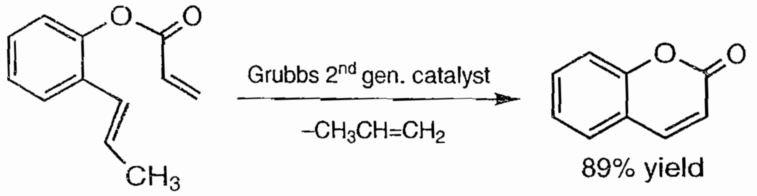
15.4.3 Ring Closing Metathesis (RCM)

This constitutes one of the major types of reactions involving olefin metathesis. A variety of compounds with ring sizes upto 30 atoms have been cyclised by this method. In order to make it work, the ring being formed cannot have appreciable ring strain. As RCM and ROMP processes involve equilibria, the RCM reaction sometimes involves running the experiment at low concentration so that most of the reactions are intra- rather than intermolecular. In the examples given in Scheme 15.10, removal of the volatile byproduct (ethylene) drives the equilibrium to the ring-closed product.[26, 27]



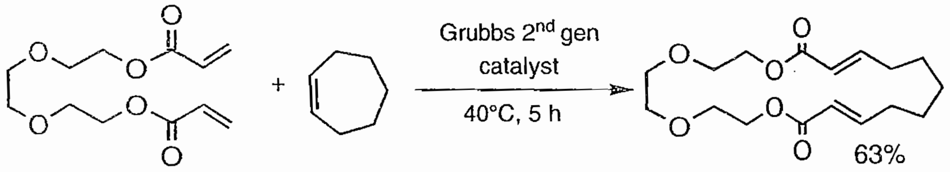
Scheme 15.10 Ring closing metathesis reactions

Ring closing metathesis has been efficiently utilised for the synthesis of many natural products and their precursors. Equation 15.1 shows how coumarins can be synthesised using RCM. Interestingly, this reaction does not proceed with Grubbs first generation catalyst.[28]



(15.1)

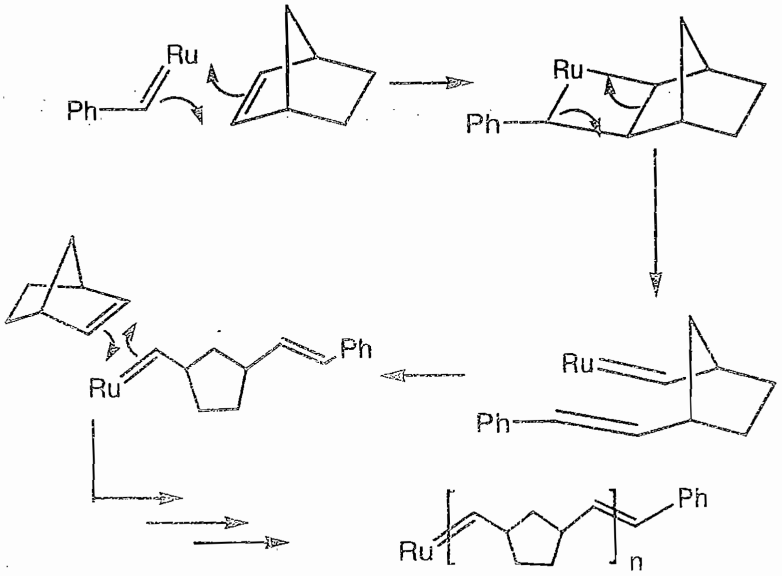
An example of the formation of a 21-membered macrocycle by the ring opening of a seven membered cycloalkene, followed by cross metathesis with an unsaturated carbonyl olefin and finally ring closing metathesis using the Grubbs' second generation catalyst is shown in Eq. 15.2.[29]



(15.2)

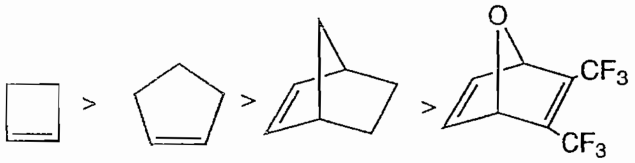
15.4.4 Ring Opening Metathesis Polymerisation (ROMP)

The reaction uses strained cyclic olefins to produce stereoregular and monodisperse polymers and copolymers. The ROMP reaction involves a metal carbene catalyst and its mechanism is identical to the normal metathesis mechanism with two important differences.



Scheme 15.11 Mechanism of ring opening metathesis polymerisation (ROMP)

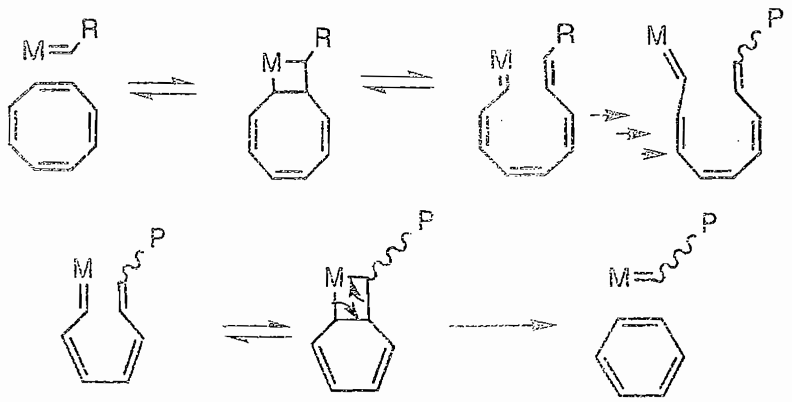
First, since the reaction involves a cyclic olefin, the new olefin that is generated remains attached to the catalyst as part of a growing polymer chain. The second difference is that the driving force for the ROMP reaction is often the relief of ring strain. Therefore, the second step is essentially irreversible. Olefins such as the cyclohexenes have little or no ring strain and cannot be easily polymerised with the usual catalysts. Strained cyclic olefins such as those shown below, have sufficient ring strain to make this process possible.[30]



(15.3)

Monomers based on norbornene derivatives are especially popular as they can be readily synthesised from cyclopentadiene by the Diels–Alder reactions. Only the unsubstituted bonds are ring-opened. It is difficult to metathesise or ROMP tri- and tetrasubstituted olefins or larger rings with the Grubbs first generation catalyst. However ROMP of larger rings and of those which are sterically hindered, such as 1,5-dimethyl cyclooctadiene, is possible with more active catalysts like the Grubbs' second generation catalyst.

The polymers produced in the ROMP reaction typically have a very narrow range of molecular weights, something that is very difficult to achieve by standard polymerisation methods such as free radical polymerisation. The polydispersities (PDI: the weight average molecular weight divided by the number average molecular weight) are typically in the range of 1.03 to 1.10. These molecular weight distributions are so narrow that the polymers are said to be monodisperse. An important feature of this mechanism is that ROMP systems are typically living polymerisation catalysts. For example, one can polymerise 100 equivalents of norbornene and then add a second monomer after the first one is consumed. ROMP is a superior method for making diblock and triblock copolymers and permits one to tailor the properties of the resulting material. The catalysts used for ROMP are the same catalysts as used in olefin metathesis. However, one has to be a little more careful when selecting a ROMP catalyst. If the catalyst is too active, it can metathesise the unstrained olefinic bonds in the growing polymer chain (a process called *back biting*), thereby reducing the molecular weight and increasing the molecular weight distribution.[31]



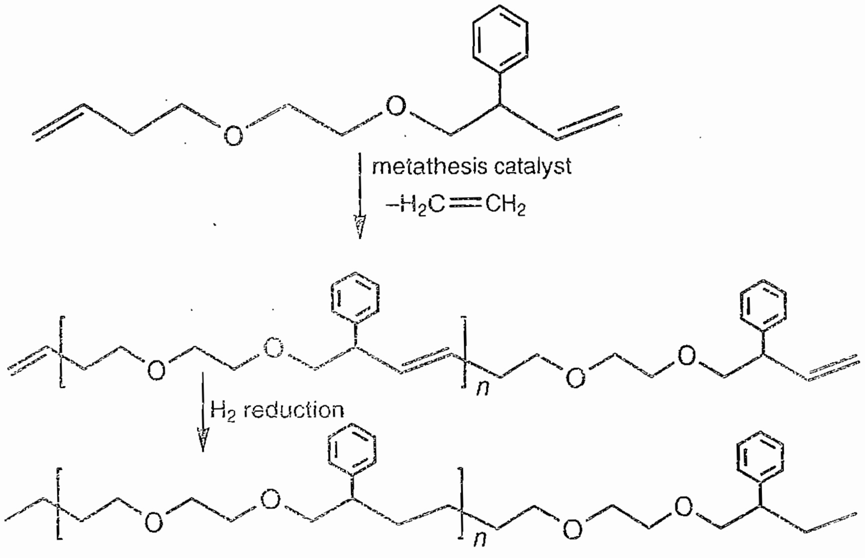
Scheme 15.12 Mechanism of back biting in ring opening metathesis polymerisation

For example, consider the synthesis of polyacetylene from cyclooctatetraene by ROMP. Back biting occurs when the growing polymer chain orients to undergo an intramolecular metathesis and generates benzene, a thermodynamic sink. To prevent back biting in this or other systems, one must make sure that the catalyst does not react with internal olefins.

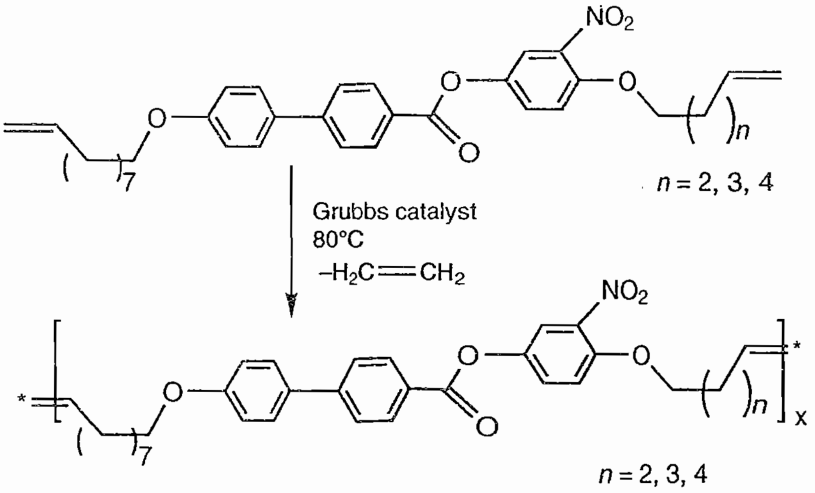
The most well known and widely commercialised ROMP polymer is polydicyclopentadiene (poly DCPD) whose precursor, endo-dicyclopentadiene is easily available as a byproduct from the cracking of naphtha. Although other catalysts are available for the polymerisation, the ruthenium based carbene catalysts provide a high degree of polymerisation which helps also to get rid of unreacted DCPD which has a strong odour, from the finished products. Polydicyclopentadiene is available commercially under trade names such as *polyDCPD, Metathene, Metton, Pentam, Prometa* and *Telene.*[32]

15.4.5 Acyclic Diene Metathesis Polymerisation (ADMET)

The ADMET method uses α dienes to produce polymers. The reaction is driven by the removal of ethylene from the system, which can be accomplished with a nitrogen purge. The method is quite useful for the synthesis of ferroelectric liquid crystals and especially for making regular copolymers as achieving regularity is difficult when one has many monomers in a copolymerisation reaction. The unsaturation in the regular polymer can be removed by hydrogenation, thereby providing stability to the new polymer. Grubbs' ruthenium catalysts allow polymerisation to occur in the presence of fillers, additives, stabilisers and other ingredients in a polymer formulation. Ruthenium technology also produces stable or mouldable polymer formulations, which make it easy to fabricate complex parts.[33, 34]



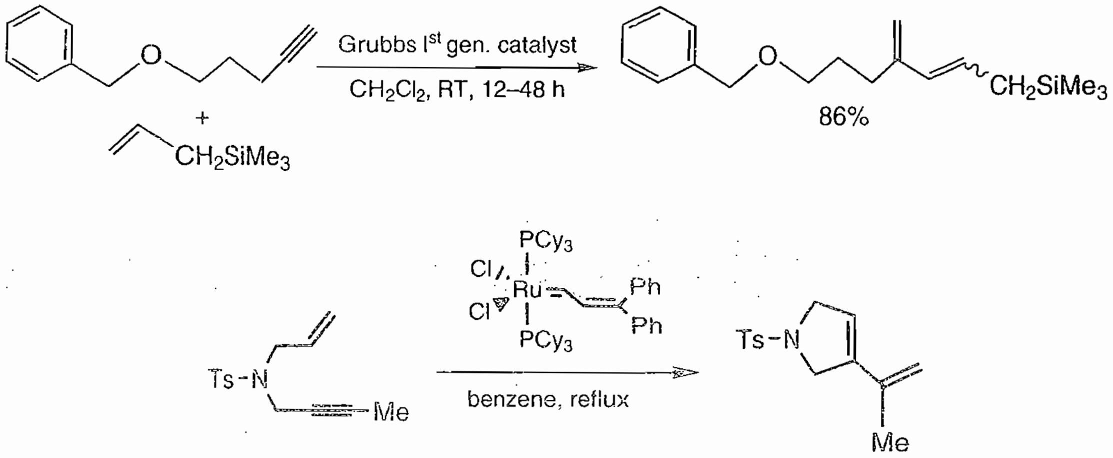
Scheme 15.13 Preparation of regular copolymers by ADMET method



Scheme 15.14 ADMET polymerisation for making ferroelectric liquid crystals

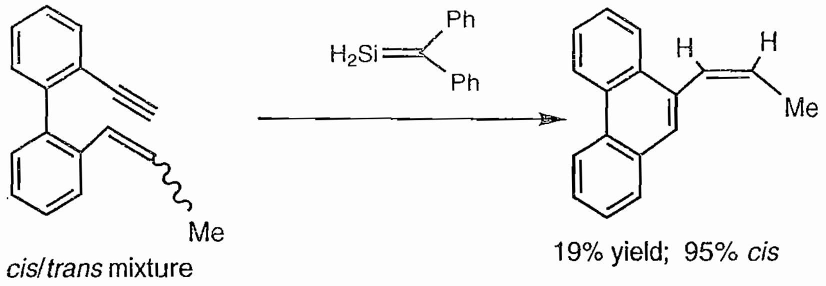
15.4.6 Enyne Metathesis (EM)

Enyne metathesis is best described as a metathesis reaction between an alkyne and an alkene in the presence of a metal carbene as catalyst which results in a 1,3-diene product. The reaction can be intermolecular or intramolecular and when it happens in an intramolecular manner, it is described as a ring-closing enyne metathesis or RCEYM.[35–37]



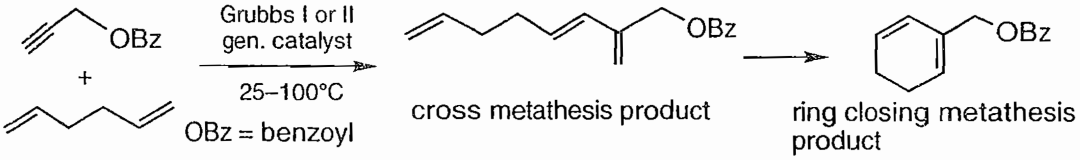
Scheme 15.15 EM and RCEYM reactions

The reaction was first described by Katz in 1985 and involved the conversion of the enyne biphenyl to the substituted phenanthrene using a tungsten based Fischer carbene as catalyst (Eq. 15.4). The metal atom exclusively adds to one of the alkyne carbon atoms in the initial step. This enyne bond reorganisation reaction is atom economical and unlike many other metathesis reactions, does not involve the release of any small alkene molecule such as ethylene or propylene. The driving force for the reaction is the enthalpic stability of the conjugated 1,3-diene product.[38]



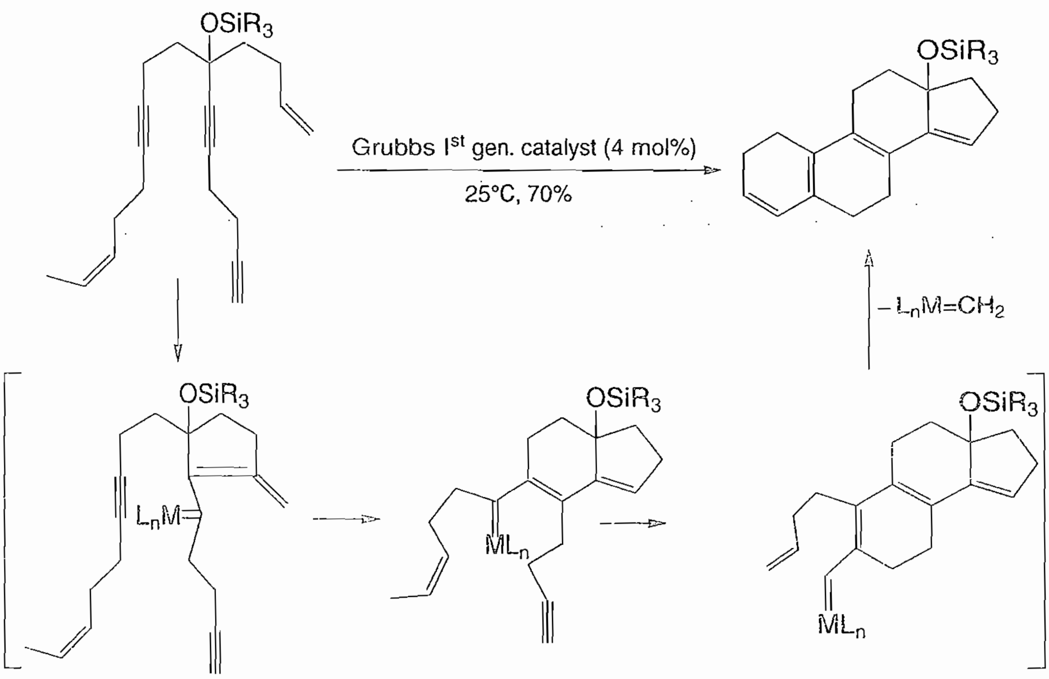
(15.4)

Tandem dienyne cross metathesis/ring closing metathesis as well as cascade enyne metathesis/ring closing metathesis are observed on many substrates having both alkenyl and alkynyl moieties (Scheme 15.16).[39]



Scheme 15.16 Tandem dienyne cross metathesis/ ring closing metathesis

Many reactions involving tandem (cascade) ring closing metathesis have been studied. Scheme 15.17 illustrates one of the best examples. Here, the alkene is attacked before the alkyne and a less sterically hindered (or terminal) alkene/alkyne is attacked before a hindered alkene/alkyne.[40]

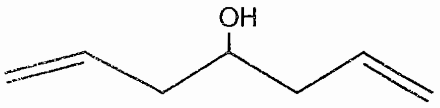
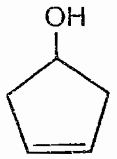
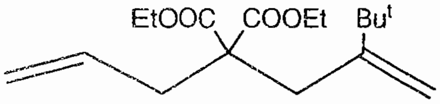
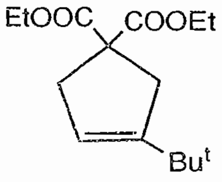
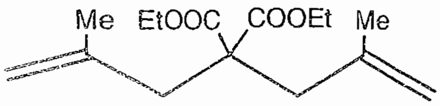
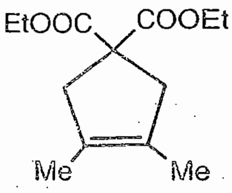
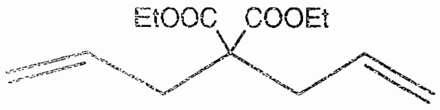
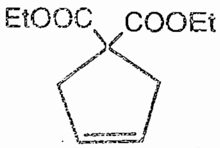
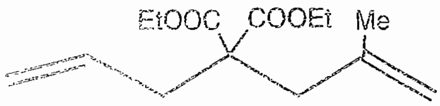
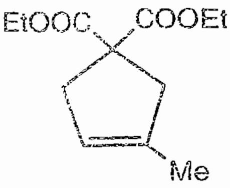


Scheme 15.17 Mechanism of tandem ring closing enyne metathesis

15.5 COMPARISON OF CATALYSTS

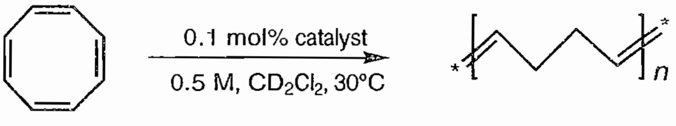
New olefin metathesis catalysts with varied activities are being prepared and some of them show better TON than the existing Schrock, Grubbs and Hoveyda catalysts. For example, for the self metathesis of 1-octene, the second generation Grubbs' catalyst gave a TON 5 times higher than that of the first generation catalyst while maintaining a high degree of selectivity for the formation of the product, the 7-tetradecene. The catalyst (SIPr)(PCy$_3$)(Cl)$_2$Ru=CHPh, bearing the extremely bulky 1,3-bis(2,6-diisopropylphenyl)-4,5-dihydroimidazol-2-ylidene ligand (SIPr, see Table 4.4), gave a TON 6 times higher (TON >640,000) and an initial TOF 20 times higher than those of second generation Grubbs' catalyst at ambient temperature. Table 15.5 gives a few selected examples where Schrock's molybdenum catalyst is compared with Grubbs first and second generation catalysts in terms of yields of products.[41]

Table 15.5 Comparison of Schrock and Grubbs catalysts in RCM reactions

Substrate	Product	Time	Schrock's	Grubbs' I	Grubbs' II
		10 min	NP	NP	Quant
		60 min	37%	NP	Quant
		4 days	93%	NP	17%
		10 min	Quant	Quant	Quant
		10 min	Quant	20%	Quant

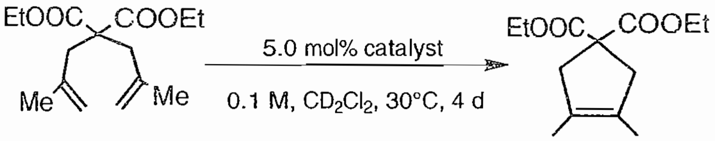
NP = No product; Quant = Quantitative yields

In 2006, Grubbs came out with a set of standard transformations to serve as a useful, general and easily applicable platform for the comparison of olefin metathesis catalysts.[42] Seven of the most common catalysts were compared in terms of efficiency, selectivity, activity and stability. The outcome of this study was that there is no single best catalyst and that the relative efficiency of a catalyst can be compared only within a particular reaction or class of reactions. The comparison given in Schemes 15.18–15.20 in ring opening metathesis polymerisation, ring closing metathesis and cross metathesis reactions exemplifies this observation.



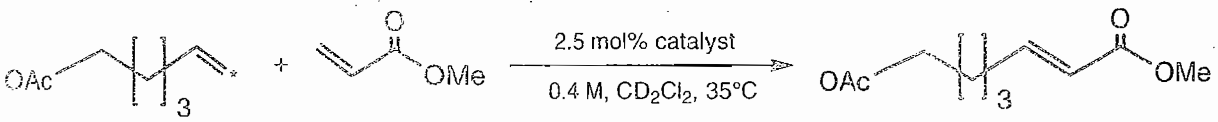
Grubbs I	20% conversion after 30 min
Grubbs II	100% conversion after 5 min
Grubbs III	100% conversion after 0.5 min

Scheme 15.18 Comparison of Grubbs I–III catalysts in ROMP of cyclooctatetraene



Grubbs I	0 % conversion
Grubbs II	17% conversion
Grubbs III	0% conversion
Grubbs Hoveyda	6% conversion

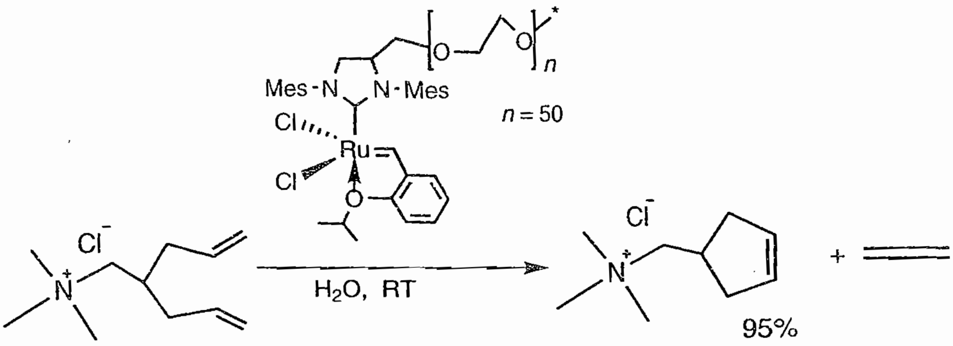
Scheme 15.19 Comparison of Grubbs I–III and Grubbs–Hoveyda catalysts in RCM of hindered olefins



Grubbs I	8 % conversion after 3 h
Grubbs II	95% conversion after 2 h
Grubbs III	35% conversion after 15 min and no further change

Scheme 15.20 Comparison of Grubbs I–III catalysts in cross metathesis reactions

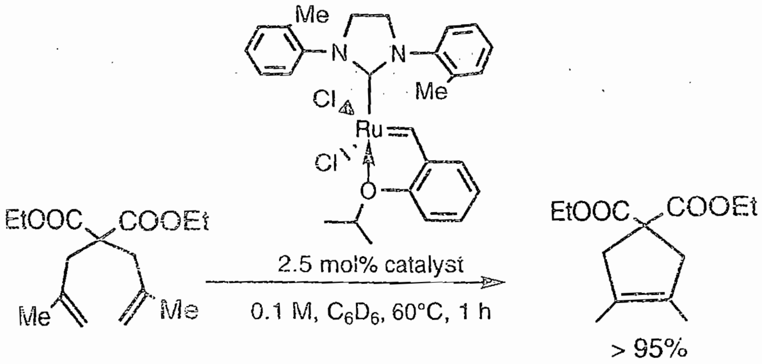
High reactivity comes at the price of catalyst lifetime and the TON often gets reduced. The requirement of high catalyst loading leads to product contamination with spent catalyst and sometimes metal impurities degrade the products too. Recent efforts have therefore been directed to reduce the catalyst loss. This has been done by immobilising the catalyst by anchoring to polymers and to solid supports or by modifying the catalyst for better recovery. Efforts have also been directed towards making the catalysts water soluble for aqueous olefin metathesis. The first fully water soluble variation of the Grubbs–Hoveyda catalyst was reported in 2006 and this was used to bring about RCM of a water soluble substrate (Scheme 15.21).[43]



Scheme 15.21 Ring closing metathesis using a water soluble catalyst in aqueous medium

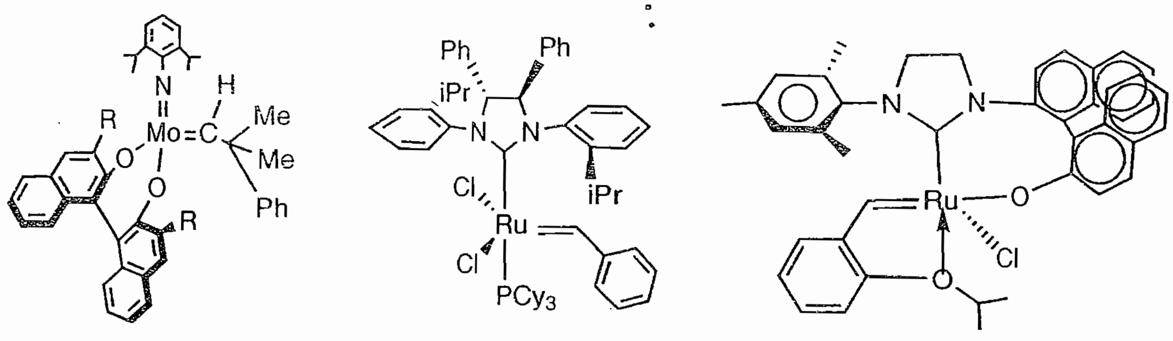
15.6 METATHESIS OF HINDERED OLEFINS

Till 2007, the metathesis of hindered olefins, especially RCM to form tetra subsbtituted cycloalkenes remained a difficult task with a maximum yield of 17% attainable with the Grubbs II catalyst. The related unsaturated NHC based carbene catalyst gave a modest yield of 31%. Grubbs and coworkers, by modifying the NHC, obtained a high yielding (>95%) route for the RCM of dimethylallyl malonates. The basic change made in the catalyst was that the mesityl groups on the NHC were replaced with mono *ortho*-alkyl substituted aryl groups. The methyl substituted NHC based compound was found to be the best in activity. In comparison, the Hoveyda–Grubbs II catalyst gave only 30% conversion for the same reaction in 24 hours.[44]



Scheme 15.22 Ring closing metathesis of hindered olefins

The activity in olefin metathesis using homogeneous catalysts has recently shifted to the synthesis of chiral catalysts and their use in enantioselective synthesis. The following are some of the first catalysts which have been used for this purpose.[45]

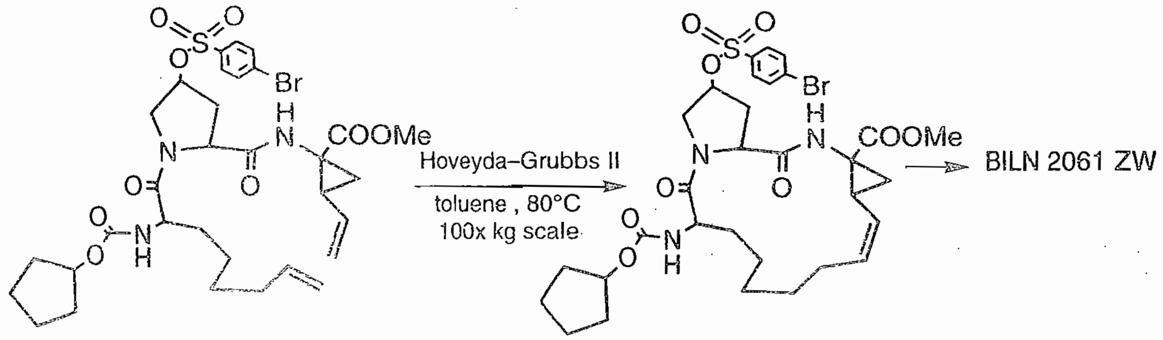


Schrock–Hoveyda Grubbs Hoveyda

Scheme 15.23 Chiral olefin metathesis catalysts

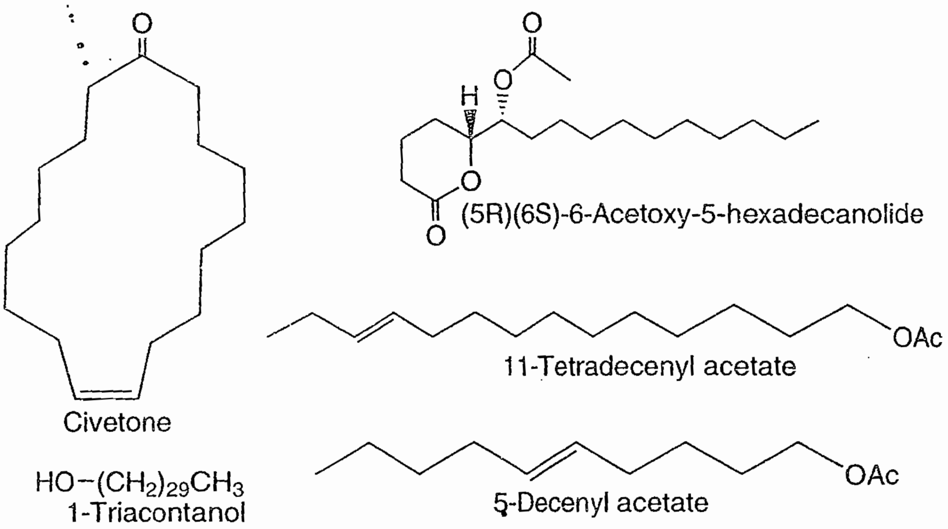
15.7 APPLICATIONS OF CATALYTIC OLEFIN METATHESIS

Many medicinally relevant compounds and precursors are being synthesised using olefin metathesis reactions. An efficient route to yield only the active enantiomer could prove profitable to drug companies. A key pyrrole intermediate for the synthesis of an anti-inflammatory drug, Ketorolac, is prepared from an α,β-unsaturated aldehyde which is produced by cross metathesis between crotonaldehyde and allyl benzoate. In the synthesis of BILN 2061 ZW, an active anti-hepatitis C protease inhibitor, the ring closing metathesis has been efficiently carried out in multi-kilogram quantities (Scheme 15.24).[46, 47]



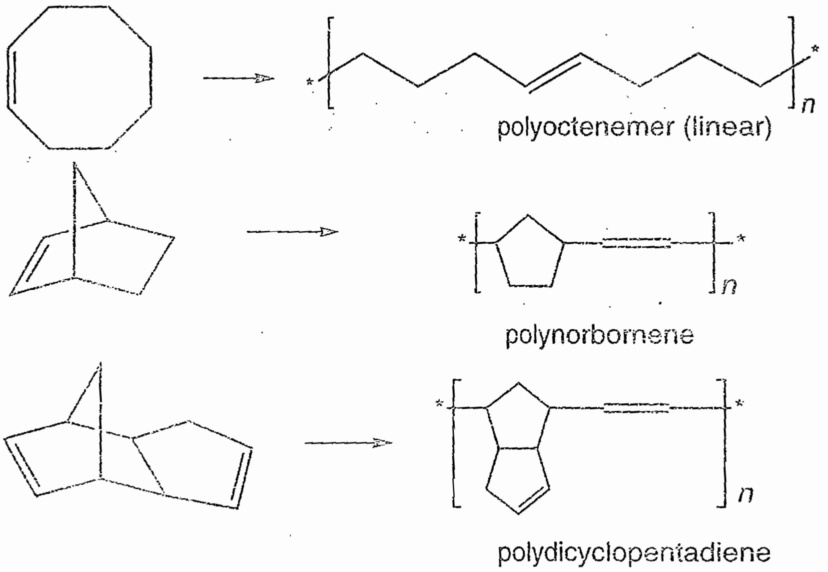
Scheme 15.24 Ring closing metathesis step in the synthesis of BILN 2061 ZW

Another application especially of cross metathesis is in the preparation of synthetic perfumes and pheromones. Civetone (the ingredient in musk perfumes), 1-triacontanol (a plant growth stimulant), (*E*)-5-decenyl acetate (a pheromone of peach twig borer, *Anarsia lineatella*), a mixture of (*E*)- and (*Z*)-11-tetradecenyl acetate (pheromone of omnivorous leafroller, *Platynota stultana*) and (5*R*,6*S*)-6-acetoxy-5-hexadecanolide, the mosquito oviposition pheromone (female mosquitoes of the genus *Culex* release this compound when they lay eggs to attract other egg laying females to the site) are compounds industrially prepared using catalytic metathesis reactions (Scheme 15.25).[2]



Scheme 15.25 Perfumes and pheromones prepared using cross metathesis reactions

A variety of useful polymers have been prepared by ROMP under mild conditions and by using commercial catalysts. Commercially available polymers prepared by ROMP include polyoctenamer (from cyclooctene), polynorbornene (from norbornene) and polydicyclopentadiene (Scheme 15.26). Poly-DCPD resins are highly engineered thermosets, widely used around the world for the production of body panels for truck, agricultural and earth moving equipment, cell covers for chloralkali plants, domestic waste water treatment units and large waste containers. Grubbs' ruthenium catalysts allow polymerisation to occur in the presence of fillers, additives, stabilisers, and other ingredients in a polymer formulation. It has been demonstrated that a 1.5 inch thick poly-DCPD resin prepared with ruthenium technology is impenetrable to 9 mm bullets. Block copolymers made of polynorbornene and decaborane are useful in the synthesis of nano structured boron carbonitride.[5]

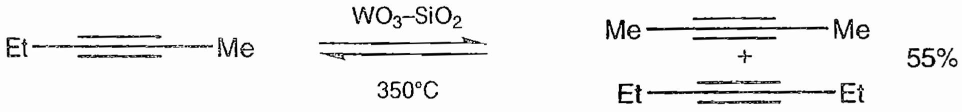


Scheme 15.26 Useful polymers prepared by ROMP method

The robust nature of ROMP has been instrumental in the design of self healing materials especially automatic healing of polymer composities. During fabrication, a microencapsulated healing agent (for example, dicyclopentadiene) is embedded in a structural composite matrix along with other microcapsules containing Grubbs first generation catalyst capable of polymerising the healing agent. If a crack occurs on the rigid composite, it will rupture the microcapsules (both monomer and catalyst) and the monomer healing agent will fill the crack. Once it comes in contact with the catalyst, on the spot polymerisation happens sealing the crack. Self healing is thus triggered by crack-induced rupture of the embedded capsules. This technology has been suggested to be useful in protecting systems subject to extreme variations in temperature, for example, material used for fabricating body of spacecrafts.[48–50]

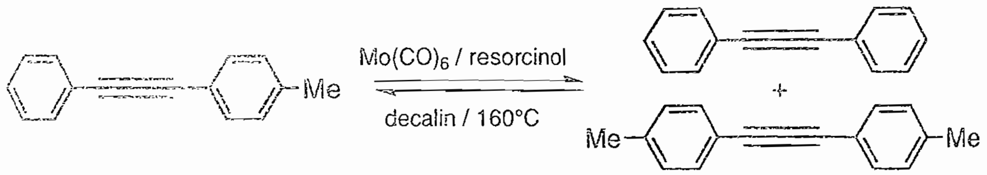
15.8 ALKYNE METATHESIS

Although not as popular as alkene metathesis, alkyne metathesis has been developed as a synthetic tool in organic chemistry especially for the synthesis of natural products having a ring size of 12 atoms or more. A variety of heterogeneous and homogeneous catalysts are known to bring about alkyne metathesis and some of them are metal carbyne complexes.[51] A typical difference between alkene and alkyne metathesis is the fact that alkyne metathesis takes place only with internal alkynes while alkene metathesis occurs with both internal and terminal alkenes. The ease with which terminal alkynes can undergo a competing trimerisation reaction to form aromatic rings is a possible reason for this difference. Another disadvantage of alkyne metathesis is related to the strain involved in forming an internal alkyne as part of a ring which will be much more than the strain involved for the formation a cyclic internal alkene. Therefore alkyne ring closing metathesis happens only above a particular ring size of the product, say 12 atoms or more.



$$\mathrm{Et{-}C{\equiv}C{-}Me} \xrightleftharpoons[350^\circ\mathrm{C}]{\mathrm{WO_3{-}SiO_2}} \begin{matrix}\mathrm{Me{-}C{\equiv}C{-}Me} \\ + \\ \mathrm{Et{-}C{\equiv}C{-}Et}\end{matrix} \quad 55\% \qquad (15.5)$$

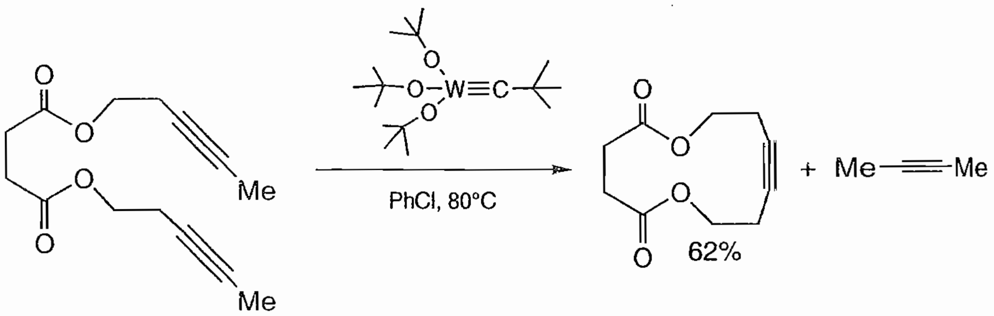
While the first heterogeneous catalyst for alkyne metathesis was developed by Banks and Bailey in 1968 using a WO_3/SiO_2 combination (Eq.15.5), the first homogenous catalysts were developed by Mortreux in 1974 when a combination of $Mo(CO)_6$ and resorcinol converted phenyl-*p*-tolyl acetylene to a mixture of diphenylacetylene and di-*p*-tolyl acetylene (Eq. 15.6).[52,53] While this reaction was carried out at 160°C, by changing resorcinol to phenol, the temperature was brought down to 110°C and it could also be carried out photochemically. The use of 4-chlorophenol or o-trifluoromethyl phenol was found to increase the efficiency of this reaction many times.



(15.6)

While the active catalyst in this reaction could not be identified clearly, it is assumed that a molybdenum alkylidene is formed in situ from these ingredients. Preheating $Mo(CO)_6$ with phenol did not show any catalytic activity whereas preheating $Mo(CO)_6$ with the alkyne resulted in catalytic activity. It was shown that a non-carbonyl catalyst (MoO_2/ $AlEt_3$/ArOH) can also bring about alkyne metathesis.

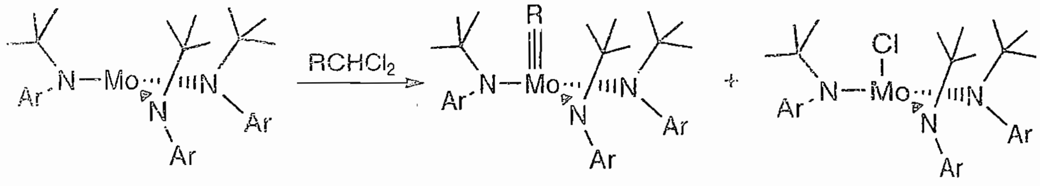
Among the most effective alkyne metathesis catalysts are the tungsten and molybdenum alkylidynes—Schrock carbynes. The tungsten catalyst, $(t\text{-}BuO)_3W{\equiv}CCMe_3$ is readily prepared by the cleavage of the triple bond of $(t\text{-}BuO)_3W{\equiv}W(t\text{-}BuO)_3$ with neoheptyne.[54] Its metathesis activity has been demonstrated on a range of substrates (Eq. 15.7).



(15.7)

The activity in ring closing metathesis of $(t\text{-}BuO)_3W{\equiv}CCMe_3$ was compared with that of $Mo(CO)_6$/4-ClC_6H_4OH.[55] While yields of ring closed products were more or less comparable, the tungsten catalyst was found to be inactive in the presence of thioether and basic nitrogen functional groups. Secondary amide groups and silyl ether groups on the substrate were found to be intolerant towards the $Mo(CO)_6$/phenol system. Although handling of the $Mo(CO)_6$/phenol system is much easier, the high temperatures required for the reaction (~140°C) is a deterrent. The mechanism of alkyne metathesis was first proposed by Katz and is analogous to that for alkene metathesis. Three different types of intermediates were proposed in alkyne metathesis. The first two, a metal–cyclobutadiene complex and a metallacyclopentadiene were found to be too stable to revert to the alkynes. So the accepted mechanism now is that the reaction goes through a metallacyclobutadiene intermediate similar to the intermediate suggested in olefin metathesis. The role of phenol in the $Mo(CO)_6$ catalyst has been proposed as a reagent which by interacting with the alkynes favours isomerisation of the alkyne and avoids trimerisation.[56]

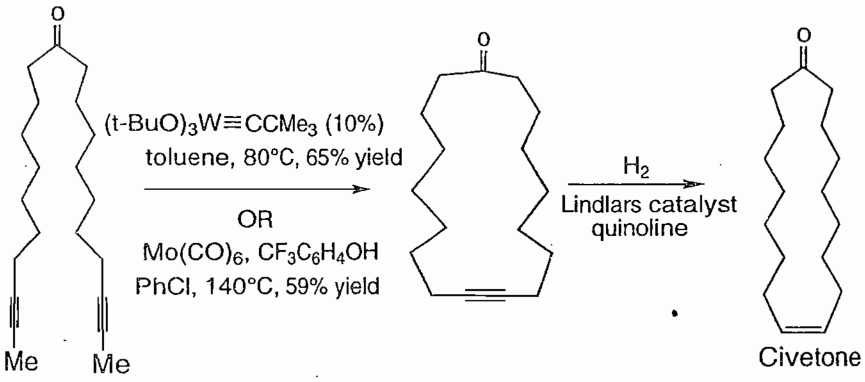
A relatively recent approach to alkyne metathesis was reported by Fürstner where a sterically hindered trisamido molybdenum based catalyst along with dichloromethane was found to effectively bring about alkyne metathesis (Eq. 15.8).[57] The in situ formation of an alkylidyne was proposed in this reaction. An advantage of these types of catalysts is that they have better functional group tolerance compared to Schrock's carbyne catalysts.



Ar = 3,5-dimethylphenyl

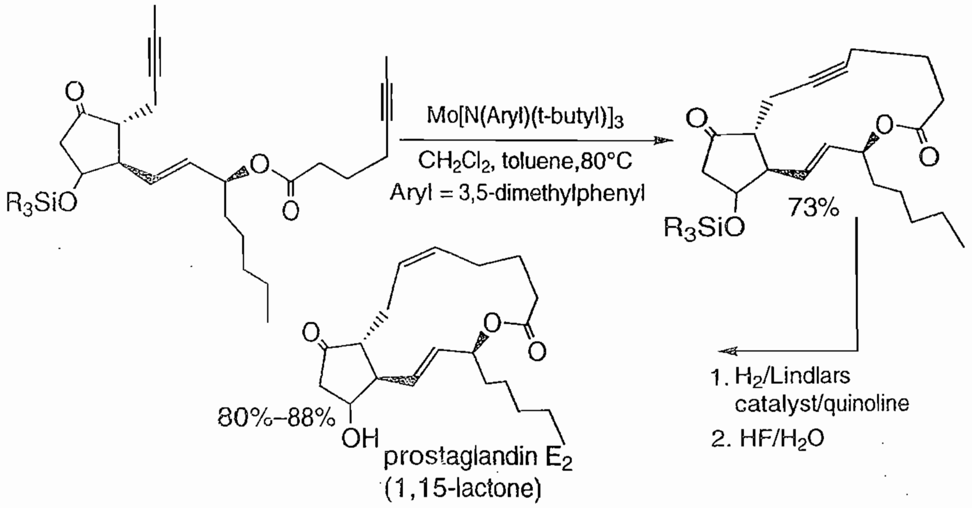
(15.8)

The application of alkyne metathesis has been demonstrated in the synthesis of many natural products. One among them is the synthesis of the 17-membered cyclic ketone civetone, which is one of the oldest known ingredients in perfumes. It is a pheromone, sourced from the African civet cat and is closely related to muscone, the principal odoriferous compound found in musk (Eq. 15.8).[58]



(15.9)

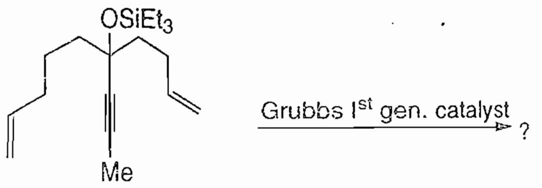
Another interesting use of alkyne metathesis is in the synthesis of a 13-membered 1,15-lactone which upon hydrolysis, yields prostaglandin E_2 a biomediator in mammals, that regulates gastric secretion (Eq. 15.9).[59]

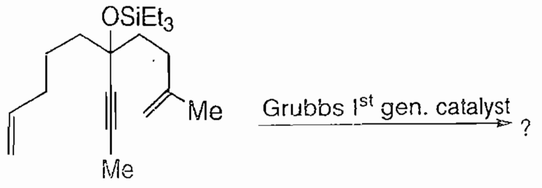


(15.10)

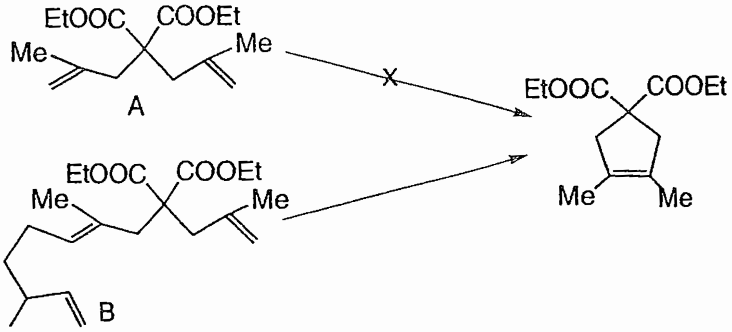
Problems and Exercises

15.1. Predict the outcome of the reactions with Grubbs I generation catalyst. Indicate the steps involved.

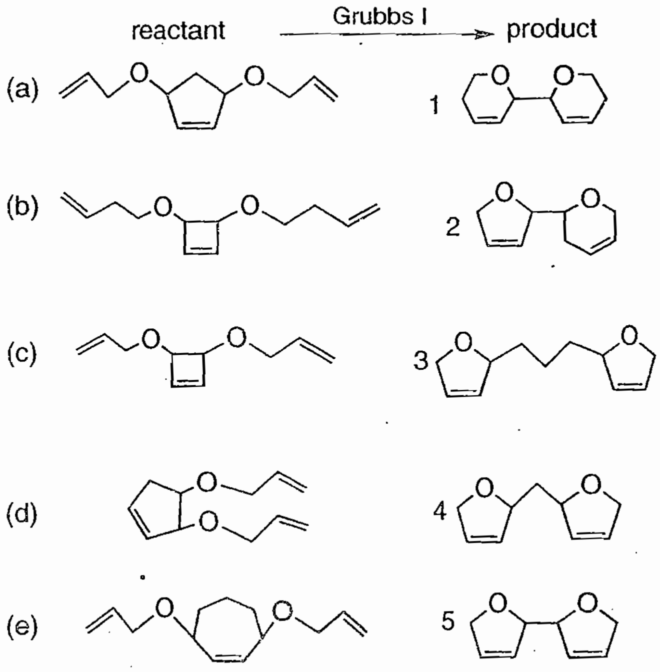




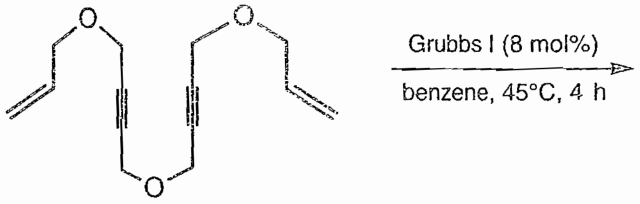
15.2. Between compounds A and B, only B undergoes reaction with Grubbs I generation catalyst yielding the given product. Explain this observation with the mechanism of the reaction if necessary.



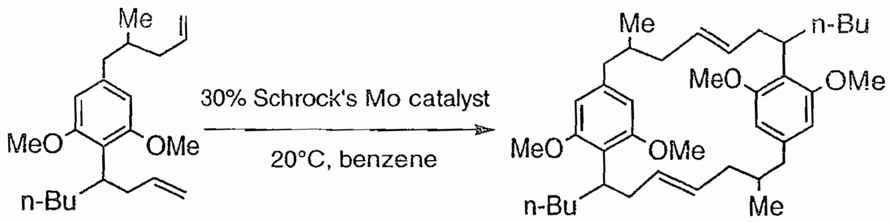
15.3. Match the reactants on the left with the products given on the right which are obtained on reaction with Grubbs I generation catalyst.



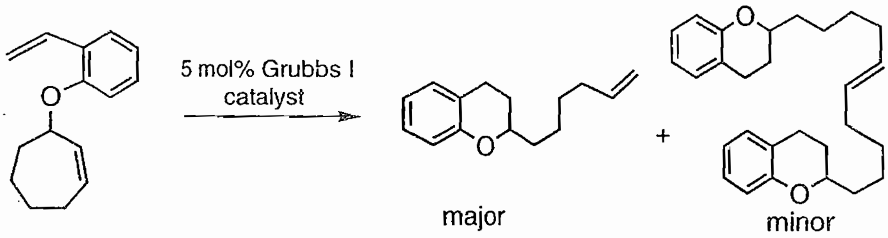
15.4. Write the mechanism and arrive at the structure of the product obtained from the following ring opening/ring closing metathesis reaction using the Grubbs I catalyst.



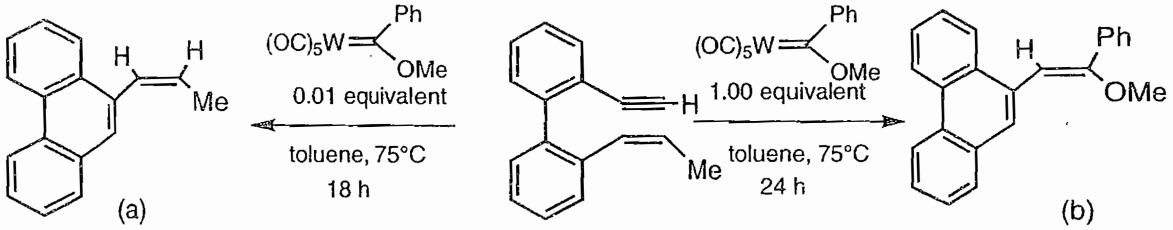
15.5. Indicate how the following reaction occurs by writing the structure of the organic intermediate(s) formed and indicate the type of metathesis reactions occurring during the process.



15.6. Reaction of the given compound with Grubbs I generation catalyst results in major and minor products as shown below. Show the mechanism for the formation of both.



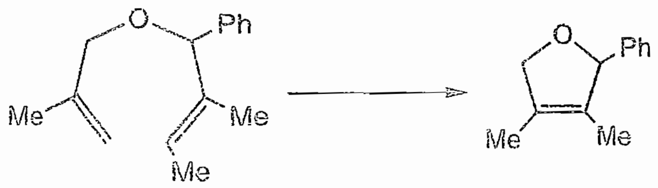
15.7. The following scheme shows that two different products are formed from the reaction of the same starting material with the same metal carbene complex but in different stoichiometric ratio. Explain the reason for the difference in the product formed.



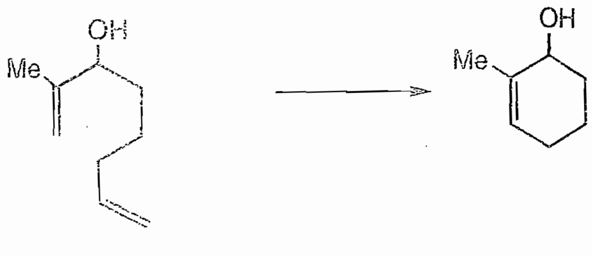
15.8. In general, for cross methathesis reactions involving acrylonitrile, Schrock's molybdenum catalyst gives very good yields, the Grubbs–Hoveyda (second generation) catalyst gives moderate yields while Grubbs II catalyst gives very poor yields of products. Given that CuCl readily forms complexes with phosphines, indicate if additon of CuCl to the reaction mixture will affect the reaction in any way.

15.9. For the following reactions, pick the olefin metathesis catalyst (Schrock's molybdenum catalyst or Grubbs II catalyst) and justify your answer.

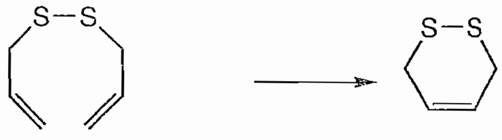
(a)



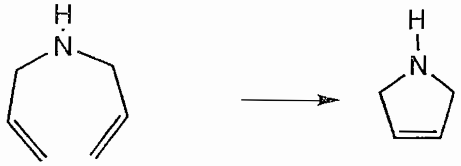
(b)



(c)



(d)



Supplementary reading

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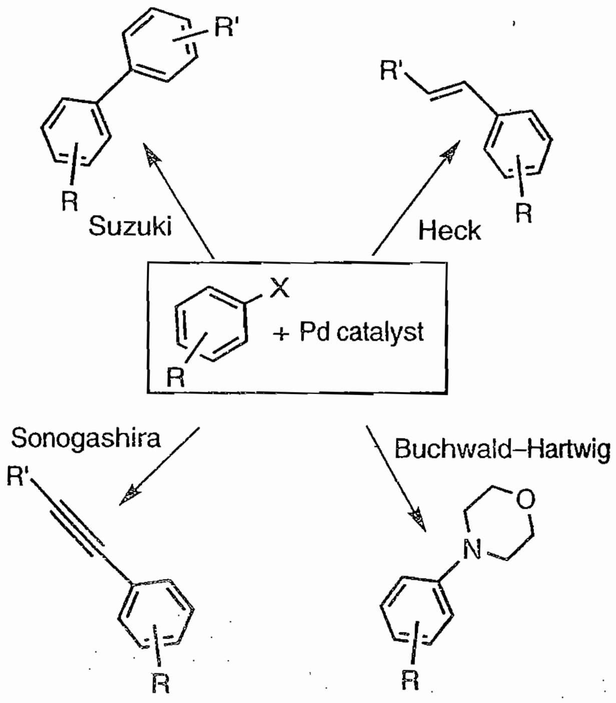
PALLADIUM CATALYSED C–C AND C–N CROSS COUPLING REACTIONS

CHAPTER

16

16.1 DISCOVERY OF PALLADIUM CATALYSED CROSS COUPLING REACTIONS



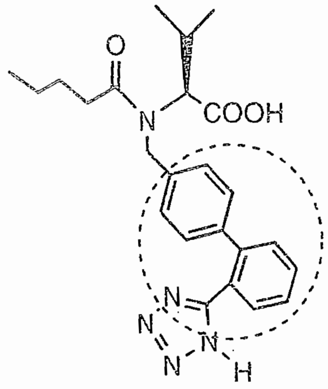
Carbon–carbon bond formation is one of the most important reactions in organic chemistry. Reactions involving aryl-aryl coupling or aryl–alkene coupling using traditional noncatalytic methods generally involve many steps. Although copper mediated aryl–aryl homocoupling using aryl iodide was introduced by Ullmann in 1904, the major discoveries in the cross coupling reactions, catalysed by palladium, began in 1972 with the Heck reaction[1] (cross coupling of an aryl halide with an alkene) and the Kumada reaction (cross coupling of an aryl halide and Grignard reagent).[2] The most important contribution of all cross coupling reactions, however, came from Akira Suzuki, Professor at Hokkaido University, Japan. In 1979, the seminal paper of Suzuki and Miyaura in *Tetrahedron letters* laid the ground work for what is now arguably the most important and useful transformation for the construction of the carbon–carbon bond in modern day organic chemistry. The reaction is known as the Suzuki (or Suzuki–Miyaura) coupling.[3] Since then, research by various groups over the past 30 years has led to vast improvements of this reaction. Sonogashira brought in palladium catalysed aryl-alkyne coupling in 1975.[4] Later Buchwald and Hartwig introduced aryl C–N and aryl C–O coupling using palladium as catalyst. In the mean time, a host of other coupling reactions were also reported, prominent among them being the Stille (organotin), Hiyama (organosilicon) and Negishi (organozinc) coupling reactions.

Over the years, Suzuki coupling has gained much more prominence than the other coupling reactions. Many modifications have been introduced on the original Suzuki and related reactions; for example, the use of aryl chlorides in place of iodides and bromides, introduction of electron rich and sterically bulky phosphines, carrying out the reaction at room temperature, and using a palladium catalyst in ppb levels. This has certainly expanded the scope of palladium catalysed cross coupling reactions. The 2010 Nobel Prize for chemistry was awarded to Suzuki, Heck and Negishi for their contributions in palladium catalysed cross coupling reactions.[5]

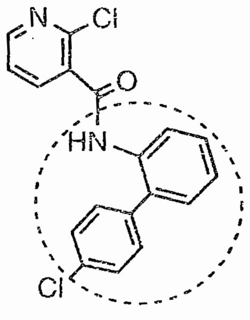
Contrary to the belief that these reactions are applicable only to *sp*^{2} carbon substrates, post 2000 has witnessed the development of alkyl–alkyl Suzuki cross coupling of unactivated primary and secondary alkyl halides using 9-BBN derivatives and nickel catalysts instead of palladium. Functional group tolerance has been the hallmark of many palladium catalysed cross coupling reactions. Efficient one step Suzuki arylation of unprotected halonucleosides using water soluble phosphines and palladium catalysts has also been achieved, thus extending the reach of these reactions to biological chemistry as well. Suzuki coupling has recently been extended also to perfluorinated aryl compounds.

16.2 INDUSTRIAL APPLICATIONS OF CROSS COUPLING REACTIONS

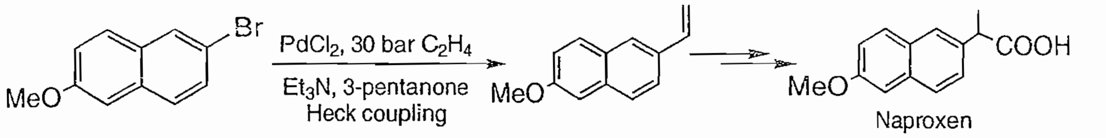
As biaryls are common substructures in many natural products, Suzuki cross coupling has been used in the industrial preparation of many natural products and bioactive compounds. The well known antihypertensive drug Valsartan, is manufactured by Novartis.[6] The use of Suzuki coupling has considerably reduced the number of steps in its synthesis. Another compound manufactured in bulk quantities by BASF using Suzuki coupling is the fungicide Boscalid, used on food crops.[7] The Suzuki coupling has been used in making many advanced materials such as light emitting polymers (such as polyphenylene vinylenes and polythiophenes). Organic LED manufactures use Suzuki coupling in large measures. Other cross coupling reactions also find use in many industrial applications. Albermarle Corporation uses the Heck reaction in the synthesis of drugs like Naproxen and Ketoprofen.[8] The Heck reaction is also used for the industrial synthesis of the common sunscreen agent 2-ethylhexyl-*p*-methoxycinnamate, herbicide Prosulfuron (Novartis) and Singulair, an anti-asthma agent (Merck).[9] An important application of Sonogashira coupling is in the ene–diyne synthesis of compounds which are used in anticancer therapy for Bergman cyclisation.



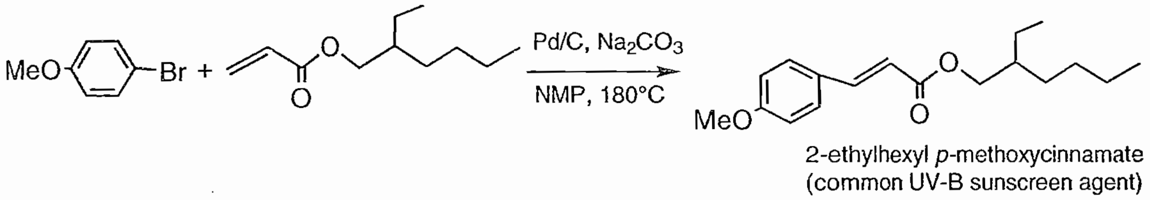
Valsartan



Boscalid



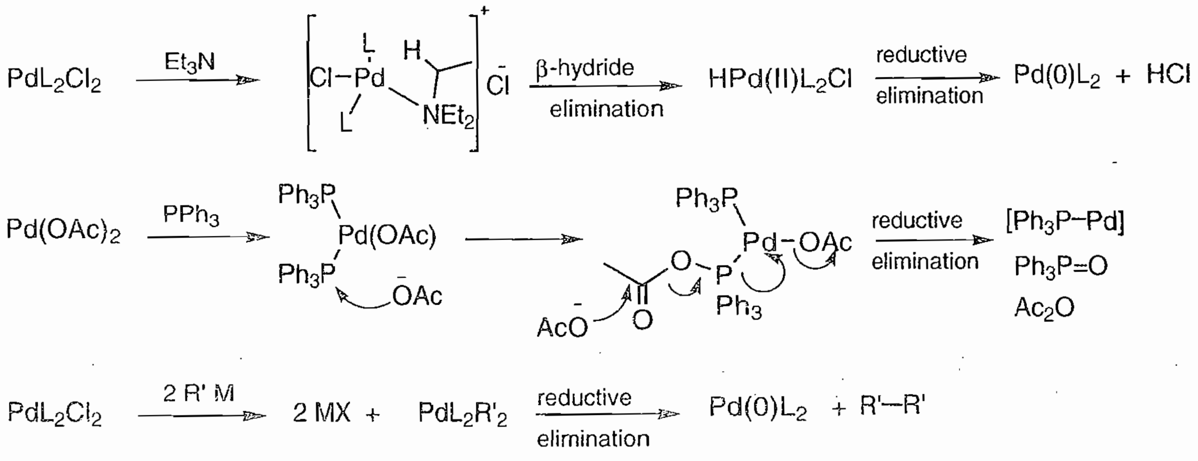
(16.1)



(16.2)

16.3 THE CROSS COUPLING CATALYST

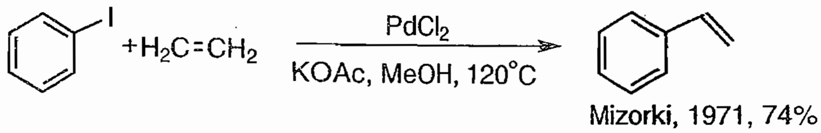
Though there are examples of metals such as Ni, Rh, Cu and Pt used in cross coupling reactions, palladium is indeed the most widely used metal for these reactions. Even palladium colloids and nanoparticles can be used and often the metal is associated with some ligands. Both Pd(0) complexes [for example, $Pd(PPh_3)_4$, $Pd_2(dba)_3$] and Pd(II) compounds [for example, Na_2PdCl_4, $Pd(OAc)_2$, $PdCl_2(PPh_3)_2$] are used. However, the active species is Pd(0) in all these cases. Pd(II) presumably gets reduced to Pd(0) by amines, phosphines, organometallic reagents such as n-butyllithium, trialkyl aluminum and also by alkenes. Scheme 16.1 indicates how this reduction could possibly take place.[10]



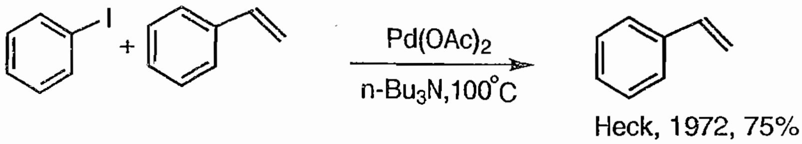
Scheme 16.1 Possible ways of generation of Pd(0) species in the reaction medium

16.4 THE HECK REACTION

Heck olefination or simply the *Heck reaction* was discovered independently by the efforts of T Mizorki and R F Heck.[1] The classical Heck reaction involves the palladium catalysed substitution of the vinylic hydrogen with a vinyl, aryl or benzyl group. The coupling can be intra- or intermolecular. Palladium as Pd(II) in the form of a salt or complex, or as Pd(0) with a concentration of 1–5 mole%, is the most widely used catalyst for this reaction. A base (example, an amine) is necessary to remove the liberated acid, HX. This coupling reaction is stereoselective with a propensity for *trans* coupling as the palladium halide group and the bulky organic residue move away from each other in the reaction sequence by bond rotation. Typical catalysts are Pd(0)–phosphine complexes, $Pd(PPh_3)_4$, or in situ catalysts such as $Pd(OAc)_2/PPh_3$. Chelated phosphines with larger bite angles such as dppf and $Ph_2P(CH_2)_nPPh_2$ ($n = 2–4$) have also been used in several cases along with $Pd(OAc)_2$, $Pd_2(dba)_3$ and (π-allyl)Pd complexes.[9, 11, 12]

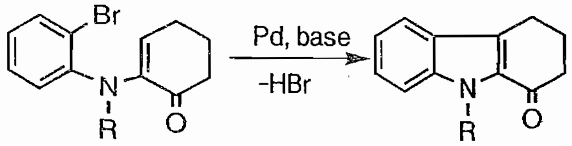


(16.3)



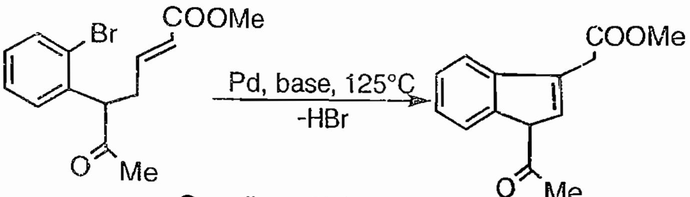
(16.4)

Intermolecular Heck coupling



(16.5)

Intramolecular Heck coupling

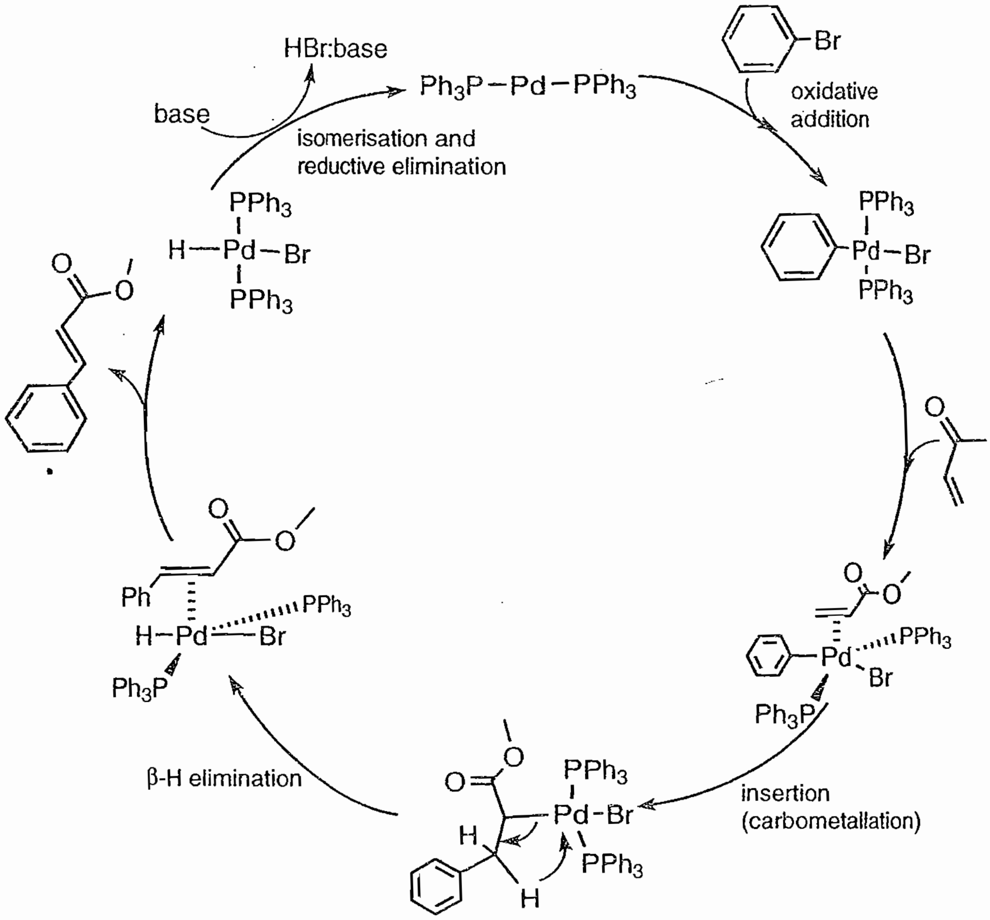


(16.6)

Coupling with isomerisation

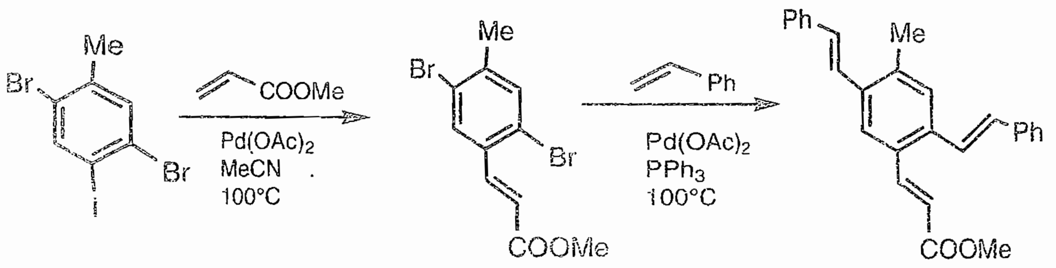
Generally, such reactions are conducted in polar aprotic solvents like MeCN, DMSO or dimethylacetamide (DMAc). The reaction time and temperature depend on the nature of the organic halide to be activated. Iodo derivatives are more reactive and hence auxiliary ligands (phosphines) can be avoided. In these cases polar solvents such as DMF, DMAc and NMP in combination with NaOAc as a base are especially beneficial.

The Heck reactions are useful on the inter- and intramolecular level, although intermolecular reactions are more common. Organic halides containing β-hydrogens cannot be used as they tend to form olefins at the Pd(II) center. Electron rich, disubstituted or cyclic olefins are less reactive than electron deficient, monosubstituted olefins. Many functional groups are compatible with Heck conditions, which enables the synthesis of carbo- and heterocyclic compounds and C–C bonded isomerised products including natural products. The active form of the catalyst is a 14e Pd(0) complex with two PPh_3 ligands. The 1,2-migratory insertion step (π to σ complex formation) is often referred to as carbometallation in palladium based catalytic cycles.



Scheme 16.2 Catalytic cycle for Heck coupling reaction

Discrimination in reactivity is possible in Heck reactions by controlling the reaction conditions. In the following reaction when PPh_3 is not added, only iodide is replaced by acrylate whereas upon addition of PPh_3, the bromides also react giving the tri-alkenyl substituted toluene.[13]



(16.7)

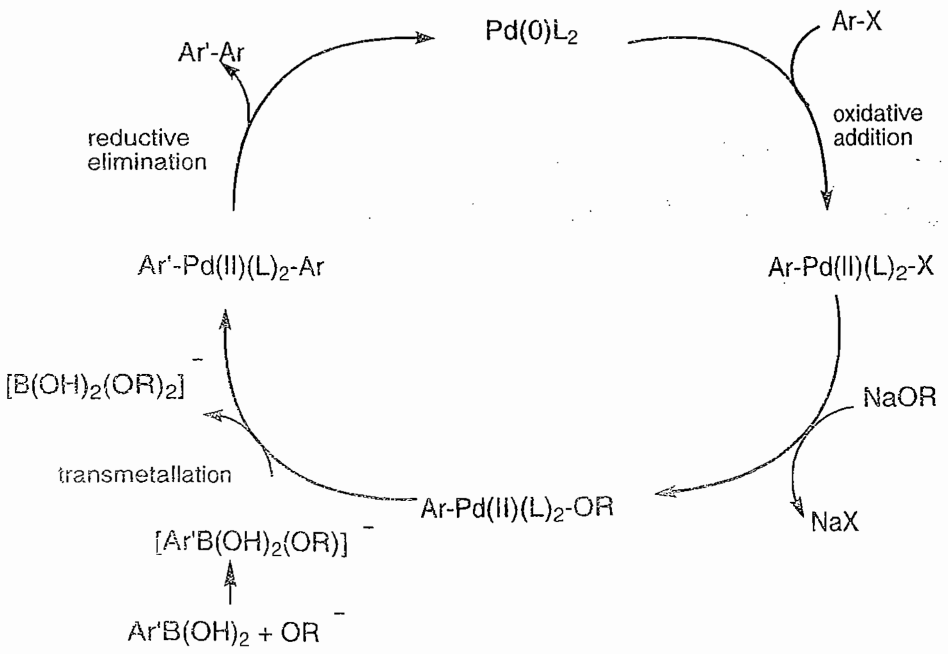
16.5 SUZUKI–MIYAURA COUPLING

Suzuki coupling can be described as a Pd catalysed cross coupling reaction of organoboron compounds (usually a boronic acid or ester) with organic halides.[14-17]

$$R{-}BY_2 + R'{-}X \xrightarrow{[Pd],\ base} R{-}R' \qquad (16.8)$$

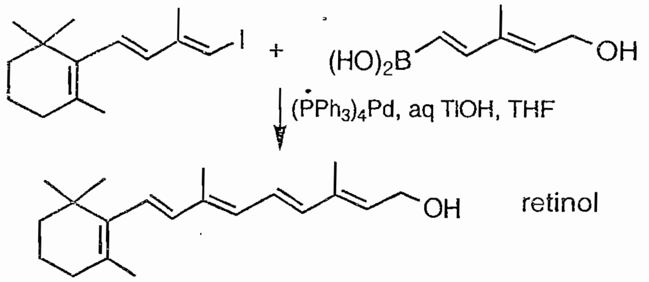
where $BY_2 = B(OH)_2$, $B(OR'')_2$, 9-BBN, $BF_3^-K^+$, $B(CHCH_3CH(CH_3)_2)_2$,
X = I, Br, $OSO_2(C_nF_{2n+1})$ and also Cl (with bulky electron rich phosphines),
R = aryl, alkenyl and also alkyl (under special conditions),
R′ = aryl, alkenyl, alkynyl, benzyl, allyl,
[Pd] = $Pd(PPh_3)_4$, $PdCl_2(R_3P)_2$, $Pd(OAc)_2$, $Pd_2(dba)_3$, $PdCl_2(dppf)$,
base = Na_2CO_3, NaOEt, NEt_3, TlOH, K_3PO_4 or CsF.

This is one of the most powerful reactions in synthetic organic chemistry for carbon–carbon bond formation as it can tolerate the presence of functional groups in the coupling partners. Older conventional methods for coupling of aryl groups typically require reagents and catalysts that are incompatible with molecules bearing polar functional groups. The Suzuki reaction requires conditions milder than that for the Heck reaction. The boronic acids are air and water stable as well as nontoxic. The pharmaceutical industry therefore prefers this reaction since the boron species that is formed as a side product is relatively nontoxic (unlike the Stille coupling which results in tin based toxic side products, Section 16.7). Recent developments in the catalyst and methodology have enormously broadened the possible applications of this reaction and the reaction partners are not restricted to aryls only, but include alkyls, alkenyls and alkynyls. Trifluoroborates, organoboranes or cyclic boronate esters can also be used in the place of boronic acids. However, the base is a necessary component of the reaction (Scheme 16.3). One difference between the Suzuki reaction and the Stille coupling is that the boronic acid must be activated with a base. This activation of the boron atom enhances the polarisation of the organic ligand and thus facilitates



Scheme 16.3 Catalytic cycle for Suzuki–Miyaura coupling

transmetallation. Equations 16.9 and 16.10 show how Suzuki coupling has been utilised in the synthesis of retinol and polyparaphenylene.[18, 19]



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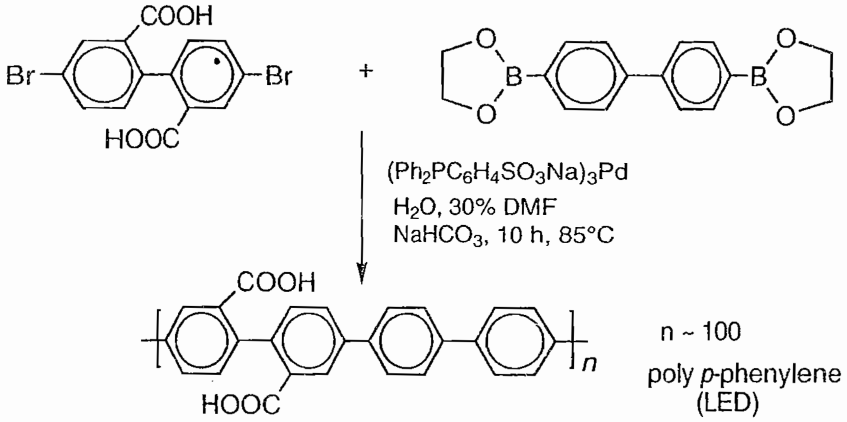
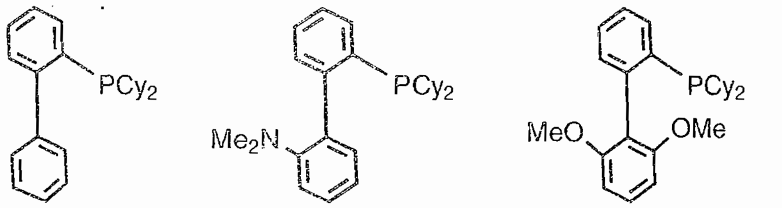


(16.10)

There has been a vast improvement and increase in the scope and utility of this reaction in the recent past. This includes the use of aryl chlorides as substrates, the ability to conduct the reaction at very low catalyst loading, to carry out the reaction at room temperature, to couple highly hindered substrates and to carry out asymmetric synthesis. The phosphine component in the metal catalyst has also undergone wide changes. An important breakthrough came in 1998 from the work of Stephen Buchwald and Gregory Fu of MIT. They found systems that could catalyse coupling of aryl chlorides under mild conditions. The Buchwald system used Pd with an electron rich phosphine bearing biphenyl while the Fu system contained a bulky aliphatic phosphine, P(t-Bu)$_3$. They were able to achieve Suzuki coupling of aryl chlorides even at room temperature. Buchwald later came up with further modified phosphines whose performances were even better (for example, phosphine 3, Fig. 16.1).[20]



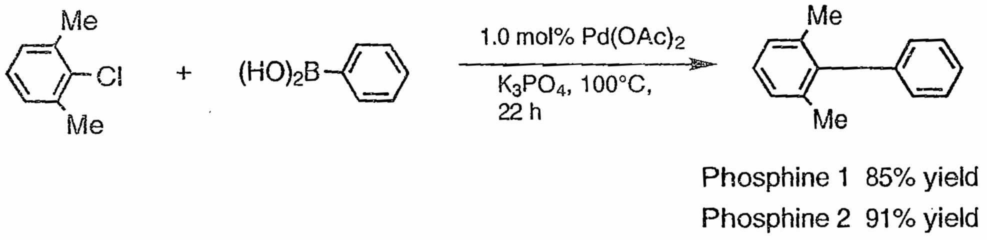
Phosphine 1
Buchwald (1999)

Phosphine 2
Buchwald (1999)

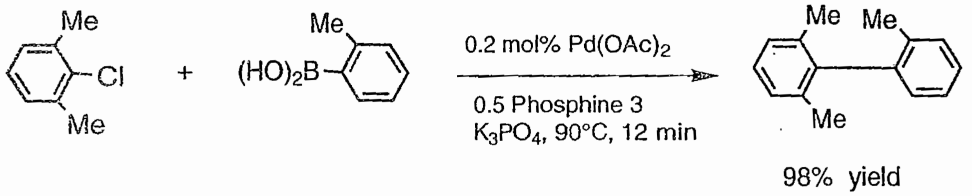
Phosphine 3 (S-Phos)
Buchwald (2004)

Fig. 16.1 Sterically hindered and electron rich Buchwald phosphines

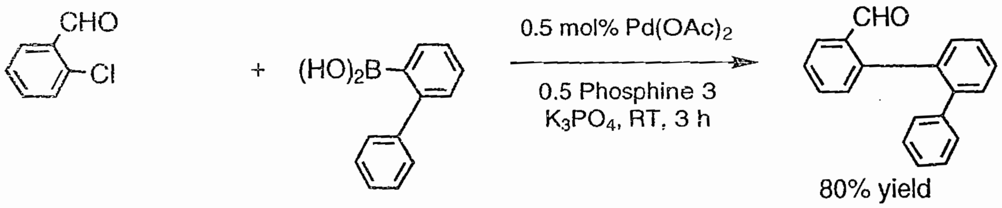
The success of these ligands over conventional phosphines has been due to a combination of two factors (i) their electron richness enhances the rate of oxidative addition of aryl chlorides to Pd and prevents the palladium complex from precipitating out, and (ii) their steric bulk enhances the rate of reductive elimination. In addition, the presence of the *o*-biphenyl moiety confers air stability to the ligand.



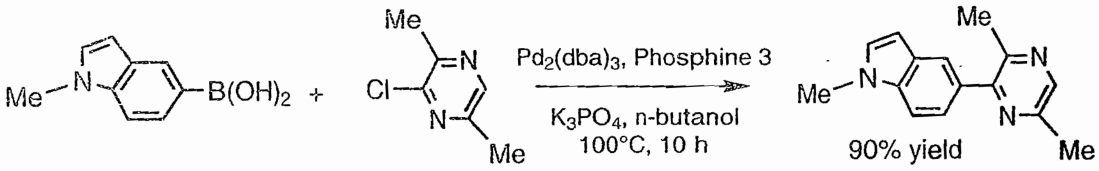
(16.11)



(16.12)

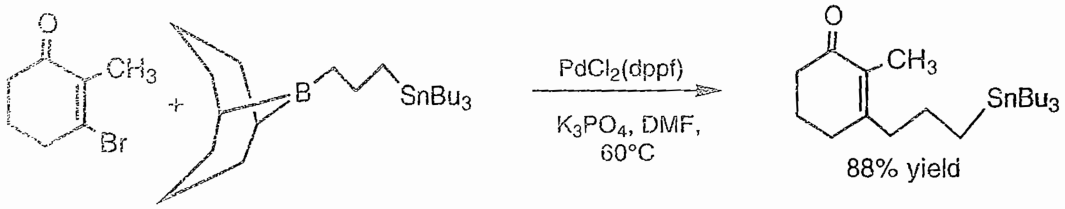


(16.13)



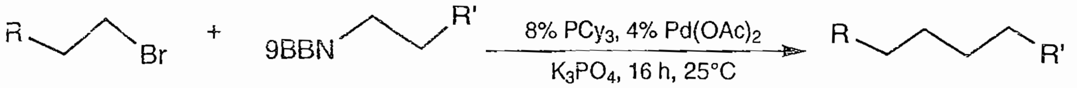
(16.14)

The coupling of alkyl groups (bound to 9-BBN) to aryl and vinyl moieties became possible by the use of bis(diphenylphosphino) ferrocene (dppf).[21] The large bite angle of dppf is believed to produce a catalyst with a more favourable rate constant for facilitating reductive elimination over β-hydrogen elimination. In 2001, Fu showed that even alkyl–alkyl coupling was possible at room temperature by using electron rich and bulky alkyl phosphines like PCy_3. The strategy used in these reactions was to make oxidative addition of the alkyl halide facile and prevent β-hydrogen elimination.[22]



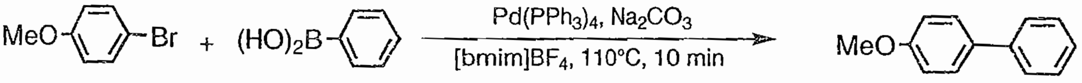
(16.15)

The reaction conditions have also undergone a variety of changes. These include carrying out the reaction in ionic liquids [$(bmim)BF_4$] or in water with microwave radiation and



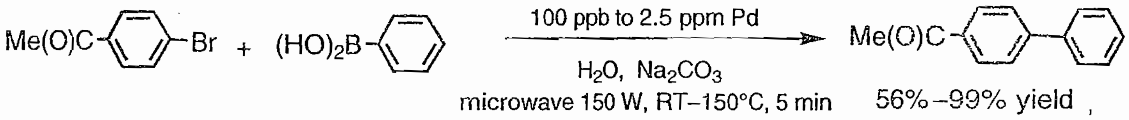
(16.16)

conducting the reaction with extremely small amounts of palladium.[23] Nicholas Leadbeater, who initially proposed that the reaction could be carried out even without palladium under microwave conditions, later found out that it was the palladium impurities present in ppb quantity in the commercial Na_2CO_3 that brought about the Suzuki (as well as Sonogashira and Heck) coupling under microwave conditions.[24]



(16.17)

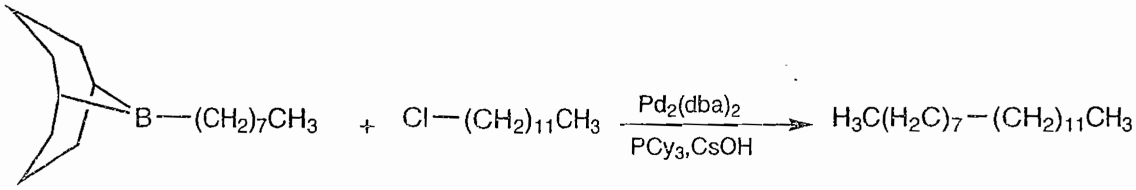
ionic liquid: Ist use 81% yield
4th use 82% yield



(16.18)

56%–99% yield

The following examples show how the Suzuki reaction has been extended further to coupling between two unactivated primary or secondary alkyls and between alkyl and aryl groups. Nickel based catalysts along with amine bases are often required for these reactions.[25]



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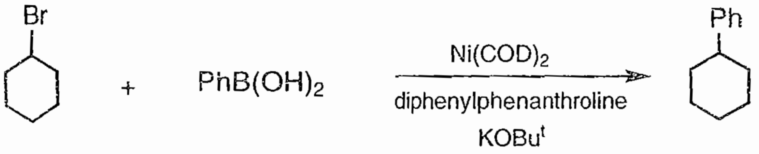

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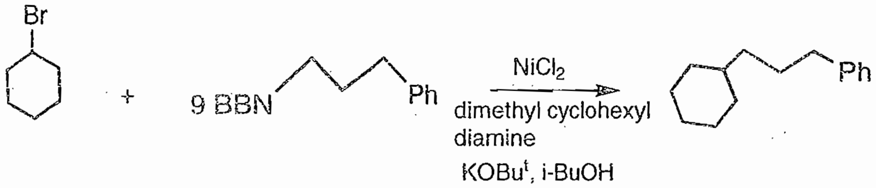
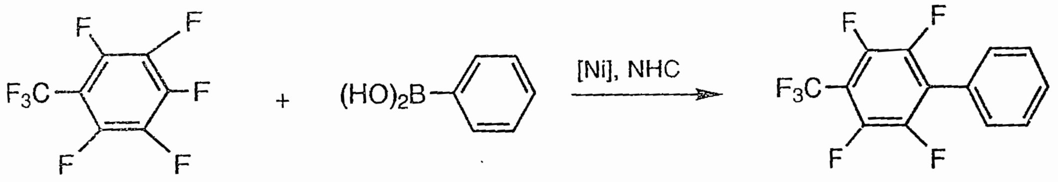


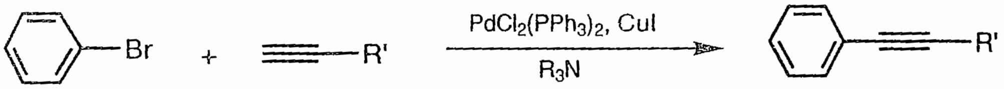
(16.21)

For a long time, aryl fluorides seemed inaccessible for Suzuki coupling. The first example of Suzuki cross coupling reaction involving perfluorinated arenes was reported in 2006 by Udo Radius and his coworkers.[26] There has been a great interest among chemists ir C–F bond activation reactions, in part to synthesise fluorinated drug analogues. The ver strong C–F bond helps modulate the lipophilicity of a drug to improve its bioavailabilit and helps control drug metabolism. So far, most cross coupling reactions have involve converting monofluorinated arenes into nonfluorinated derivatives, while fluorinated aren products have remained elusive. Radius's group has developed a Ni catalyst stabilised b N-heterocyclic carbene ligands, that selectively activates the C–F bond para to the electro withdrawing CF_3 group in perfluorotoluene or C_6F_5 group in perfluorobiphenyl. The catalyst then mediates coupling of the intermediate with a phenyl or biphenyl boronic acid to form polyfluorinated biphenyl or triphenyl products.



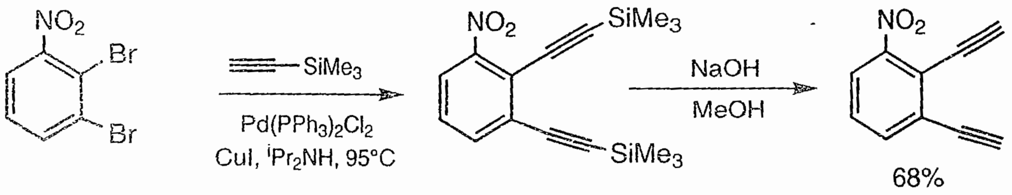
(16.22)

16.6 SONOGASHIRA COUPLING



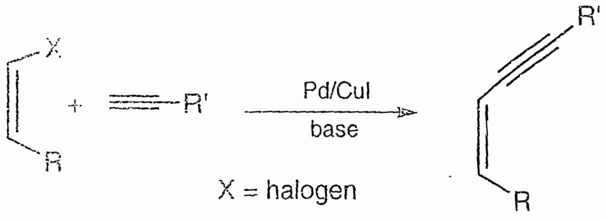
(16.23)

This coupling of terminal alkynes with aryl or vinyl halides is performed with a Pd catalyst, a Cu(I) cocatalyst and an amine base. Typically, the reaction requires anhydrous and anaerobic conditions, but newer procedures have been developed where these restrictions are not important. In the Sonogashira reaction, alkynylcuprate, formed by the reaction of copper with alkyne, reacts further with a palladium catalyst (Scheme 16.4). The reaction is very similar to Castro-Stevens coupling where cuprous acetylide is coupled with aryl halides in the presence of a base under drastic conditions. The Sonogashira reaction usually uses mild conditions, often room temperature, and therefore it can tolerate the presence of a large number of functional groups. Sonogashira coupling of trimethylsilyl alkyne followed by treatment with a strong base or a fluoride source is a common strategy used for introducing terminal alkyne groups.[4, 27–29]



(16.24)

If the Sonogashira reaction is performed on a haloalkene, the geometry about the double bond is usually preserved, making this an extremely useful reaction for the synthesis of enyne molecules with specific geometry. The reaction provides a method for making even conjugated acetylenic compounds—an important class of molecules that have found application in diverse areas ranging from natural products and pharmaceuticals to molecular organic materials (example, molecular wires) in nanoscience.



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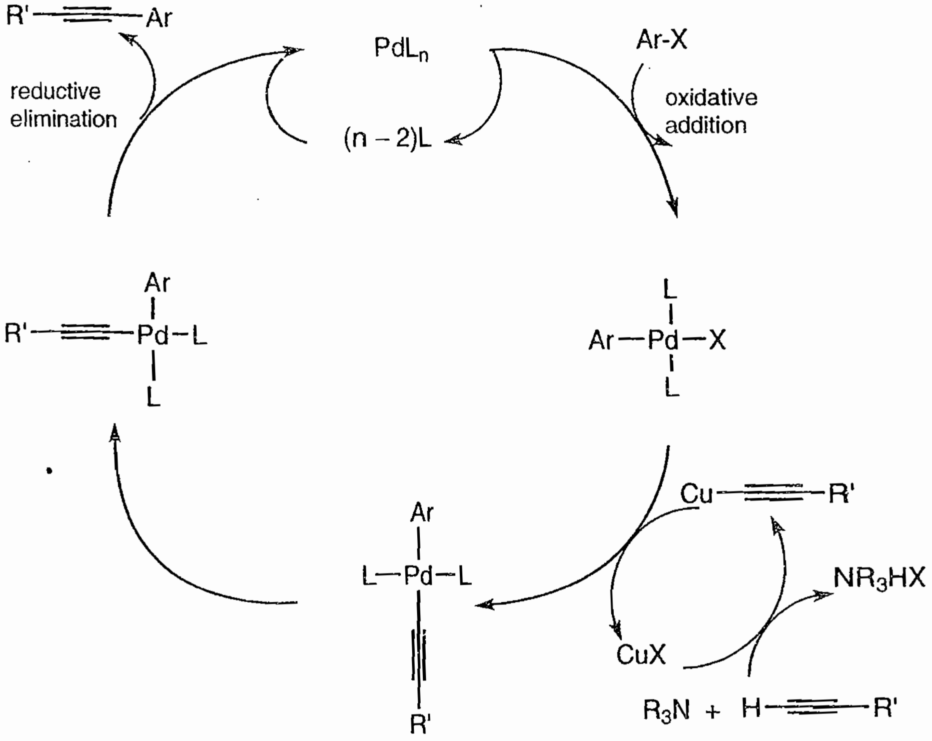
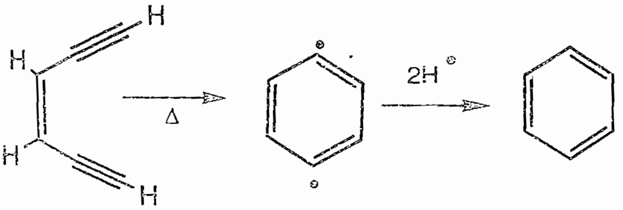


Scheme 16.4 Catalytic cycle for Sonogashira coupling

The Sonogashira coupling has found use in the synthesis of (Z)-enediynes, which are useful substrates in Bergman cycloaromatisation reactions (Eq. 16.26), named after Prof. Robert G Bergman. Although he was not the first to report arene formation from (Z)-enediynes, he was the first to propose and prove the existence of 1,4-aryldiradical intermediates in 1972. The reaction was largely ignored till the 1980s when the enediyne class of anticancer drugs was discovered. Cycloaromatisation occurs when a (Z)-enediyne is heated; the 1,4-diradicals formed cleave the H radicals in their vicinity and form an aromatic ring. The diradical can even abstract chlorine atoms from CCl_4 to form *p*-dichlorobenzene and with dissolved oxygen it can form quinones.

The Sonogashira reaction has also been extended to unactivated alkyl bromides (Eq. 16.27) using NHC ligands such as IAd (see Chapter 4).[30]



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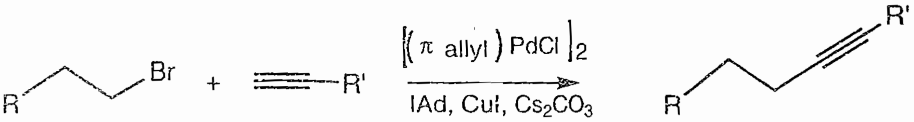


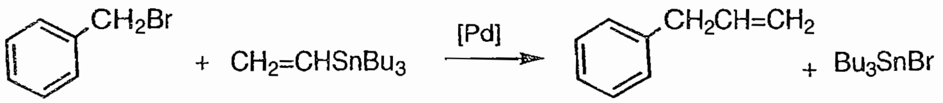
(16.27)

16.7 STILLE COUPLING

Palladium catalysed cross coupling reactions involving organotin based reagents and organohalides are referred to as Stille coupling reactions. The organometallic reagent may in some cases be completely aliphatic, but coupling can still occur as shown below.[31–34]

$$R^1X + R^2SnR^3_3 \xrightarrow{PdL_2} R^1{-}R^2 + R^3_3SnX \qquad (16.28)$$

X = Br, I, OSO_2CF_3, OAc, Cl (when L = PBu^t_3)
R^1 = acyl, alkenyl, aryl, allyl, benzyl
R^2 = alkynyl, alkenyl, aryl, allyl, benzyl, acetonyl
R^3 = Me, n-Bu



(16.29)

This reaction – introduced by J K Stille in 1971 – between stannanes and halides or pseudohalides, has very few limitations on the R groups. The toxicity of the tin compounds used and their poor solubilility in water due to their low polarity are the main drawbacks of this reaction compared to Suzuki coupling. This has limited its use in pharmaceuticals.

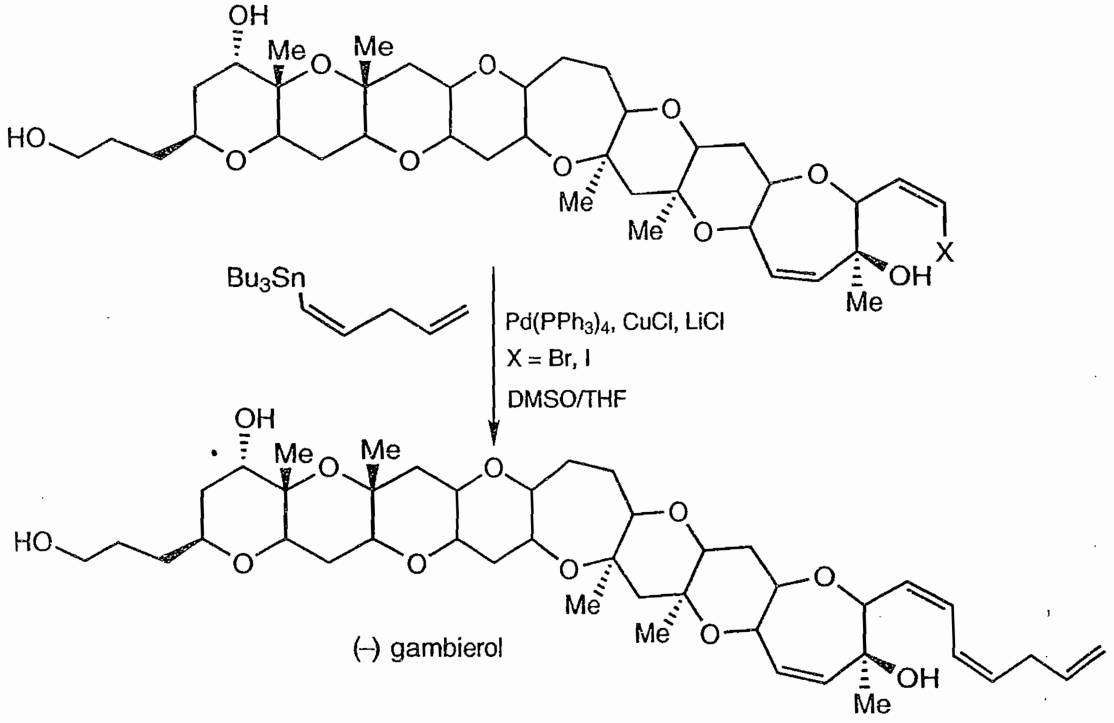
Unlike Suzuki coupling, no activation of the organostannyl reagent is required. The R group of the halide covers a broad range but should preferably not have β-hydrogens as this will initiate β-hydrogen elimination instead of reductive elimination. The organostannane, however, can have β-hydrogens present (see step 3 in the catalytic cycle, Scheme 16.6). Unlike in Suzuki coupling, no base is required for this reaction. A wide range of functional group tolerance is also observed and the halide substrate with NO_2, CN, OMe, COOR, COOH and even CHO groups are tolerated. The presence of air also does not affect the reaction.

Gambierol, a neurotoxin, which has a 6,6,6,6,7,6,6,7-polycyclic ether skeleton including 18 stereocenters and a triene side chain, was isolated from the cultured cells of *Gambierdiscus toxicus* (a species found attached to some form of marine algae).[35] Modified Stille coupling with additional reagents such as CuCl and LiCl was successfully applied for the construction of the triene side chain in the laboratory synthesis of this compound (Scheme 16.5). Stille coupling facilitates the reactions without protection of the three hydroxyl groups.

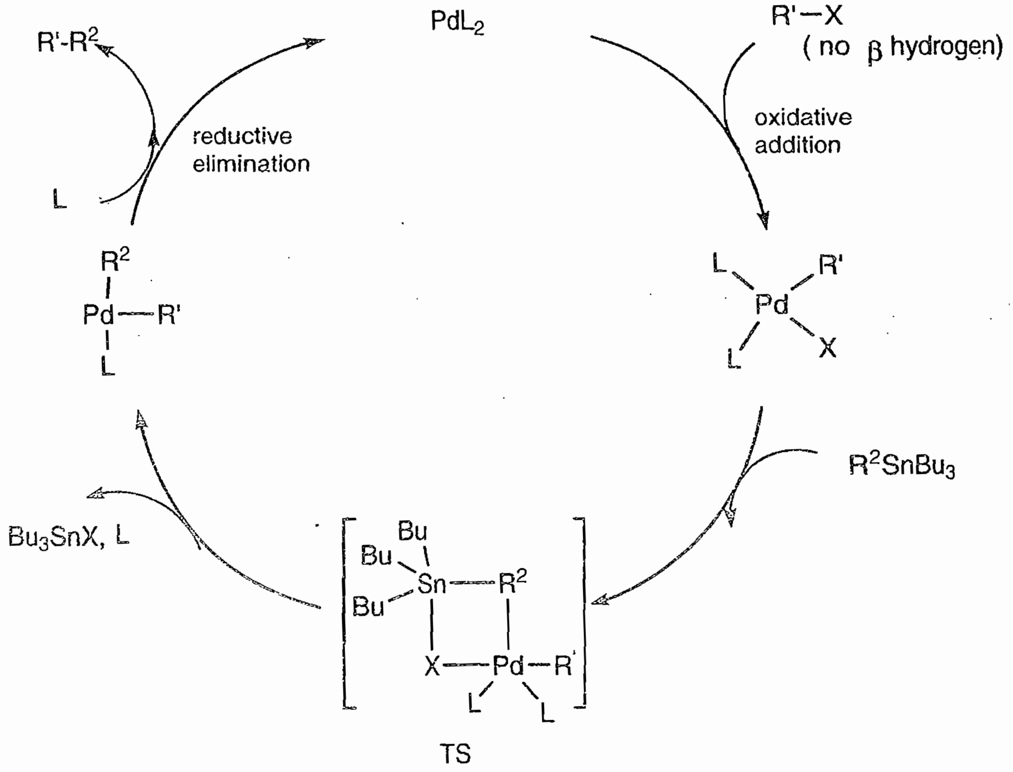
The mechanism of Stille coupling (Scheme 16.6) has been subjected to detailed investigations. A cyclic transmetallation as an associative process has been proposed which leads to the exchange of L for R^2 and forces retention of configuration. An open mechanism cannot be ruled out especially on halide containing complexes.

16.8 KUMADA COUPLING

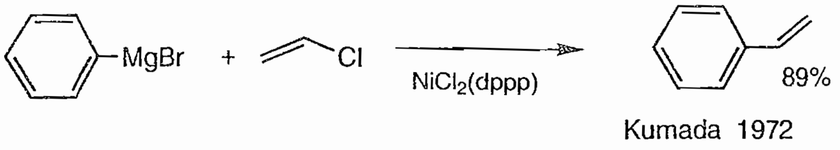
Kumada coupling or Kumada–Corriu coupling is the nickel or palladium catalysed cross coupling reaction between an alkyl, aryl, vinyl halide or triflate and aryl, alkenyl or alkyl Grignard reagents. The reaction type was reported independently by two groups in 1972.[2,36]



Scheme 16.5 Stille coupling step in the synthesis of (–)gambierol



Scheme 16.6 Catalytic cycle for Stille coupling



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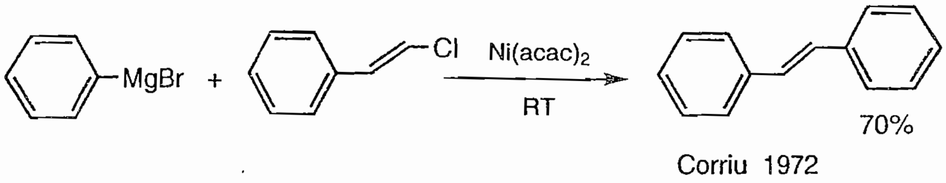
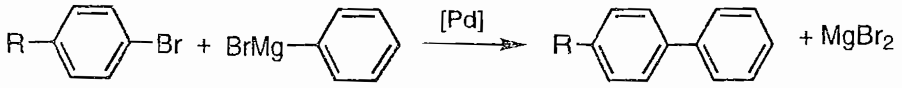


(16.31)

The reactivity of the halides follows the order I > Br > Cl when Pd is used as catalyst, whereas with certain Ni catalysts, the order is Cl > I > Br. The reaction is important since it gives access to styrene compounds (example, *cis*-stilbene). Kumada coupling has been developed based on two earlier reports—coupling of Grignard reagents with a catalytic amount of silver halide and stoichiometric Grignard coupling.

(Z)-Alkenyl-Grignard reagents couple non-stereospecifically with nickel catalysts, but the reaction is stereospecific with palladium catalysts. The phosphine ligand also has a strong influence on the yield. For example, bidentate ligands generally bear a higher activity than monodentate phosphines and bis(diphenylphosphino)propane is optimal for most reactions. Palladium catalysts were introduced to this chemistry by Murahashi in 1975.[37] He found that palladium(0), similar to the Ni catalysed reaction, was able to catalyse the reaction of alkyl and aryl Grignard regents with aryl and alkenyl halides.

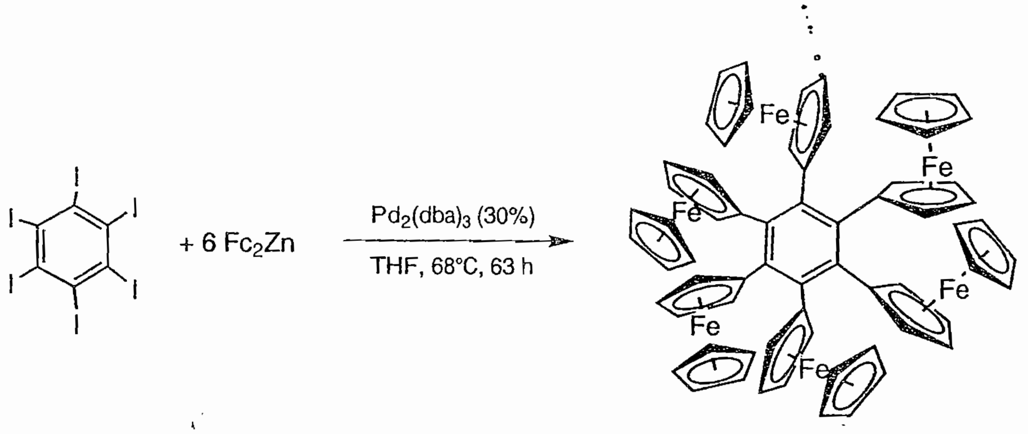


(16.32)

The application of the Kumada coupling reaction is somewhat limited because of the incompatibility of Grignard reagents with certain functional groups. However, recently, the scope of this reaction has been extended to aryl–aryl coupling with improved functional group tolerance.

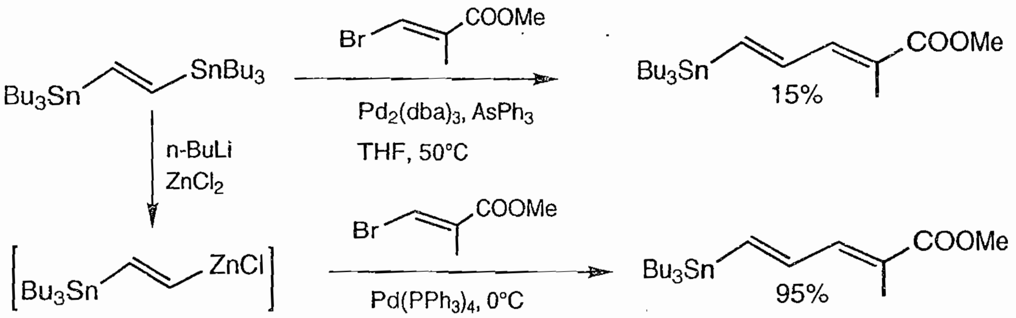
16.9 NEGISHI COUPLING

The Negishi coupling is a cross coupling reaction that involves an organozinc compound, an organic halide and a nickel or palladium catalyst and creates a new carbon–carbon covalent bond. Coupling of heterocyclic rings is often done using this method. The Negishi coupling, reported in 1977, was the first reaction that allowed the preparation of unsymmetrical biaryls in good yields.[38] The active catalyst in this reaction is Pd(0) and the reaction in general proceeds through an oxidative addition of the organic halide, followed by transmetallation with the zinc compound and finally, reductive elimination. This versatile reaction has broad scope, and is not restricted to the formation of biaryls. Both organozinc halides and diorganozinc compounds can be used as starting materials. Well known compounds prepared by exclusive use of Negishi coupling include pentaferrocenylcyclopentadienylmanganese tricarbonyl, $[(\mathrm{Fc})_5\mathrm{C}_5]\mathrm{Mn}(\mathrm{CO})_3$ and hexaferrocenyl benzene (Eq. 16.33).[39, 40]



(16.33)

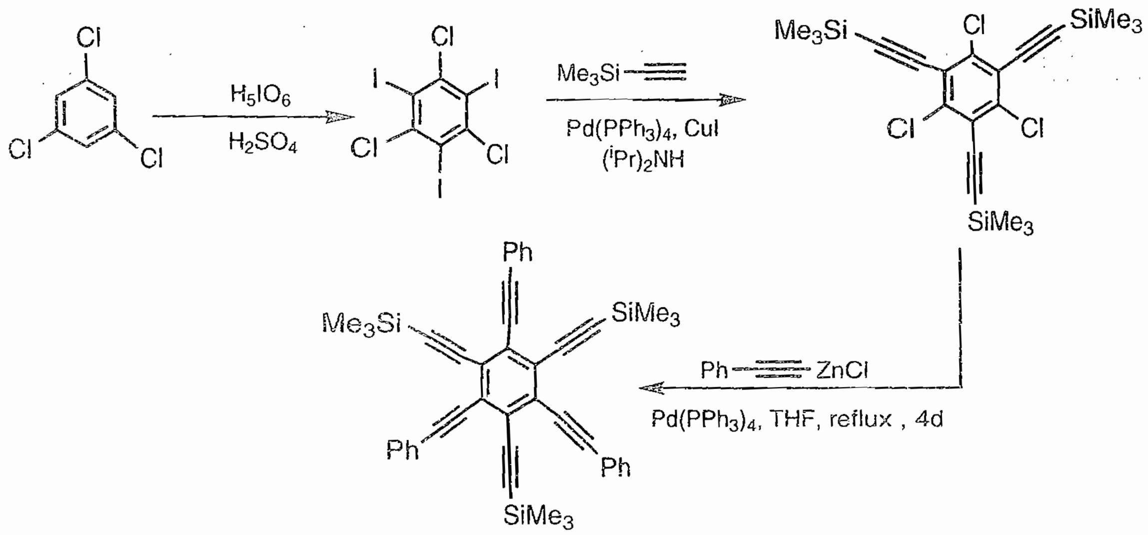
The palladium catalysed alkenylation coupling under Negishi conditions has been one of the most sought after cross coupling protocols along with Suzuki coupling. Negishi coupling is often preferred over Stille coupling for alkenylation as shown in the following example.[41]



(16.34)

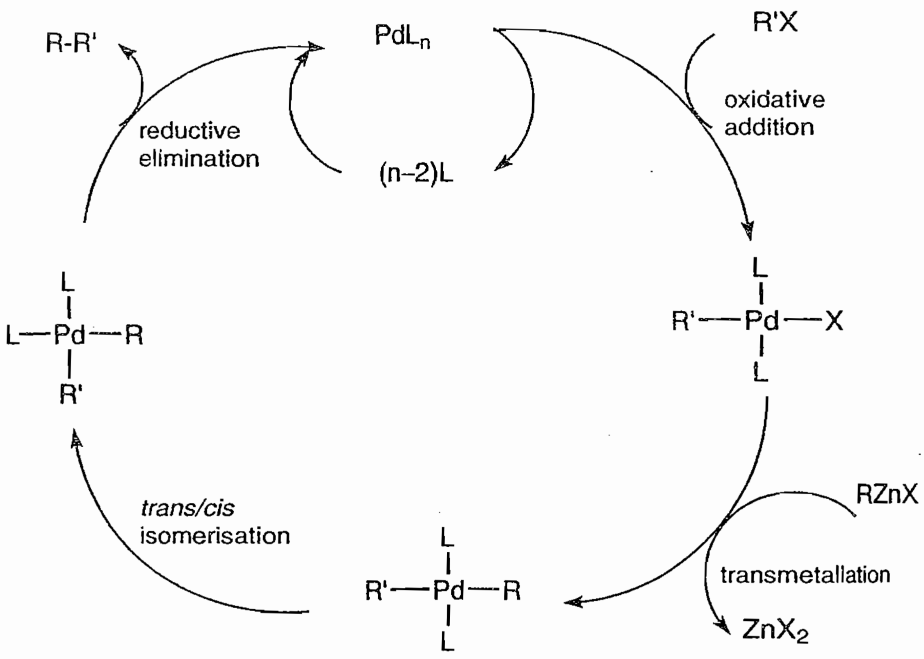
(16.35)

Negishi coupling also has an upper hand over Sonogashira coupling in many reactions. For example, Sonogashira coupling occurs preferentially on aryl iodides but aryl chlorides (activated to some extent by the substituted alkynyl groups) can be made to undergo further alkynation by Negishi coupling (Eq. 16.36). Cyanuric chloride ($C_3N_3Cl_3$) also undergoes alkynation readily under Negishi conditions to give the trialkynyl derivative.[42]



(16.36)

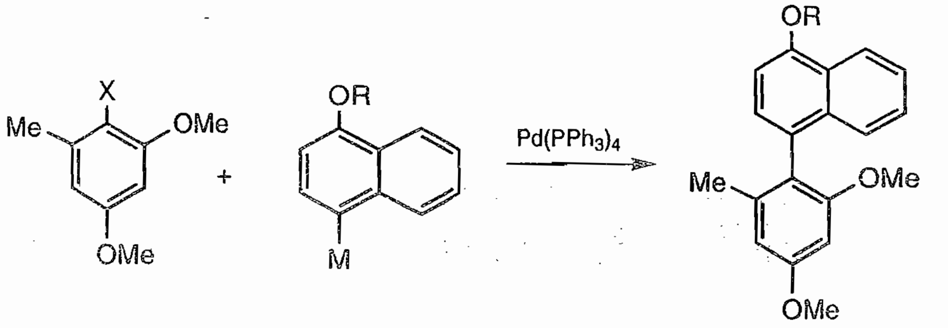
The mechanims of Negishi coupling and Kumada coupling are quite similar (Scheme 16.7). Both involve oxidative addition of RX to the Pd(0) catalyst followed by transmetallation



Scheme 16.7 Catalytic cycle for Negishi coupling

of RZnX or RMgX on the palladium. *Trans* to *cis* isomerisation followed by reductive elimination gives the coupled product.

A comparison of some of these reactions under similar conditions points to the advantage of the Suzuki method over the Stille and Negishi reactions.[43]

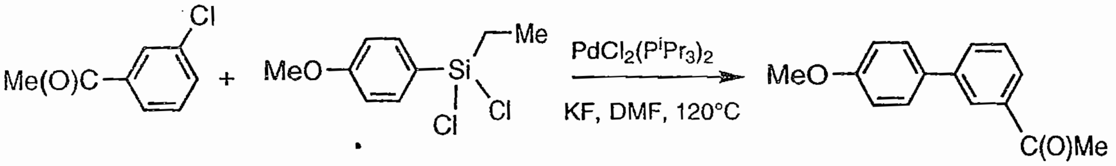


(16.37)

X	M	Conditions	% Yield
Br	$SnBu_3$	PhMe-reflux	0
I	$SnBu_3$	PhMe-reflux	0
Br	$B(OH)_2$	PhMe-Na_2CO_3-reflux	56
I	$B(OH)_2$	PhMe-Na_2CO_3-reflux	73
Br	ZnCl	THF-reflux	16
I	ZnCl	THF-reflux	50

16.10 HIYAMA COUPLING

Hiyama coupling is the Pd-catalysed C–C bond formation between aryl, alkenyl, alkyl halides or pseudohalides and organosilanes.[44] This reaction is comparable to the Suzuki coupling but it requires an activating agent such as the fluoride ion or a base. The polarisation of the Si–C bond is important for the success of Hiyama coupling. Therefore, the first necessary step is the activation of the silane with a base or fluoride ion that leads to a pentavalent silicon compound.



(16.38)

The reaction rate is also increased by using silanes with the fluoro or alkoxy group instead of alkyl. In fact, there are only a few examples of successful coupling reactions with trimethylsilane derivatives.

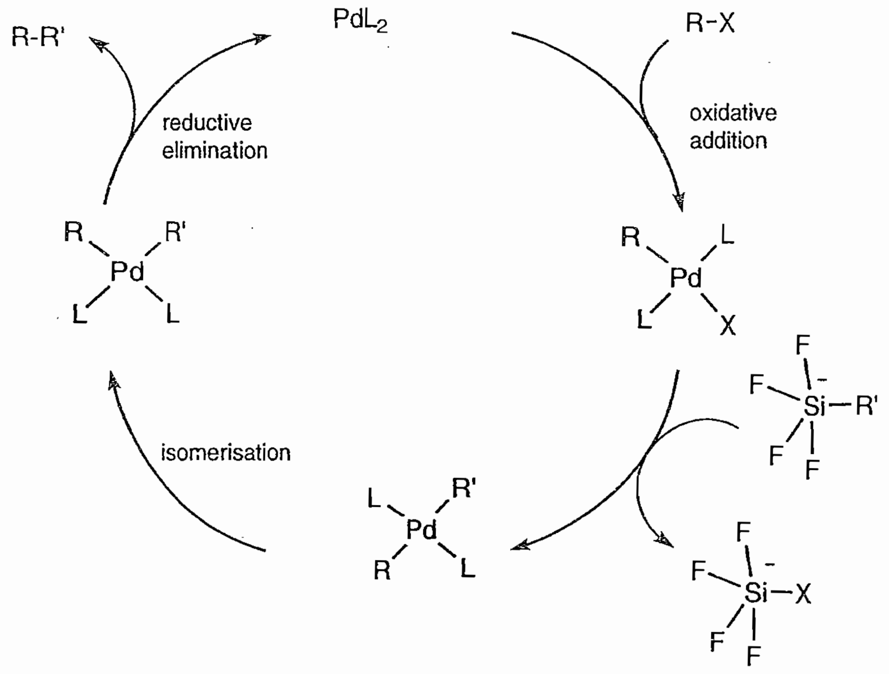
Hiyama couplings were first reported by Yasuo Hatanaka and Tamejiro Hiyama in 1988. They reacted 1-iodonaphthalene with trimethylvinylsilane and obtained 1-vinylnaphthalene. The catalyst used was allyl palladium chloride dimer dissolved in HMPA and TASF [tris(dimethylamino)sulphonium difluorotrimethylsilicate] reagent was used as the fluoride source. Organosilanes are stable compounds with low toxicity and can be easily prepared. Many improvements in the reaction conditions have been reported which has made Hiyama coupling an interesting alternative to the Suzuki coupling and it offers a comparable scope for conversions. However, the commercial availability of boronic acids and boronates currently makes the Suzuki coupling a more convenient choice. The Hiyama coupling possesses advantages such as low environmental impact, high atom efficiency and safe handling compared with the coupling reactions of organoboron, organozinc or organotin compounds.

The reaction proceeds through oxidative addition, transmetallation, ***trans–cis*** isomerisation and reductive elimination sequence (Scheme 16.8) The purpose of the fluoride ion is to activate the conversion of silicon compound $RSiR'_3$ to a pentacoordinate $[RSiR'_3F]^-$ intermediate which is more amiable to transmetallation. Without the added fluoride, the organosilicon compound is simply too stable. Reactions in which the fluoride ion is replaced by a strong base have also been reported for Hiyama coupling (Eq. 16.39).[45, 46]

$$\mathrm{ArSi(OR)_3} + \mathrm{Ar'{-}Br} \xrightarrow[\mathrm{H_2O,\ polyethyleneglycol,\ 60°C}]{\mathrm{Pd(OAc)_2,\ 3\ eq.\ NaOH}} \mathrm{Ar'{-}Ar} \tag{16.39}$$

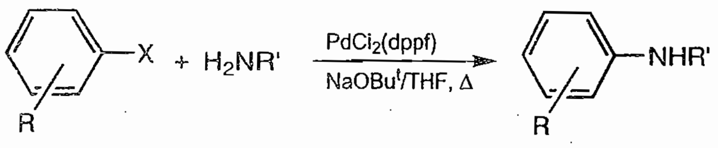
16.11 BUCHWALD–HARTWIG C–N CROSS COUPLING

The coupling of an aryl halide with an amine forms aromatic amines. This reaction was made practical by Pd based catalytic systems and was developed almost simultaneously by Stephen L Buchwald of MIT and John F Hartwig of Yale University in 1995.[47, 48]



Scheme 16.8 Catalytic cycle for Hiyama coupling

Before their method, no general reaction for the conversion of aryl halides into aromatic amines was available. This reaction has a profound effect on drug discovery as many drugs are aromatic amine derivatives. Although initially this reaction worked with aryl bromides and iodides, the use of bulky phosphines made the reaction work well with aromatic chlorides as well.[49]

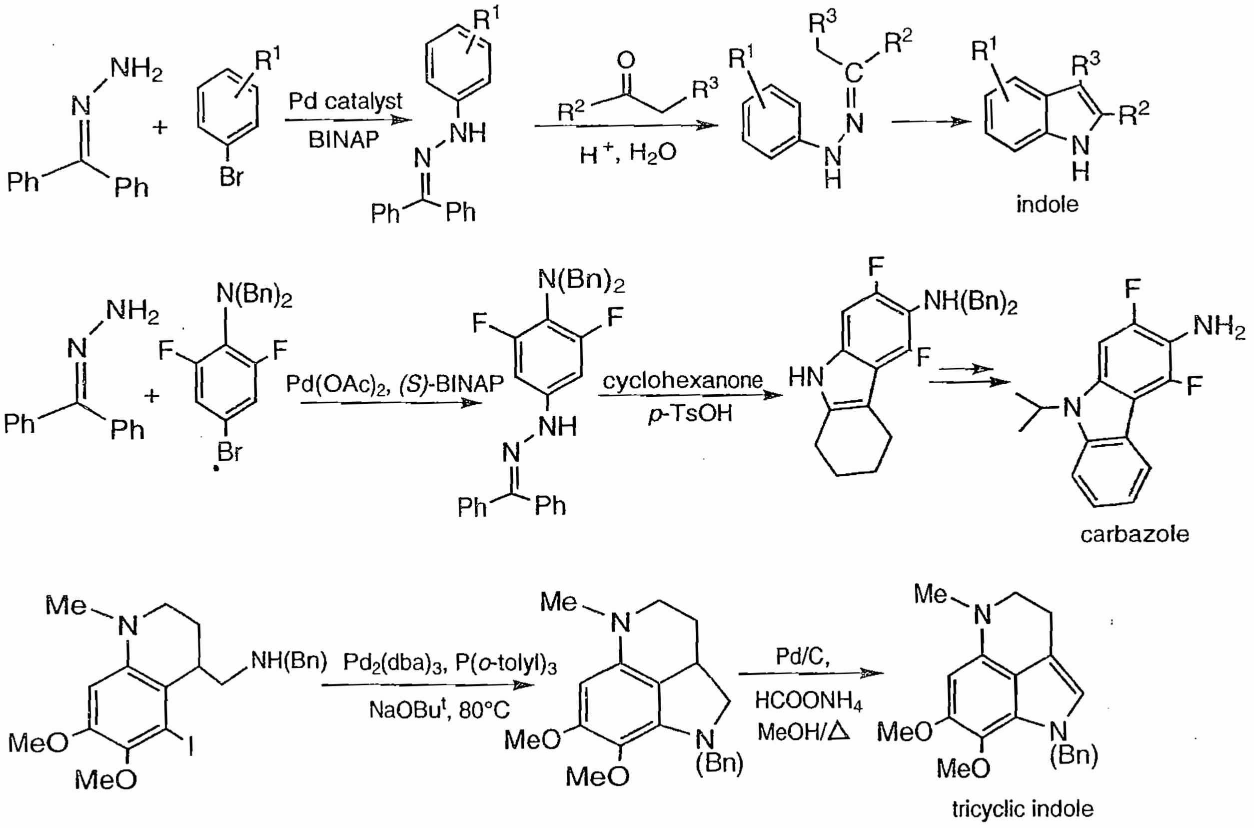


(16.40)

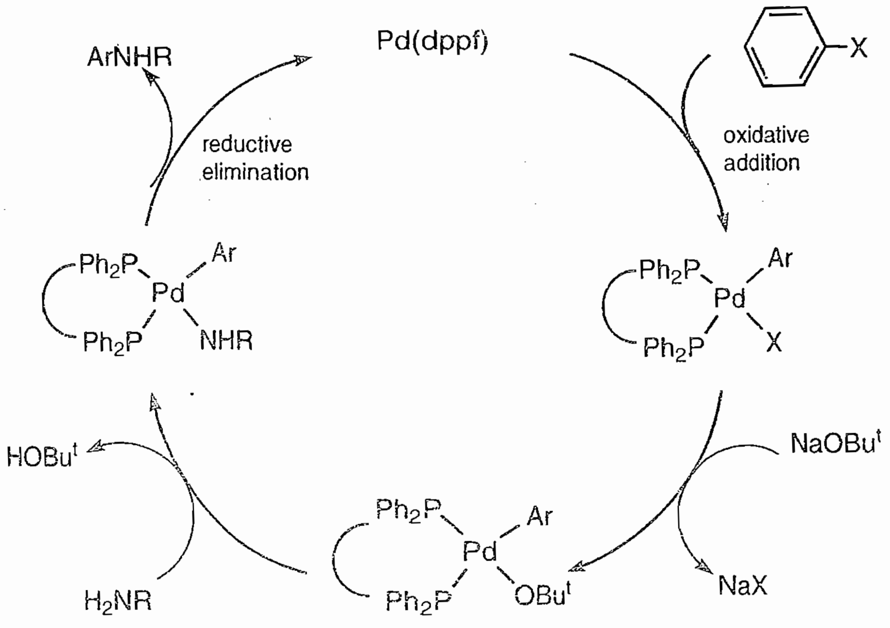
X= Br, I, OTf; R = alkyl, CN, C(O)Ph, $C(O)NEt_2$; R' = alkyl, aryl

This reaction has been used in the synthesis of many natural products and nitrogen containing heterocycles even on an industrial scale. In 1999, Buchwald described a very simple one pot synthesis of indoles using benzophenone hydrazone and an aryl halide. Using this protocol, an analogous synthesis of carbazoles was achieved by the pharmaceutical company AstraZeneca. A tricyclic indole was also synthesised using Buchwald–Hartwig coupling which is a precursor to natural products such as Makaluvamine C and Damirone A and B (alkaloids found in marine sponges).[50]

The catalytic system contains four components to generate the desired C–N bond. The palladium precursor is typically stabilised in solution by an adequate ligand which increases the electron density at the metal to facilitate oxidative addition and is also sufficiently bulky to accelerate reductive elimination of the product. A base is required to deprotonate the amine substrate prior to or after coordination to the palladium centre (Scheme 16.10). The



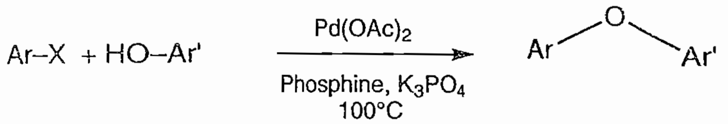
Scheme 16.9 Synthesis of indoles and carbazoles by Buchwald–Hartwig coupling



Scheme 16.10 Catalytic cycle for Buchwald–Hartwig C–N cross coupling

solvent also plays a prominent role in this reaction as compared to other cross coupling processes due to the heterogeneous nature of the reaction and it also takes care of the solubilities of the base and the substrate.

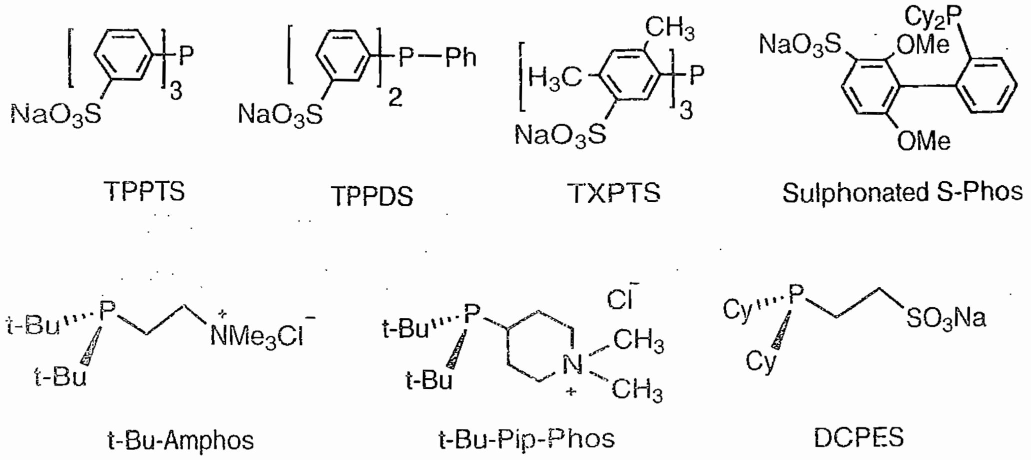
A variation of this reaction is also available for C–O cross coupling reactions.[51, 52]



(16.41)

16.12 Cross Coupling Reactions in Aqueous Media and with Functional Group Tolerance

Water is an often sought after replacement for organic solvents as it is inexpensive, nontoxic and nonflammable besides allowing easy separation of the organic product from an aqueous biphasic reaction mixture. The functional group tolerance shown in many Pd catalysed cross coupling reactions has prompted synthetic chemists to attempt reactions even in water medium and on fragile, biologically important molecules having a host of functional groups. An important feature of cross coupling reactions conducted in aqueous medium is the requirement of water soluble phosphines and catalysts. While $Pd(OAc)_2$, $Pd(NO_3)_2$, $PdSO_4$, Na_2PdCl_4 and $PdCl_2(CH_3CN)_2$ work well as water soluble palladium compounds, a variety of phosphines have been synthesised specifically for this purpose. Most of them have either a sodium sulphonate group or an amine hydrochloride group bound at a distance to the trivalent phosphorus centre. A list of water soluble phosphines used in such cross coupling reactions is given below.[53]



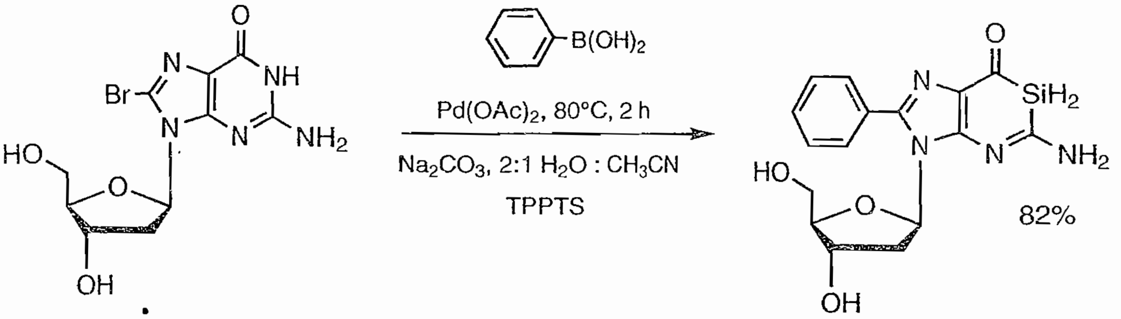
TPPTS TPPDS TXPTS Sulphonated S-Phos

t-Bu-Amphos t-Bu-Pip-Phos DCPES

Fig. 16.2 Water soluble phosphine ligands used in cross coupling reactions

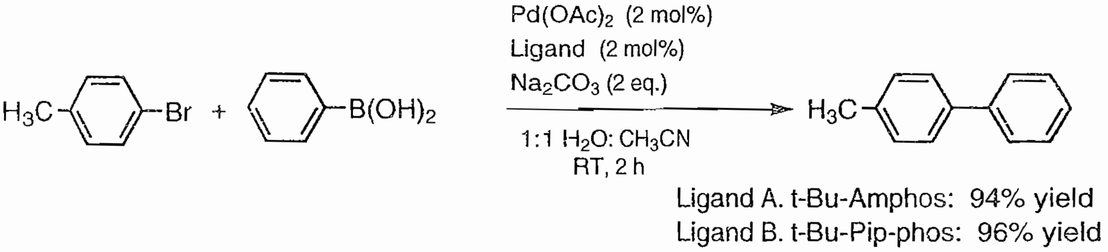
Interesting results on functional group tolerance have been observed in the synthesis of non-natural nucleosides. C-modified nucleosides show significant antiviral and anticancer activity and also serve as model compounds for studying DNA modifications caused by carcinogens. A host of functional groups are present in these molecules and normally one has to protect them before the C-arylation is carried out and then deprotect them later.

But, by using water soluble phosphines such as TPPTS and TXPTS, Suzuki coupling can be carried out without protecting the functional groups. Very good yields of the C-aryl nucleosides are obtained using TPPTS/ $Pd(OAc)_2$ conditions as shown below. The reaction can also be extended to unprotected halopurine bases, halonucleosides, nucleotides and nucleoside triphosphates.[54]



(16.42)

While TPPTS and related ligands typically require aryl iodide or activated aryl bromide substrates and moderately high temperatures, by using t-Bu-Amphos or t-Bu-Pip-phos along with Pd salts, Suzuki coupling on unactivated aryl bromides can be performed at room temperature. These reactions can be carried out in pure water, water–acetonitrile or water–toluene biphasic mixture media. The added advantage is that the catalyst derived from t-Bu-Amphos can be recycled up to three times without any decrease in catalytic activity. Heck and Sonogashira coupling was also possible using t-Bu-Amphos at 80°C and 50°C respectively in aqueous medium.[55]



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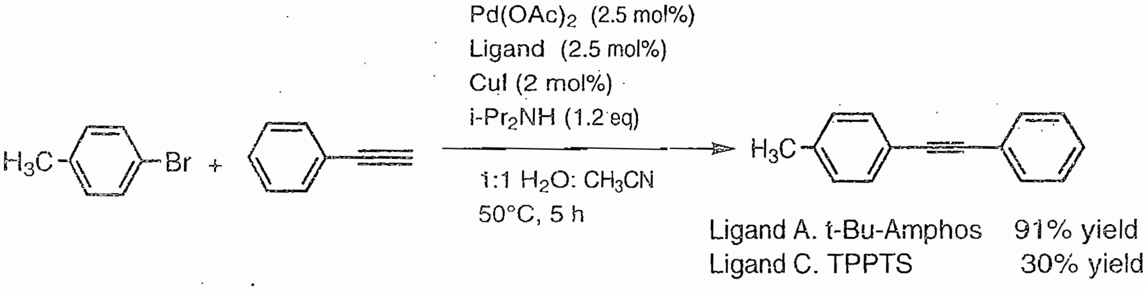


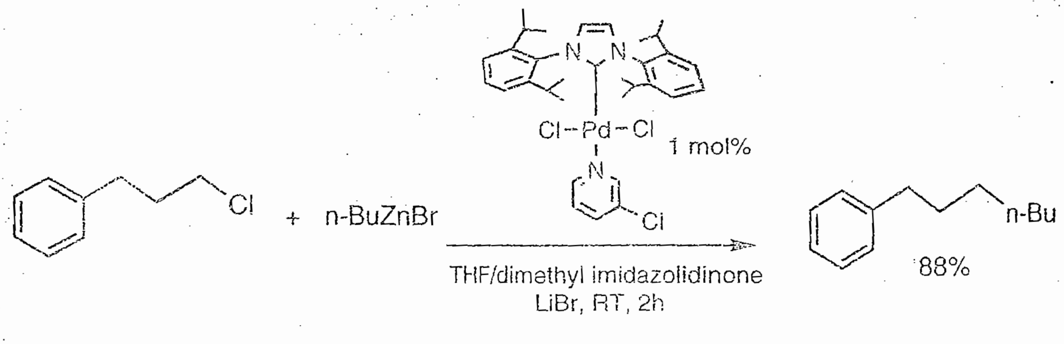
(16.44)

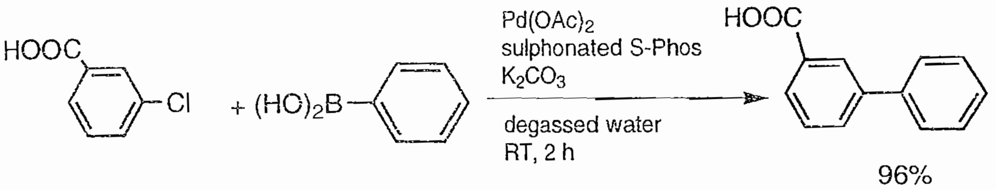
Using Buchwald's sulphonated 2-(phosphinyl)biphenyl ligand, Suzuki coupling of aryl chlorides in aqueous solvents under mild conditions can be carried out. This ligand was also successfully applied to Sonogashira coupling of aryl chlorides and bromides and was the first catalytic system to couple a deactivated aryl bromide with propiolic acid.

NHCs in cross coupling reactions: The PEPPSI catalysts[56]

A major initiative in cross coupling reactions in recent years has been on replacing costly and air sensitive phosphines with N-heterocyclic carbenes (NHCs) on the palladium catalyst. NHCs are good σ donors with high basicity and form bonds to metals which are stronger than that of the most electron rich phosphines. While phosphines and NHCs are electronically similar, there is a major difference in their topology when coordinated to a metal. While the three substituents on a phosphine project backwards, the substituents on the nitrogen of NHCs project forward to form a pocket around the metal. There are many advantages of using NHCs as ligands instead of phosphines in Pd-mediated reactions. The strong σ donor ability of NHCs results in the palladium centre which is capable of undertaking oxidative addition onto bonds that are otherwise resistant to oxidative addition (groups such as alkyl halides and aryl chlorides). The steric bulk of the NHCs facilitates reductive elimination similar to bulky phosphines and the strong Pd–NHC bond and limited catalyst decomposition pathways ensure that the metal is kept in a soluble and catalytically active state with only a single NHC attached.

Some of the best examples of user friendly, very active and highly air and moisture stable NHC based palladium catalysts appear under the title 'PEPPSI catalysts'. These catalysts are easily prepared and are suited for intermolecular cross coupling reactions, aminations and intramolecular Heck transformations even at the industrial scale. Mike Organ of York University and coworkers developed these elegant palladium catalyst systems in 2006 by reacting $PdCl_2$ with bulky NHC ligands and 3-chloropyridine in air. The title PEPPSI™, stands for *Pyridine-Enhanced Precatalyst Preparation Stabilisation and Initiation*. After a systematic study on a variety of NHC ligands, it was found that the IPr NHC ligand is most effective and efficient in enabling high catalyst performance. The 3-chloropyridyl ligand functions as a 'throw-away' ligand providing added stability to the precatalyst and gets removed when the active catalyst is formed. The bulky IPr ligand improves reductive elimination of the substrate which in turn increases the TONs. Many reactions occur at room temperature without the need for additional ligands. Unlike traditional palladium catalysts, these can be stored indefinitely outside an inert atmosphere and can even be subjected to a water workup without observable decomposition. Most impressively, the PEPPSI-IPr catalyst has been heated in DMSO at 120°C for hours without decomposition and deactivation of the catalyst. The Pd(II) complex becomes active in situ through reduction to the Pd(0)–NHC active catalyst. PEPPSI-IPr is a highly efficient and mild catalyst for forming alkyl–alkyl bonds under Negishi conditions as illustrated below. Couplings mediated by this catalyst sp^3(RX)–sp^3(RZnX) include a wide spectrum of functionalities such as esters, nitriles, amides and acetates.





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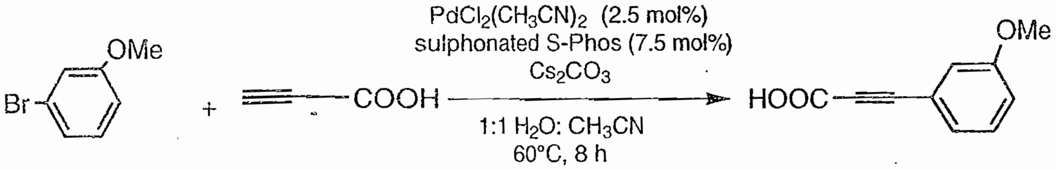


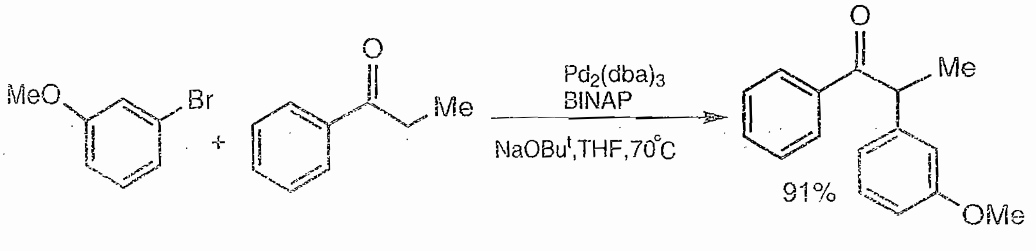
(16.46)

16.13 CROSS COUPLING REACTIONS OF ORGANOHALIDES WITH NON-ORGANOMETALLIC AND NON-HETEROATOM BASED REAGENTS

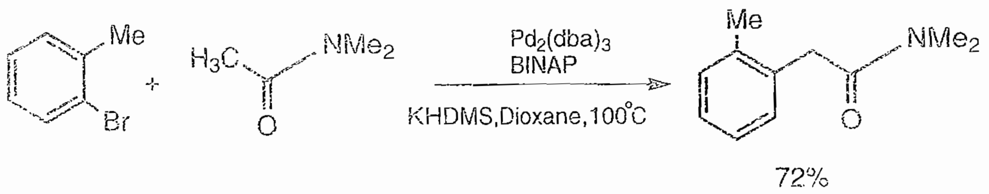
There have also been some significant developments in palladium catalysed cross coupling reactions where the conventional organometallic or heteroatom-based coupling partner has been replaced with entirely organic reactants. The most well known among these reactions are the palladium catalysed α-arylation of carbonyl compounds and decarboxylative cross coupling reactions.

Palladium catalysed α-arylation of carbonyl compounds[57]

In this reaction, an enolate coupling partner generated from a carbonyl compound (ketone, ester, amide or aldehyde) having an α(sp^3) C–H unit and a base is treated with an aryl halide or pseudohalide in the presence of a palladium(0) catalyst. A C(sp^3)–C(sp^2) coupled product is obtained through cleavage of a C–H bond. The palladium catalysed reaction was reported for the first time simultaneously by Buchwald, Miura and Hartwig in 1997.[58–60] The α-arylation was also found to occur on nitriles in place of the carbonyl compounds.



(16.47)

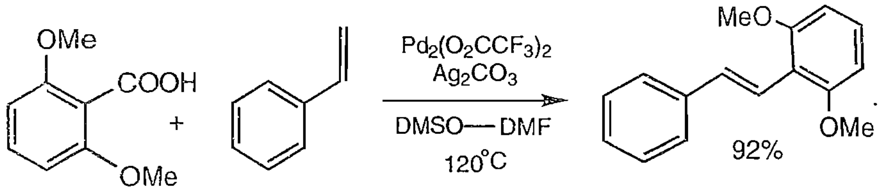


(16.48)

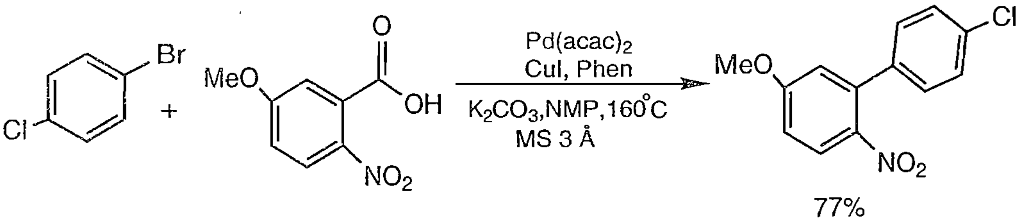
Decarboxylative cross coupling reactions

In 2002, Myers reported a palladium catalysed reaction in which decarboxylative cross coupling was carried out between an aryl carboxylic acid and styrene in the presence of silver carbonate as an added salt.[61] The reaction was later extended by Goossen to aryl halides with

CuI as a co-catalyst in 2006.[62] In 2012, a decarboxylative cross coupling where both coupling partners were carboxylic acids was also reported.[63]



(16.49)

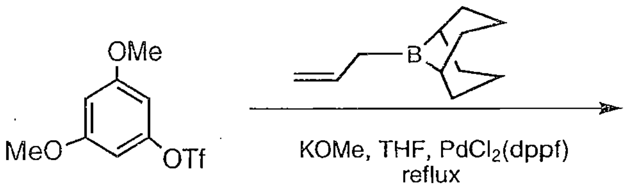


(16.50)

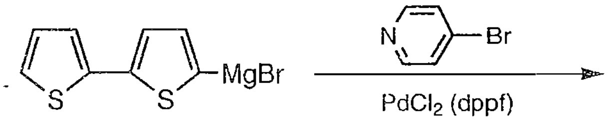
Problems and Exercises

16.1. Name the reaction and draw the structure of the product formed in the following reactions.

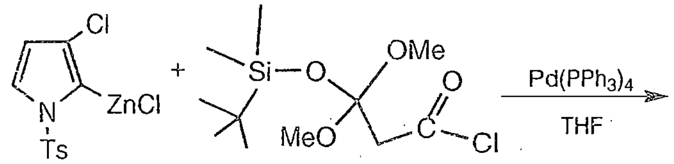
(a)



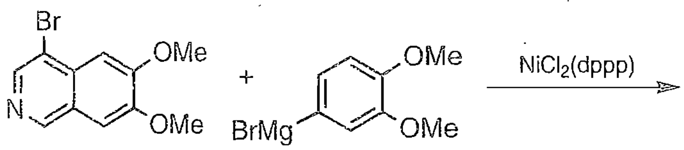
(b)



(c)



(d)



16.2. Give four basic differences between the Suzuki and Stille coupling reactions.

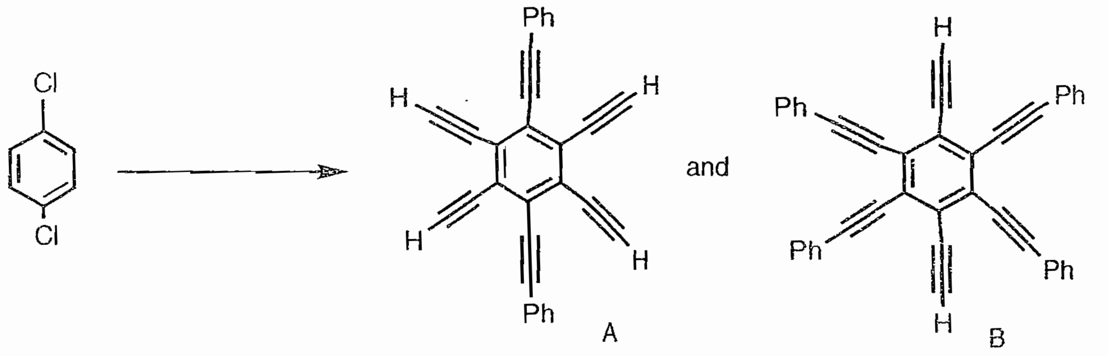
16.3. Provide two basic mechanistic differences between Heck coupling and other Pd catalysed Suzuki, Sonogashira, Stille and Negishi coupling reactions.

16.4. Although tin and silicon belong to the same group, they show mechanistic differences in the Pd catalysed Stille and Hiyama coupling reactions. Indicate the major difference between the two in their reaction mechanisms.

16.5. In what way do the Kumada, Negishi and Stille coupling reactions differ from the Suzuki, Sonogashira and Hiyama coupling reactions in terms of parameters required for coupling reactions?

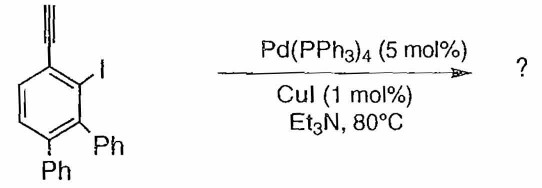
16.6. Similar to amines, phosphines and organometallic reagents, an alkene bound to a Pd(II) halide can also reduce it to an active Pd(0) species during cross coupling reactions. Provide a mechanism for this reduction.

16.7. Starting with 1,4-dichlorobenzene, suggest synthetic routes with minimum number of steps for making the following hexaalkynyl benzene derivatives.

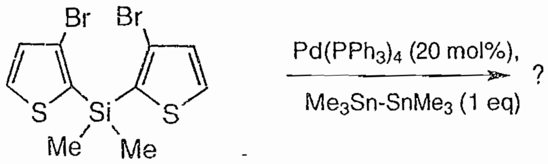


16.8. Predict the product in the following reactions.

(a)

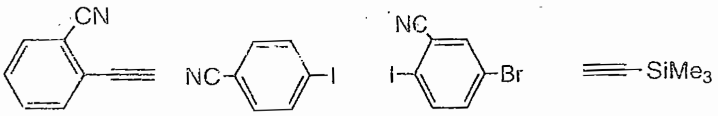


(b)

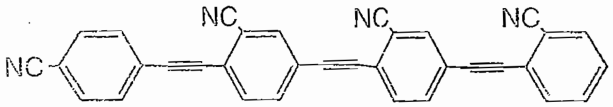


16.9. Using the following reagents, suggest a synthetic route with the minimum number of steps for the cyanoaryl oligomer shown. Show the reagent and reaction conditions at each step.

Reactants

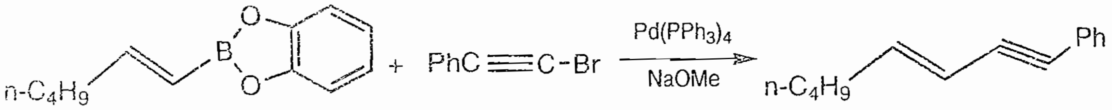


Product



16.10. Identify and name the reaction in the following transformations.

(a)



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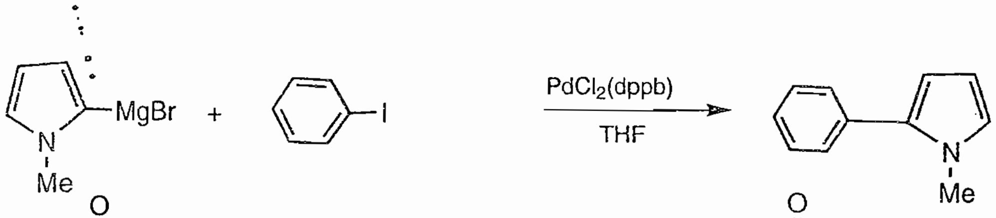

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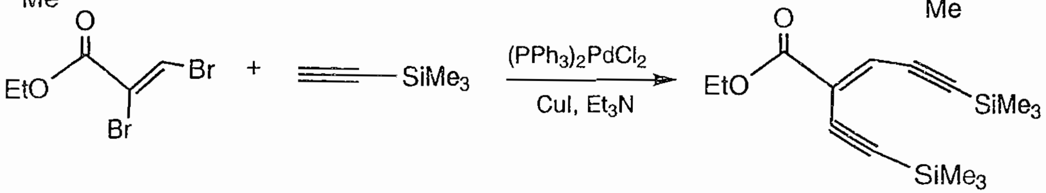

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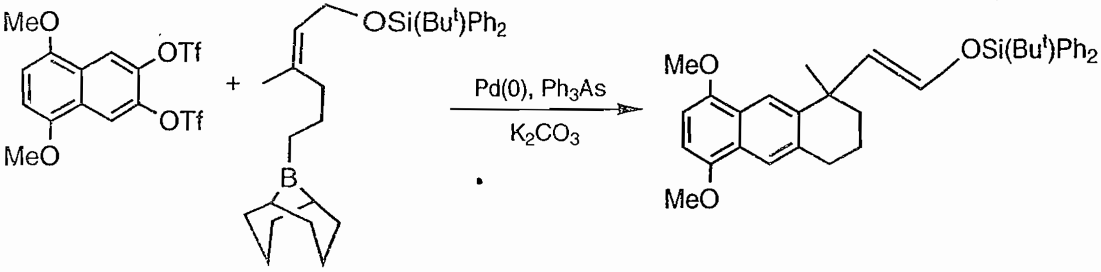
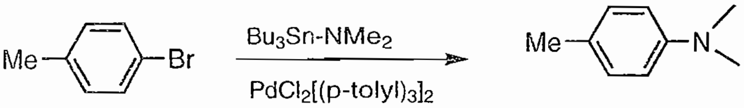
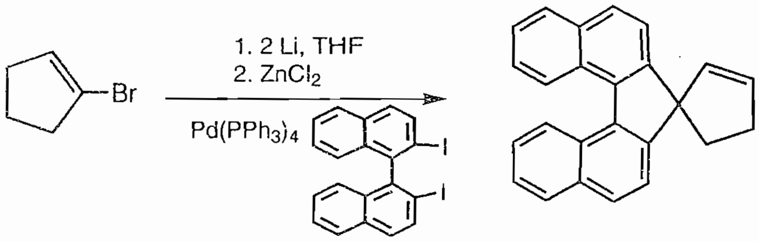


(e)

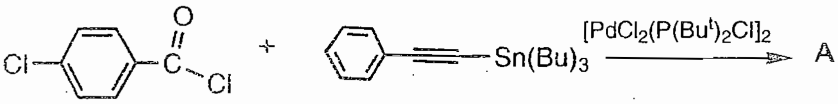


(f)



16.11. Name the reactions as well as the products in the following reactions.

(a)



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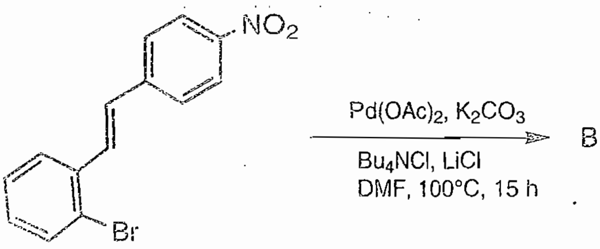
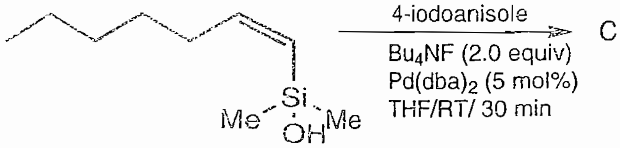
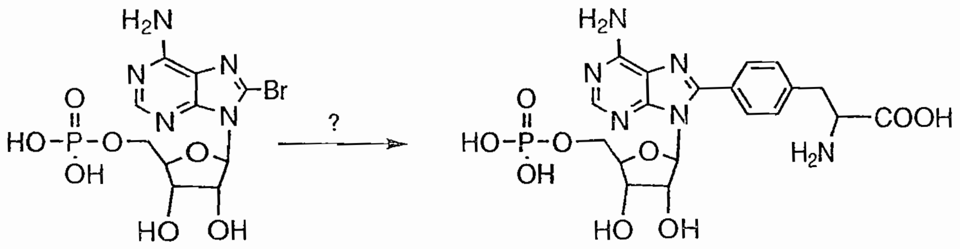


(c)



16.12. Suggest reactants and reagents to bring about the following reactions.

(a)



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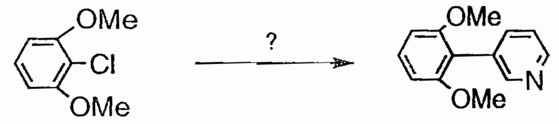
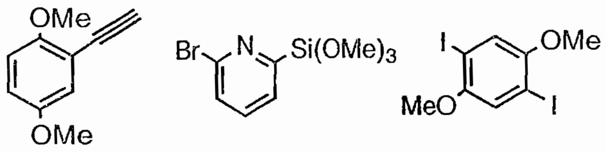
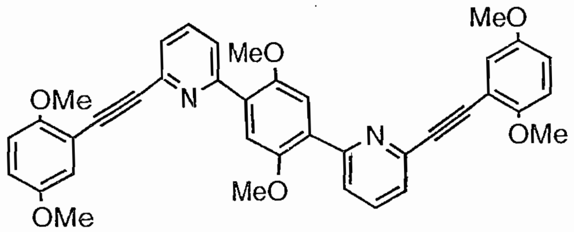


16.13. Using the given reactants, suggest a possible synthetic route specifying reagents for realising the product shown. Name the type of reaction occurring at each step.

Reactants



Product



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CHAPTER 17

OLEFIN POLYMERISATION AND OLIGOMERISATION REACTIONS

Polyethylene and polypropylene are two of the most important and widely used materials in the modern world. More than 125 million tons (2008) of these two polymers, along with other polyolefin materials are produced around the world and are by far the most important class of synthetic polymers. The annual demand for polyethylene alone is approaching 50 million tons and represents about 35 billion US dollars in sales. It is expected to grow by about 5% a year.

Discovery of polyethylene[1, 2]

The story of polyethylene began in 1932. The industrialised world was in deep recession following the Wall Street crash of 1929. It was difficult to find money for large scale research. At the Imperial Chemical Industry, England (ICI), a research program was started to look for new reactions under high pressures using different gases. Fifty different reactions were tried, all without success—but one of the failures resulted in the discovery of polyethylene through a series of coincidences. One of the suggested mixtures had included ethylene, a very light gas. The reaction hoped for had not occurred, instead, there was a white waxy solid on the walls of the reaction vessel. Analysis showed that this must have formed from the ethylene alone. In 1935, the reaction was tried again without the other components, but this time the vessel leaked; nevertheless, some polyethylene was obtained. When the process was carried out under very stringent conditions there was no polyethylene! It was only after months of work that they realised that oxygen had to be present in some form, either from air leaking in, or, as in the first experiment, indirectly from having reacted with the other component of the original mixture. These two slipups had allowed the first polyethylene to be produced.

There are various methods for making polyethylene and polypropylene. One of the widely used polymerisation methods uses a free radical initiator, a peroxide. Generally, the polymerisation of ethylene to polyethylene using an organic peroxide as free radical initiator requires about 100 atm of pressure and a temperature of around 100°C. One of the useful applications of organometallic chemistry is the polymerisation of alkenes at atmospheric pressure and ambient temperature using organometallic catalysts.[3]

17.1 CATALYSTS FOR OLEFIN POLYMERISATION

Vast quantities of polyethylene and polypropylene along with a host of similar polymers are made by using a variety of catalysts. Currently, the most well known catalysts that are exclusively used for olefin polymerisation reactions can be classified as follows.

(i) Ziegler–Natta catalysts (heterogeneous catalysts known since 1955).[4]

(ii) Metallocene based catalysts (homogeneous single site catalysts known since 1980).[5]

(iii) Post metallocene catalysts such as
   - late transition metal based catalysts (mainly having Ni, Fe and Pd) with high activity for copolymerisation of ethylene with polar comonomers and having control over polymer topology (known since 1996),[6] and
   - FI and related early transition metal based catalysts with high activity (complexes of Ti group metal chlorides with ligands such as phenoxy imine, known since 1999).[7]

17.2 TYPES OF POLYETHYLENE AND POLYPROPYLENE

Polyethylene and polypropylene polymers are further classified into different types. It is important to know and understand the different types of these polymers before we look into the role of the catalyst suited to make them.

17.2.1 Polyethylene

Various polymer properties can be realised through a control of the microstructure of the polymer backbone, which influences the polymer morphology and the observed physical properties of the polymer. The type of application of the polymers also varies depending upon their structure and properties. Polyethylene can be of many different types with varying densities, molecular weights, tensile strengths, viscosities, melting points and glass transition temperatures. Table 17.1 provides general information on some of the different types of polyethylene available for end use.

17.2.2 Polypropylene

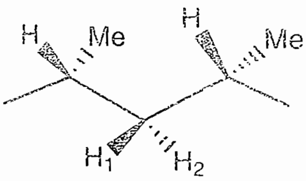
While stereoregularity is seldom important with polyethylene, it is the most important property which differentiates polypropylenes. Polymers with a stereoregular backbone possess crystalline morphology, high densities and high melting points. The first synthetic polymer with a stereoregular backbone to be synthesised and characterised was polypropylene. The broad scope of the applications of polypropylene has led to the design of its stereocontrolled syntheses.

The stereoregular nature is determined by the position of the methyl side groups along the main chain $[-CH_2-CH(Me)-]_n$. This means that the neighbouring methyl groups in the polypropylene chain can have two stereoisomeric positions with respect to each other.

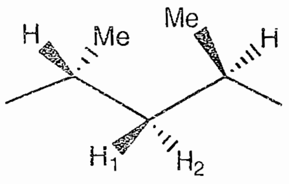
Table 17.1 Types of commercially available polyethylene and their properties

Low density polyethylene (LDPE)	It contains short and long branches and is prepared by older methods such as free radical polymerisation. Used in liners, consumer bags, heavy duty sacks, lamination films and agricultural films. m.p: 105–115°C, T_g: -40°C, viscosity: 0.017 MPa.s (density: 0.910 to 0.940 g cm^{-3}).
High density polyethylene (HDPE)	It is an ethylene homopolymer without branching and with crystallinity. This is known as linear polyethylene by scientists. It was first made using the Ziegler–Natta catalyst and later by using the Kaminksy and FI catalysts. m.p: 123–128°C, T_g: –120°C, viscosity 0.275 Mpa.s (density: 0.941 to 0.965 g cm^{-3}).
Medium density polyethylene (MDPE)	This is an ethylene polymer with a *limited* amount of comonomer, it has more flexibility and is ideal for making tubes. It is called lightly branched polyethylene by scientists. Only a limited quantity of other monomers can be incorporated this way. m.p: 117–123°C (density 0.926 to 0.940 g cm^{-3}).
Linear low density polyethylene (LLDPE)	It is a polymer made by a process that allows a greater amount of comonomer. The industrialist's term 'linear' signifies the absence of long chain branching which is present in LDPE. It is particularly well suited for applications that require both flexibility and strength, and where manufacturers seek to make bags out of plastic films that are strong, thin, tear resistant and puncture resistant. It is made by using Ziegler–Natta, Kaminsky and FI catalysts (density 0.915 to 0.925 g cm^{-3}).
Ultra high molecular weight polyethylene (UHMWPE)	The molecular weight is in the range of 3.5×10^6 to 6.0×10^6 g mol^{-1}. It has the highest sliding abrasion resistance (better than stainless steel and teflon) and the highest notched impact strength of any commercial plastic. It is made by using Ziegler–Natta and Kaminsky catalysts but the best is by using FI catalysts. It is used in the bottom part of skis and for making artificial joints. 1.4 million patients around the world use it every year for hip, knee, upper extremities and spine artificial parts. m.p: 144–152°C (density 0.930–0.935 g cm^{-3}).
Ultra low density polyethylene (ULDPE)	Ultra low density polyethylene or very low density polyethylene is made by copolymerisation of ethylene with short chain α-olefins using metallocene catalysts. The polymer is used for hose and tubing, ice and frozen food bags, food packaging and stretch wrap as well as impact modifiers when blended with other polymers (density ~0.880–0.905 g cm^{-3}).

The three stereo configurations that can be distinguished in polypropylene are: isotactic, syndiotactic and atactic. The *meso* and *racemic* terminology can be seen from the way the two protons of the CH_2 group experience the field.



H_1 and H_2 experience different field: *Meso* (*m*)



H_1 and H_2 experience same field: *Racemic* (*r*)

- Isotactic (iPP) have successive monomer units with the same configuration (*m, meso*).
- Syndiotactic (sPP) have successive monomer units with opposite configuration (*r, racemic*).
- Atactic (aPP) have a random order of configurations of monomer units (Fig. 17.1).

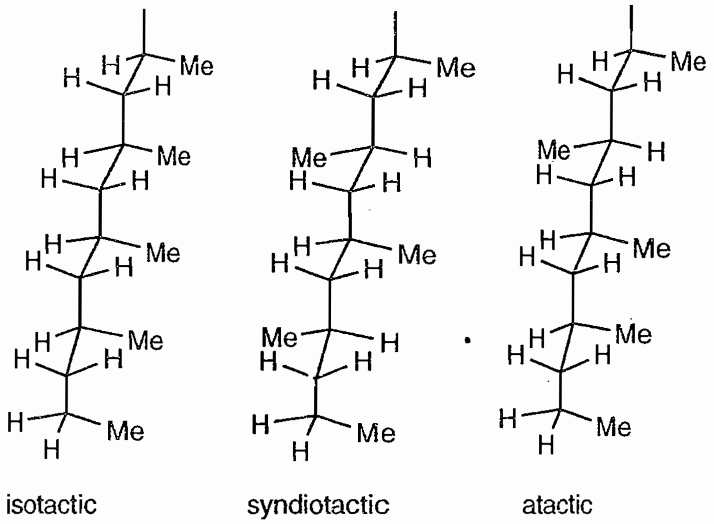


Fig. 17.1 Structurally different types of polypropylene

Isotactic polymers form helices to avoid steric repulsions between the substituents. sPP consists of a sequence of *r* relationships while iPP consists of purely *m* relationships. The classification is further based on the relative configurations between the monomer units; for example, the monomer units in a dyad is two (*m* or *r*), a triad is three (*mm, rr* or *rm*) and a pentad (ideally *mmmm* or *rrrr*) is five (Fig. 17.2).

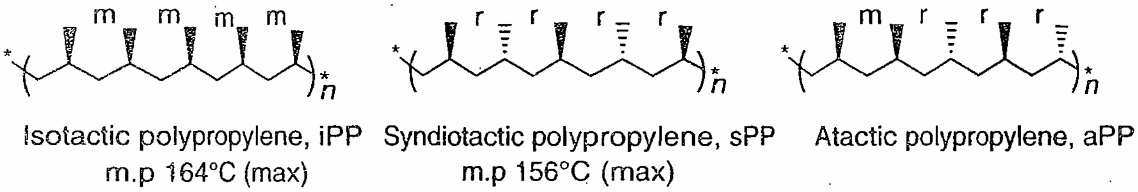


Fig. 17.2 Orientation of monomer units of pentads of iPP, sPP and aPP

^{13}C-NMR is the most commonly used tool to determine the degree of regularity within a polymer chain. Pentad content or the percentage of *rrrr* or *mmmm* in a steroisomeric polymer, which can be measured by ^{13}C-NMR, provides a more accurate description of the microstructure than does the dyad or triad content. A very high percentage of *mmmm* or *rrrr* in the ^{13}C-NMR indicates a polymer of higher isotacticity or syndiotacticity respectively. A high field NMR (> 300 MHz) is required to clearly differentiate between *mmmm, rrrr* and their various possible combinations.[8]

Ideally one expects ten different pentads in an atactic polymer since the polymer structure is random and one can expect all types of *meso/racemic* combinations (Fig. 17.3). However, two of these (*mmrm, rmrr*) have the same chemical shifts (see the middle peak in Fig. 17.3). The ^{13}C-NMR spectrum of atactic polypropylene, therefore shows nine signals.

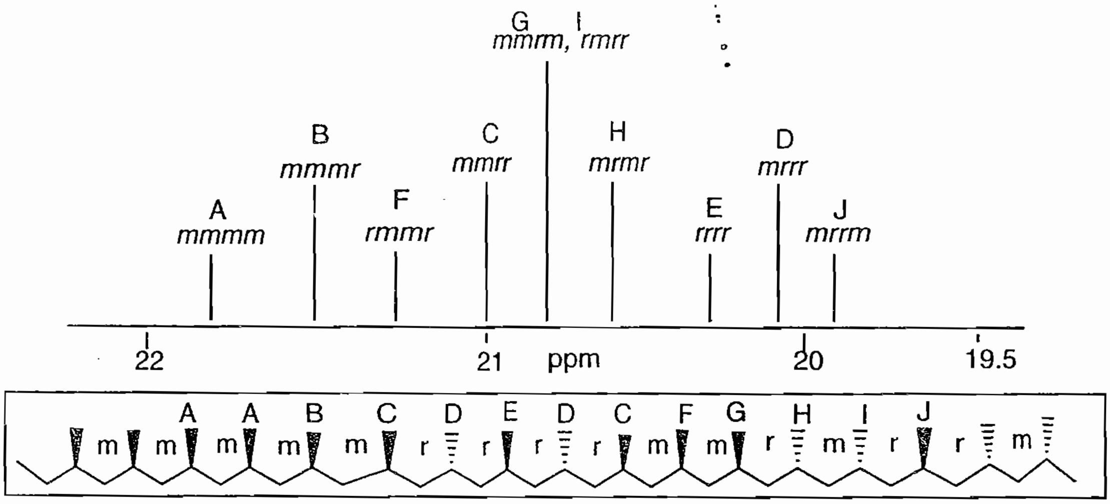


Fig. 17.3 ^{13}C-NMR spectral peaks of the methyl region (>300 MHz) of atactic polypropylene showing peak assignment of pentads

This spectral data is useful to follow up reactions and to determine if the polypropylene is isotactic, syndiotactic or atactic. For example, if one considers the first five methyl groups of the representative atactic polypropylene strand shown in Fig. 17.3, they are related to each other as *meso* and so the pentad is represented as *mmmm*; the chemical shift of the methyl groups of this pentad is seen around 21.8 ppm. Going down the strand, the seventh methyl group is oriented in the opposite direction generating two *racemic* (*r*) methylene groups on its left and right. Consequently, the pentad starting with the third methyl group is termed *mmmr* and it shows a chemical shift close to 21.5 ppm. By observing the ^{13}C-NMR of the polymer, it is possible to find out the types of pentads present and their relative intensities and determine the tacticity of the polymer. A polymer of very high isotacticity will be expected to have mostly *mmmm* pentads and should show a very strong signal corresponding to this pentad in its ^{13}C NMR. Similarly for a syndiotactic polypropylene, one expects a strong signal corresponding to the *rrrr* pentad whose chemical shift is close to 20 ppm.

17.3 THE ZIEGLER–NATTA CATALYST

In the 1950s, Ziegler and Natta showed that a binary mixture of titanium chloride and aluminum alkyl (example, $TiCl_4/Et_3Al$ and $TiCl_3/Et_2AlCl$) formed highly active heterogeneous catalysts for the production of linear HDPE and iPP. In 1953, Ziegler discovered that a hydrocarbon solution of $TiCl_4$ in the presence of $AlEt_3$ gave heterogeneous suspensions that polymerised ethylene at 1 atm and at moderate temperatures. Natta discovered that these catalysts also polymerised propylene and gave predominantly one stereoisomer, the iPP. Ziegler and Natta received the Nobel Prize in chemistry for their work in 1963. The well known mechanism for polymer chain growth on the Ziegler–Natta catalyst involves a simple migratory insertion reaction. This mechanism was proposed by Piet Cossee in 1964.[3,9]

An alternate mechanism involving a four membered metallacycle and an α-hydride elimination step was also proposed by Malcolm Green and John Rooney (known as the

Green–Rooney mechanism).[10] However, detailed deuterium labelling studies have shown that the migratory insertion mechanism is followed most often in olefin polymerisation using Ziegler–Natta catalysts. Polymerisation occurs at the edges or corners of crystallites where the metal atoms are necessarily coordinatively unsaturated (see Fig. 17.4 box). Also, in the formation of iPP it has been suggested that the methyl group of propylene avoids steric interaction with the methyl group of the polymer chain when it coordinates to the metal. Since it is a heterogeneous catalyst, the understanding of the actual mechanism is still only partial. In 1960, Natta and coworkers discovered that VCl_4 activated with Et_2AlCl produced sPP at −78°C. The different behaviour of Ti and V systems has been attributed to the difference in their reaction mechanisms. The vanadium based catalysts, however, have poor thermal stability and short catalyst life time and result in low productivity at the technically feasible process temperatures.[11]

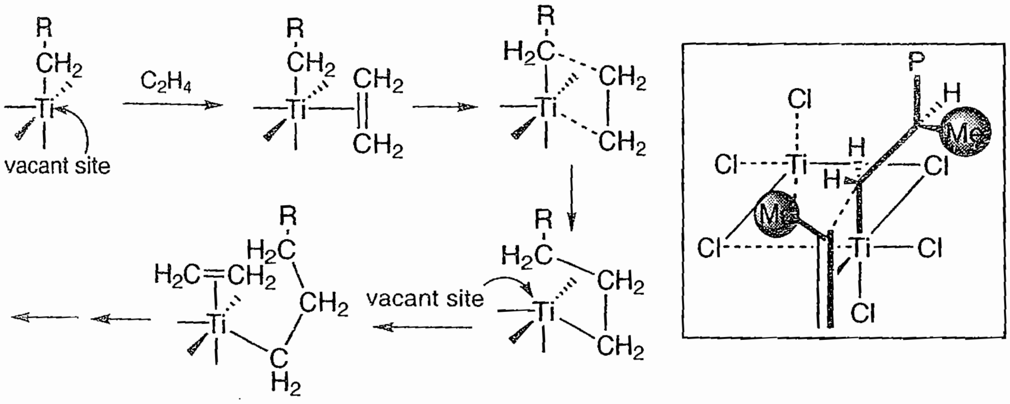


Fig. 17.4 Cossee mechanism for olefin polymerisation with active site of the catalyst shown in box

In 1960, modified Ziegler–Natta catalysts were developed for the polymerisation of propylene and these were based on $TiCl_4$ supported on $MgCl_2$. The Montecatini and Mitsui chemical company in 1968 independently patented this catalyst along with an electron donor which was further activated by trialkylaluminum (R_3Al).

Industrial plants based on these catalysts became operational in the 1980s. These new generation catalysts brought a 50-fold increase in activity and better isotacticity, so that the removal of the catalyst from the final product was no longer necessary. Industrially, even now a significant percentage of polyethylene and iPP are produced using the Ziegler–Natta catalysts.[12]

17.4 SITE CONTROL AND CHAIN END CONTROL MECHANISMS

Two mechanisms – site control and chain end control mechanism – are often used to understand stereo control in the polymerisation of propylene and similar monomers. As propylene is prochiral, a catalyst can bind to it through the *si* or *re* face. If the catalyst itself is chiral, then a pair of diasteromeric complexes is formed and the rate of migratory insertion of the two diasteromers will be different. When the catalyst adds to the same face of the next propene unit, iPP results. This kind of mechanism where the stereoregularity results from asymmetric catalysis is termed as site control mechanism. However, the interesting part is that there are many catalysts which do not have a stereogenic centre but still give stereoregular polymers. In these cases, stereo regularity results from chain end control process. In this mechanism, the last monomer inserted determines how the incoming prochiral alkene molecule should get inserted. This is because, after the first insertion has taken place, a stereogenic centre is formed on the carbon chain forcing the next alkene to add preferentially either with the *si* or *re* face (Fig. 17.5).[13, 14]

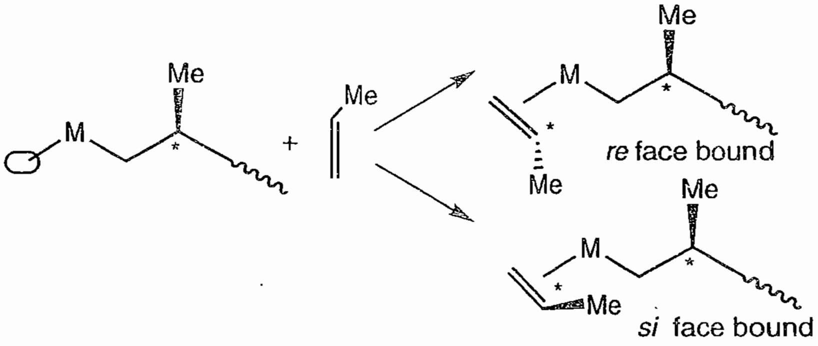
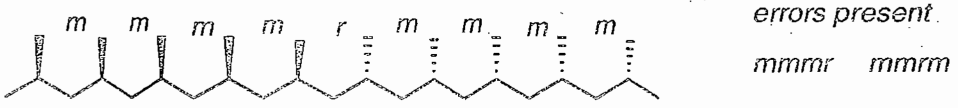


Fig. 17.5 Possible modes of addition of an alkene on a stereogenic metal centre

Though both these mechanisms operate, occasionally chain end control alone is sufficient to get enantiospecificity. These two mechanisms can be easily distinguished simply by looking at the mistakes that occur during polymerisation. For a chain end control mechanism, in a sequence of isotactic insertions (*mm*...) if a mistake (*r*) is made, this mistake will persist in the chain. The methyl groups will be oriented in the opposite direction and after one *r* the *m* comes back. In a site control mechanism, if a mistake occurs, it does not persist and the catalyst will return to produce the original configuration (this will involve two *r* units followed by *m* units, the second *r* corresponding to the return to the original direction of the methyl groups, Fig. 17.6). The ^{13}C-NMR of pentads will be different for both mechanisms as the error present in each case will be different as shown.

chain-end control mechanism (isotactic PP)



site control mechanism (isotactic PP)

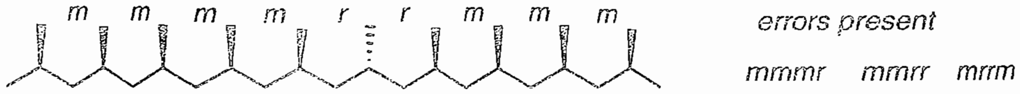


Fig. 17.6 Orientation of methyl groups in the polymer chain when chain-end control and site control mechanisms operate

17.5 METALLOCENE BASED CATALYSTS

One of the drawbacks of the Ziegler-Natta type catalysts is that the polymerisation reactions at the active site are influenced by the electronic and steric environment of the crystal lattice since the active metal centre occupies a position on the surface of the solid. Because the active centres can occupy a wide variety of lattice sites, they tend to give products with broad molecular weight distributions. Nonhomogeneous comonomer distribution is obtained in the case of olefin copolymers. So, the discovery of a homogeneous single site catalyst by Kaminsky et al. for the polymerisation of ethylene and propylene has indeed become a landmark discovery in this area.[15–24]

Homogeneous catalysts based on bis-cyclopentadienyl Ti and Zr dialkyls, first introduced by Breslow, were found to be inactive for olefin polymerisation. The breakthrough came from the work of Sinn and Kaminsky who were trying to isolate intermediates in Ziegler–Natta polymerisation by using bis-cyclopentadienyl complexes of Ti and Zr along with R_3Al. Trialkylaluminum compounds are highly sensitive to air and moisture and a coworker who accidentally allowed water to enter the system observed the formation of polyethylene in the reaction mixture. Systematic studies carried out later showed that Cp_2TiMe_2/Me_3Al system along with an equimolar ratio of water and Me_3Al showed a high polymerisation rate for ethylene. They also isolated the active form of the cocatalyst, with approximate composition $AlO_{0.7}(CH_3)_{1.5}$, from a 1:1 molar reaction of Me_3Al with water and named it methyl alumoxane (MAO).[25] The use of MAO with Cp_2TiMe_2 or even with the more stable Cp_2ZrCl_2 with no water and R_3Al was found to be 10–100 times more active than the classical Ziegler–Natta catalyst. The Cp_2ZrCl_2/MAO system was able to produce polyethylene with molecular weights up to 1 million and with a narrow molecular weight distribution. When $Cp^*_2ZrCl_2$/MAO was used instead of Cp_2ZrCl_2/MAO, polyethylene with much higher molecular weight was obtained but at a lower activity of the catalyst.[26]

The active center in the bis-cyclopentadienyl metallocene catalyst is shielded to a large extent from the influence of its immediate surroundings. This kind of catalyst yields a sharply defined product with a narrow molecular weight distribution and with minimum formation of undesirable byproducts such as the low molecular weight PE in LLDPE and atactic polypropylene (aPP) in iPP. Even though the narrow molecular weight distribution might not be desirable for all applications, the right choice of catalyst can lead to materials with desired properties.

17.5.1 Polypropylenes Using Metallocenes

The Cp_2ZrCl_2/MAO system polymerises propylene to a perfectly atactic polymer unlike the Ziegler–Natta type catalysts. With an aim to introduce chirality in the catalyst to generate isotactic or syndiotactic polypropylene, Kaminsky tried propylene polymerisation with $Cp^*CpZrCl(CH_3)$. However, it also gave only the aPP. He observed that the movement of four ligands around the metal centre was faster than the insertion of an olefin and so the complex did not form a stable enantiomer. Around the same time, Brintzinger reported the preparation of ansa metallocenes. So Kaminsky along with Brintzinger prepared ansa ethyl bridged tetrahydroindenyl zirconocene complex (Fig. 17.7, A). Here, the rotation of ligands around the metal was restricted due to the bridge and when it was used as catalyst it yielded iPP. Almost at the same time, Ewen and coworkers made iPP with 56% (*mmmm*) by using a titanium analogue.

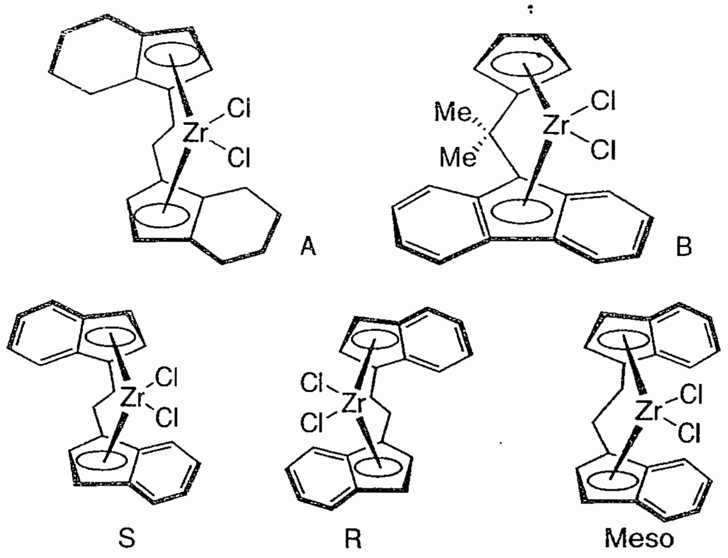
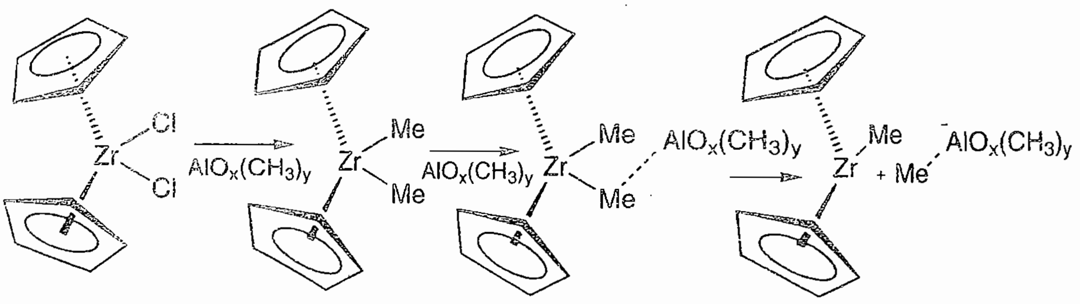


Fig. 17.7 Kaminsky's and Brintzinger's preliminary metallocene catalysts

Analogous indenyl zirconocene compounds with C_2 symmetry, $[CH_2(indenyl)]_2ZrCl_2$, were prepared which can exist in the R, S or *meso* form. The R and S forms yield the isotactic polymer whereas the *meso* form yields only the atactic polymer. Another important step forward was made by Ewen and coworkers who utilised a C_s symmetric ansa zirconocene dichloride complex with a Me_2C bridge between a Cp and a fluorenyl ring (B). The steric bulkiness and the C_s symmetry of the metallocene resulted in the selective formation of sPP with high activity with a narrow molecular weight distribution.

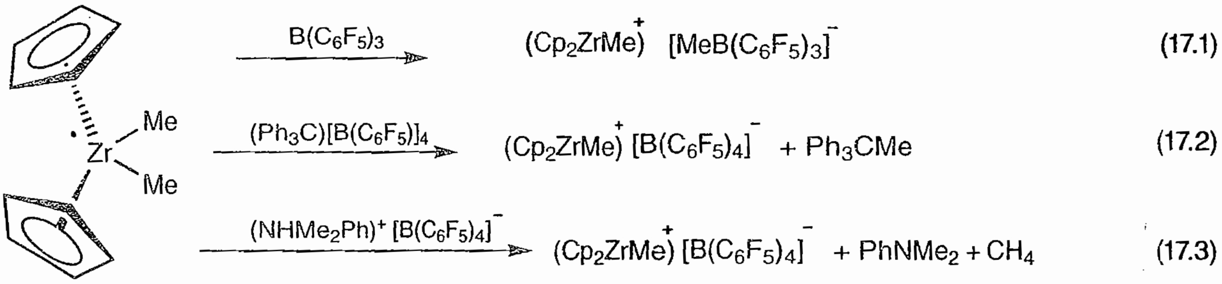
17.5.2 The Mechanism of Propylene Polymerisation by Metallocenes

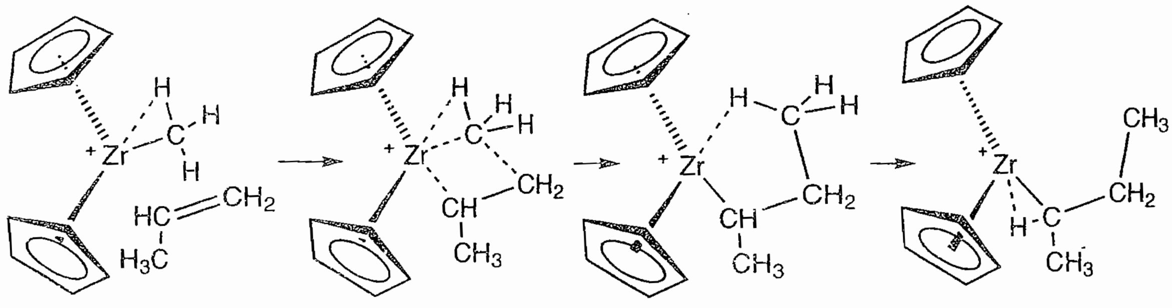
Cocatalysts hold the key to the activation of metallocenes. The important cocatalysts used are MAO and bulky boron based compounds such as perfluoroaryl borates which show weak coordination. MAO is synthesised by the controlled hydrolysis of Me_3Al.[27] It has a multifold function and its initial role is to alkylate the halogenated metallocene. Monomethylation occurs very fast and the dialkylated species is formed even at −60°C when an excess of MAO is used. The MAO then converts the metallocene to a cationic active centre.



Scheme 17.1 Activation of Cp_2ZrCl_2 with MAO

While the structure of MAO is complex, it is generally accepted that it is an oligomeric compound with a molecular weight between 1000 and 1500 g/mol. The MAO complex captures a Me^-, a Cl^- or an OR^- ion from the metallocene and forms the AlL_4^- anion which can distribute the extra electron over the whole unit, thus stabilising the charged system. The cationic species $Cp_2M(Me)^+$ so formed is the active center in olefin polymerisation. Metallocene complexes with anionic counter ions such as tetraphenyl borate $(C_6H_5)_4B^-$, carborane or fluorinated borate are found to be highly active catalysts.[28] Typically, such cationic metallocene complexes can be formed as shown in Eqs 17.1 to 17.3. These cationic centers are believed to be partly stabilised by C–H–Zr agostic interactions (Scheme 17.2) which depicts the initiation step of the polymerisation.





Scheme 17.2 Polymerisation initiation step on zirconocene based catalysts

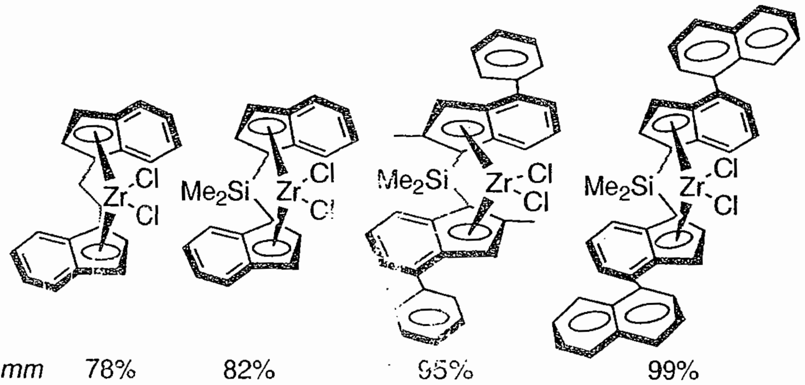
While the MAO:metallocene ratio required for an active catalyst system is around 5000:1, the ratio of borate:metallocene required is only 1:1. But the borate system is very sensitive to poisoning and decomposition and therefore must be stabilised by a small amount of an aluminium alkyl.

Zirconocene/MAO catalysts are about 10–100 times more active for ethylene polymerisation than the conventional Ziegler–Natta catalyst systems. For example, polymerising ethylene at 25°C and atmospheric pressure in the presence of Cp_2ZrCl_2/MAO yields 20,000 kg of PE/mol cat h [20.0 kg PE (mmol cat h)$^{-1}$].

17.5.3 Polypropylene and Stereochemistry

iPP has a crystalline morphology with melting points between 125 and 165°C. Its formation is associated with C_2 symmetry of the metallocene catalyst. Since iPP can be melted down and recycled without appreciable change in chemical structure, it has found many applications.

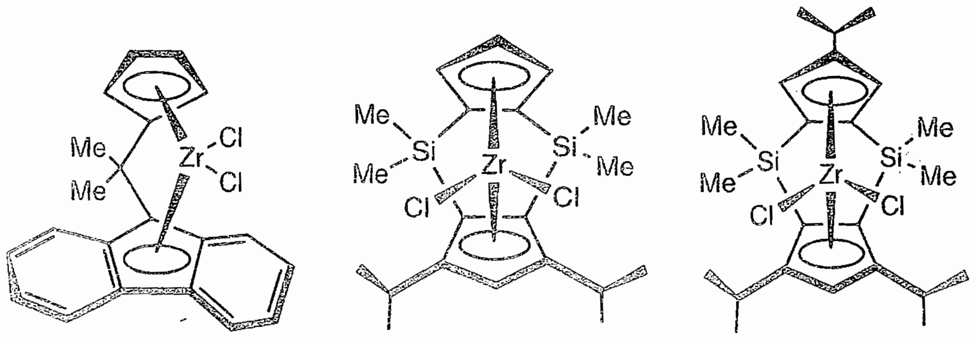
Following the ground breaking work of Ewen, Kaminksy and Brintzinger on the synthesis of iPP using Ti and Zr metallocene complexes, researchers have fine-tuned the catalyst and higher isotacticity has been achieved by increasing steric bulk at strategic positions and by locking the structural conformations more tightly with a suitable bridging moiety. The effect of higher rigidity and more steric bulk of the ligand, on the stereoselectivity of polymer formation can be seen from the comparison of catalysts (Fig. 17.8).



mmmm	78%	82%	95%	99%
m.p (°C) Polymer (iPP)	132	137	157	161

Fig. 17.8 Comparison of catalysts used for preparing isotactic polypropylene

Ewen and coworkers initially synthesised syndiotactic polymers using ansa metallocenes with C_s symmetry having Cp and fluorenyl bridged ligands but later developed double bridged zirconocenes to increase the stability of the catalyst and also to provide increased steric interactions with the polymer chain, which directed facial binding of propylene. The catalysts showed impressive selectivity for syndiotactic polymerisation as shown by the percentage of *rrrr* content (Fig. 17.9).



rrrr	82%	93.4%	97.5%
m.p (°C) Polymer (sPP)	140	151	151

Fig. 17.9 Comparison of catalysts used for preparing syndiotactic polypropylene

The general trend that relates catalyst symmetry and stereospecificity in propylene polymerisations can be explained by a detailed study of the site control mechanism. This has been determined by computational and theoretical calculations as well as by looking at the relative percentages and types of stereo defects that exist in the polymer structure. After coordination of propylene, the propylene undergoes a *cis* migratory insertion into the metal polymer bond. The stereochemical outcome is controlled by the active site geometry. Thus for the C_2 symmetric metallocenes in which the binding sites are equivalent due to symmetry, each successive monomer coordinates with the same facial selectivity to minimise steric interactions. This results in iPP. For C_s symmetric catalysts, each addition occurs at the opposite face of the propylene monomer leading to the formation of sPP.

The steric bulk of the catalyst structure directs the growing polymer chain away from the ligand in order to minimise steric interactions. The polymer chain then directs the position of the methyl group of the ligand through steric interactions before coordination and insertion. The propylene monomer approaches the catalyst with its methyl group pointed away from the largest group that is in the way—the growing polymer chain. For syndiotactic polymer formation, successive monomers approach from opposite sides of the catalyst, but their methyl groups always point in one direction. This is in contrast to the situation for iPP formation (Figs 17.10 and 17.11).

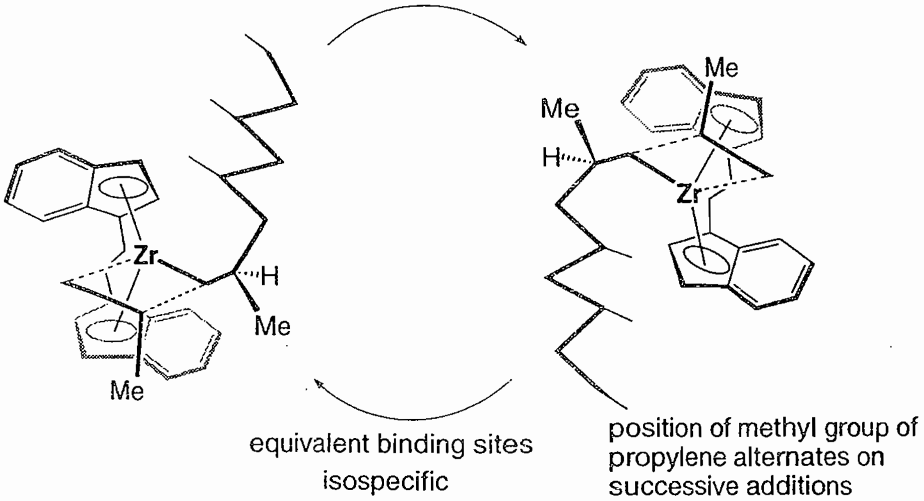


Fig. 17.10 View of the catalytic site during isotactic polypropylene formation

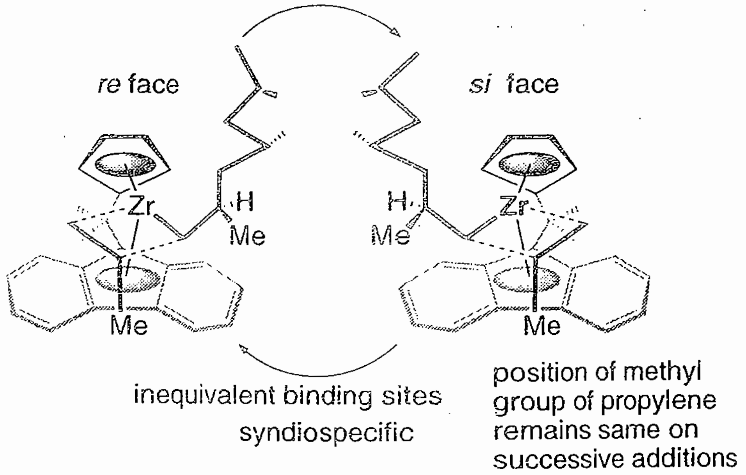


Fig. 17.11 View of the catalytic site during syndiotactic polypropylene formation

17.5.4 Stereo-block Polypropylene

Polymers with block units of varying stereochemistry have potential applications as thermoplastic elastomers. A stereoblock isotactic-atactic polypropylene has segments of crystalline isotactic and amorphous atactic units. This has been cleverly achieved by using the catalyst, bis(2-phenyl indenyl) zirconium dichloride. Since there is no ansa bridge, the 2-phenyl indenyl group can spin around freely and thereby generate the racemic and meso forms. When it is in the racemic form, it leads to the isotactic polymer block and in the meso orientation, it gives rise to the atactic polymer. The steric environment around the metal center has a dramatic impact on the kind of stereochemistry one obtains as well as on the nature of alkenes it can polymerise (Fig. 17.12).

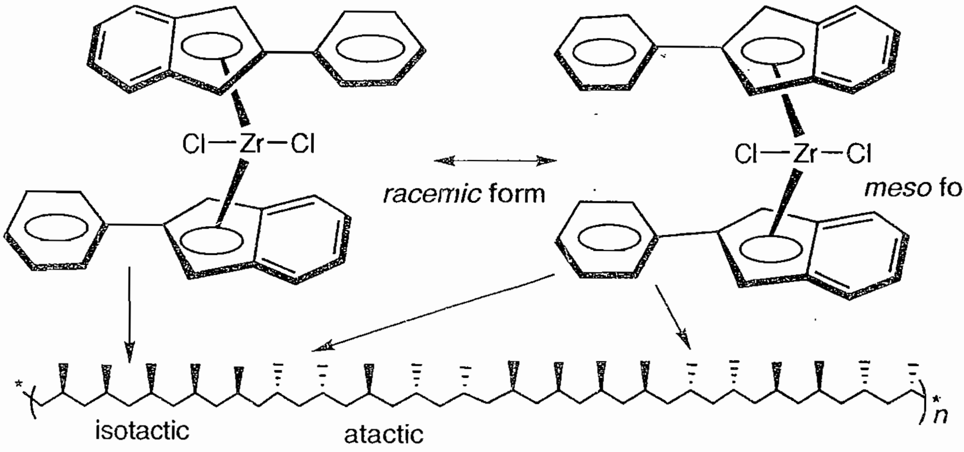


Fig. 17.12 Effect of catalytic steric environment on polymer stereochemistry

17.5.5 Constrained Geometry Catalysts

These are basically half sandwich complexes with the Cp ring having an amido or amino substituent. The open nature of these catalysts helps to incorporate higher olefins into polythene. These are ideal catalysts for making copolymers of ethylene with hexene, octene and cyclic olefins like norbornene. Synthesis of UHMWPE is generally difficult. Two catalysts separately developed by Dow chemical (*Insite*) and DSM (*Lovacat*) are shown in Fig. 17.13. Open metallocenes are also useful in polymerising bulkier monomers; for example, $CpTiCl_3$ is ideal for making syndiotactic polystyrene.[29, 30]

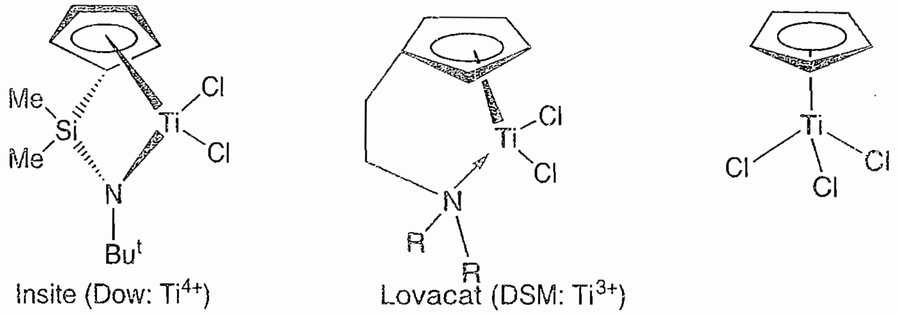


Fig. 17.13 Examples of constrained geometry catalysts

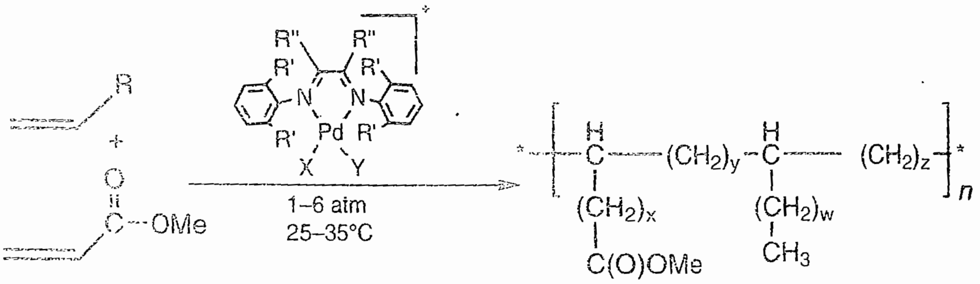
17.6 POST-METALLOCENE CATALYSTS

Post-metallocene catalysts refer, in general, to the olefin polymerisation catalysts discovered after the metallocene based Kaminsky catalysts, and do not involve metallocenes. Fujita and coworkers of Mitsui chemical company, Japan, discovered a series of high performance olefin polymerisation catalysts based on a ligand oriented catalyst design concept. These include titanium, zirconium and hafnium based metal complexes which are bound to ligands such as phenoxy-imine, pyrrolidinio-imine, phenoxy-ether and show exceptionally high olefin polymerisation activities. The main drawback of these catalysts is their high oxophilicity which often results in the catalyst getting poisoned by many functionalised olefins especially the commercially available polar comonomers such as methyl acrylate, methyl vinyl ketone, crotonaldehyde and 4-pentenoates. Similar high activity catalysts exclusively for propylene polymerisation have also been prepared by Geoffrey Coates of Cornell University.

While catalysts based on early transition metals remain as the workhorses in industrial olefin polymerisation, significant advances have been made recently in late transition metal olefin polymerisation catalysts as well. One major untapped area in olefin polymerisation is the copolymerisation of ethylene with polar comonomers. The presence of functional groups in a nonpolar polyolefin chain imparts the polymer with enhanced material properties such as toughness, barrier properties, surface properties and miscibility with other polar polymers.

17.6.1 The Brookhart Catalysts

In an effort to copolymerise polar comonomers, Maurice Brookhart at the University of North Carolina came up with late transition metal catalysts based on nickel and palladium.[31] These complexes bear bulky, neutral, α-diimine (or diketimine) ligands. The technology was further developed in the laboratories of DuPont Research. The catalysts were able to homopolymerise ethylene to a variety of structures that range from HDPE to LLDPE. As opposed to early transition metal based metallocene catalysts, the palladium based cationic catalysts randomly copolymerise ethylene with polar comonomers like methyl acrylate. A unique feature of the polymer obtained is that it is highly branched and the ester groups are predominantly located at the end of the branches. This unique phenomenon has been termed as chain walking.[32]



(17.4)

In the chain walking mechanism, the catalytic site isomerises or walks on the polymer chain during propagation, so that the new monomer unit is assembled on to any part of the polymer chain instead of at the end. Here, branching is introduced on the polymer chain by a catalyst that can control the position of the next monomer addition. This nonlinear fashion of chain propagation leads to polymers with various branching topologies. It is also shown that often the ethylene pressure determines the extent of branching as one can get linear, hyperbranched or dendritic polymer topologies as a consequence of chain walking (Fig. 17.14).

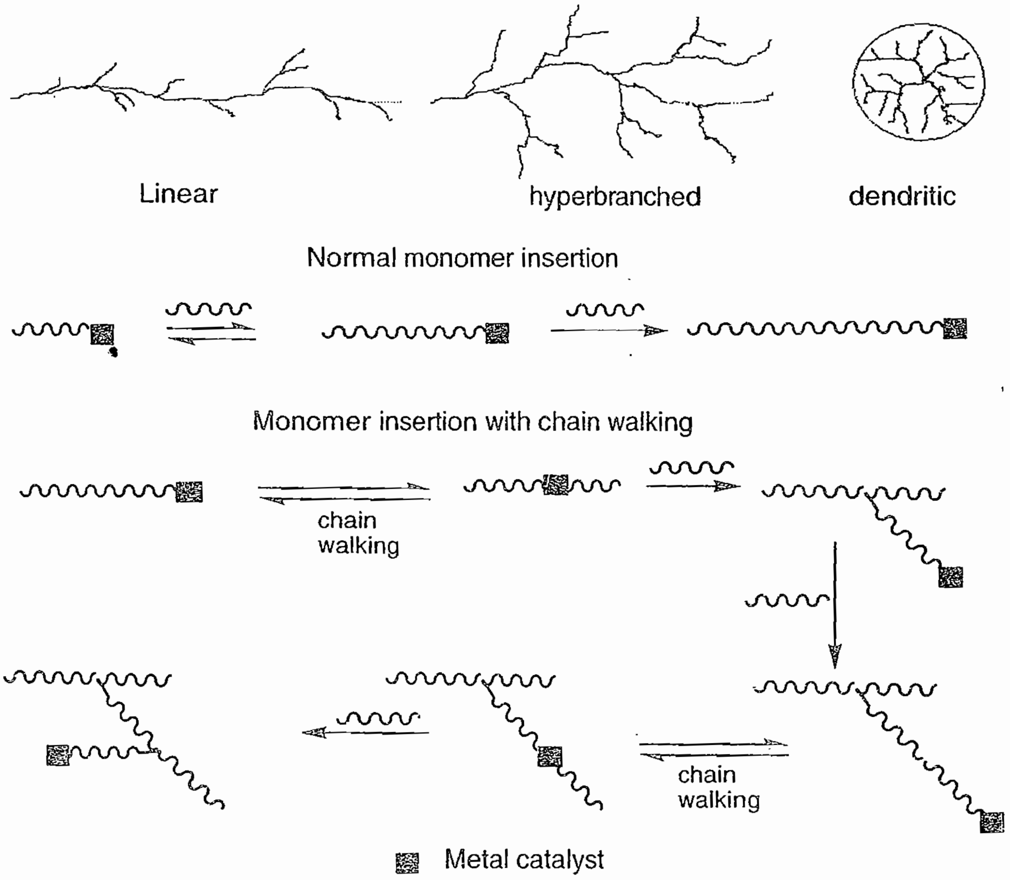
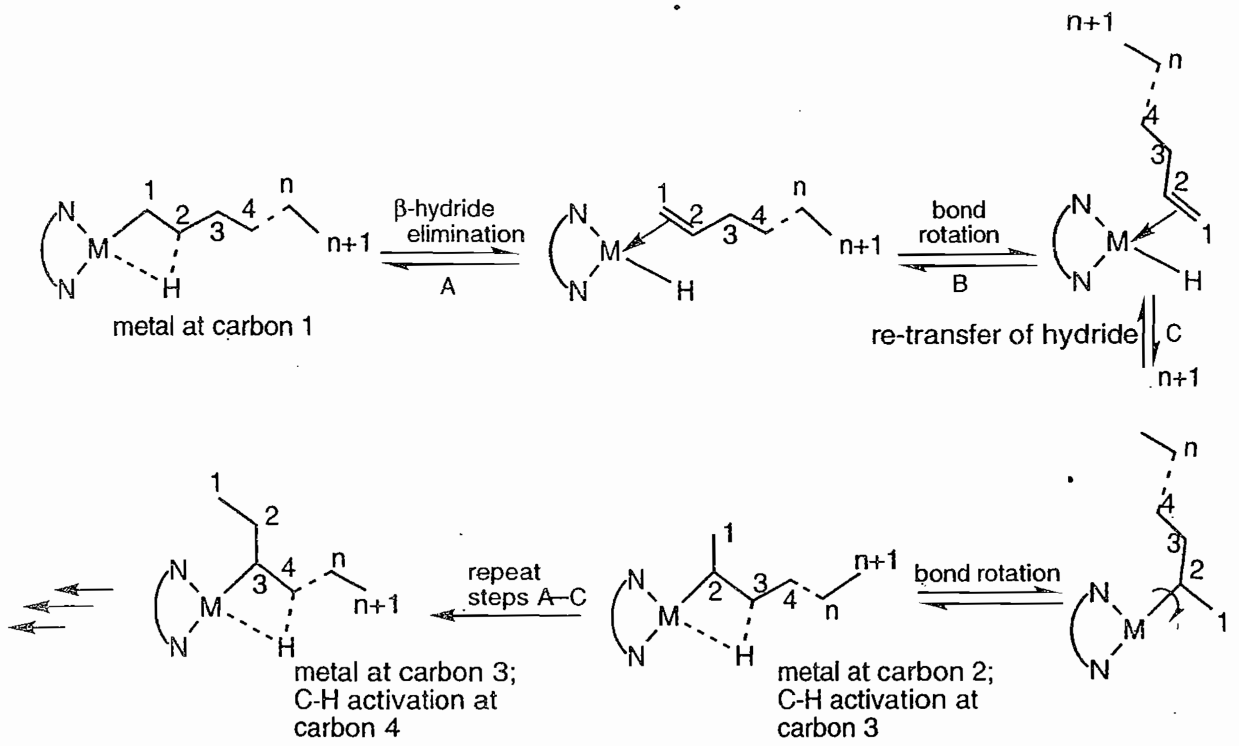


Fig. 17.14 Schematic depicting chain walking on polymers

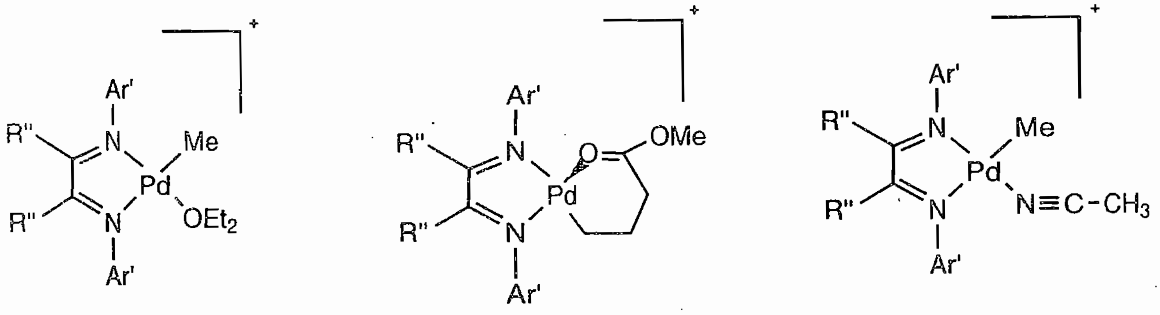
Mechanistically, chain walking can be explained as a series of β-hydrogen eliminations and re-transfer of the hydride after a bond rotation (scheme 17.3).[33, 34]

Other palladium based catalysts have also been used for the copolymerisation of ethylene with polar comonomers (Fig. 17.15). As the ether adduct (I) is air sensitive, the chelate complex (II) or the nitrile adduct (III) are generally preferred as catalysts and these are easily prepared from [(N∧N)PdMeCl], $NaBAr_4$ and the acrylate or nitrile.

Late transition metal based polymerisation catalysts are distinguished from early transition metal based catalysts by their versatility in controlling polymer topology and good functional group tolerance. If the most striking feature of Ti and Zr based Ziegler–Natta, Kaminksy and related catalysts is their capability to control the stereochemistry of polymerisation of α olefins, the most impressive property of the Brookhart catalysts is their versatality in controlling polymer topology which they achieve through chain walking.



Scheme 17.3 Mechanism of chain walking



I II III

Fig. 17.15 Pd catalysts for copolymerisation of ethylene with polar monomers

The concept of having bulky bis-imine ligands was also extended to iron complexes by Vernon Gibson and coworkers as well as by Brookhart and coworkers (Fig. 17.16).[35] These catalysts, incorporating a pyridyl moiety between the two imine groups (2,6-bis iminopyridyl) making it a tridentate ligand, showed exceptionally high activity for the polymerisation of ethylene and these were similar to and even better than the metallocene catalysts and no chain walking was observed in these systems. As a result, these complexes gave very linear high density polyethylene ($M_w = 6 \times 10^5$) with bulky substituents on the nitrogen and when the steric bulk is removed from the imino nitrogen atoms, they turned out to be active catalysts for ethylene oligomerisation leading to linear α-olefins.

Another class of catalysts, nickel complexes bearing mono-anionic bidentate ligands having N, N and N, O chelates, were also found to be very efficient in ethylene polymerisation.

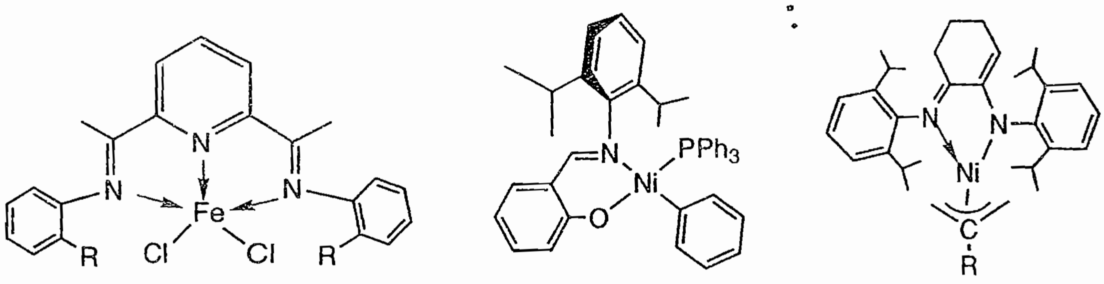
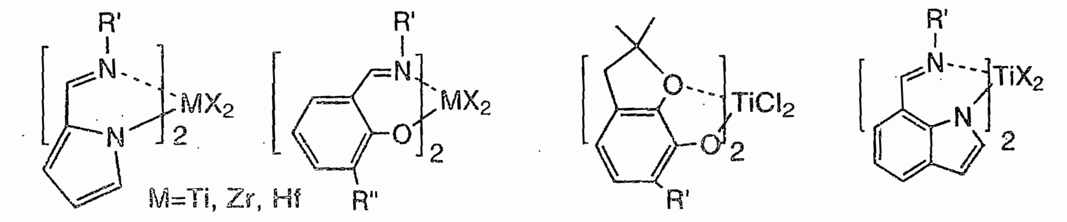


Fig. 17.16 Iron and nickel based post metallocene catalysts

One interesting feature of these catalysts is that a pendant Lewis acid functionality can be incorporated on the imino nitrogen atoms to direct the incorporation of polar comonomers. These catalysts are often better suited for the preparation of speciality oligomers and polymers having reactive functionality.

17.6.2 Fenokishi Imin (FI) and Related Ligand Based Metal Catalysts

The FI catalysts for olefin polymerisation were discovered (the letters F, I are from the Japanese term *Fenokishi–Imin–Haiishi* which means phenoxy-imine ligand) in 1999 from a systematic ligand oriented catalytic design research carried out by Terunori Fujita and coworkers at the Mitsui chemical company, Japan. G Coates' group at Cornell university also reported similar high activity catalysts, especially for propylene polymerisation. They prepared a series of complexes of Ti, Zr and Hf with bidentate or tridentate ligands. The key feature of these ligands is that these are nonsymmetric, have electronically flexible properties and contain heteroatoms. The main types of catalysts discovered by Fujita whose polymerisation features were explored are given in Fig. 17.17.[36]



Pirorido-Imin (PI) Pyrrolide-imine

Fenokishi-Imin (FI) Phenoxy-imine

Fenokishi-Eteru (FE) Phenoxy-ether

Indorido-Imin (II) Indolide-imine

Fig. 17.17 Basic structural units of FI and related catalysts

These complexes were used in conjunction with cocatalysts such as MAO, and [Ph$_3$C][B(C$_6$F$_5$)$_4$]/ ^{i}Bu$_3$Al. Many of them showed better activity than titanocene and ziroconcene based polymerisation catalysts. For example, titanium based PI catalyst (R′= cyclooctyl) showed ethylene polymerisation activity of 33.2 kg (mmol cat h)$^{-1}$ at 25°C and atmospheric pressure while Cp$_2$TiCl$_2$ gave only an activity of 16.7 kg (mmol cat h)$^{-1}$ under identical conditions. FE catalyst (R′ = t-butyl) along with MAO as cocatalyst was quite efficient in the preparation of UHMWPE (M_v = 5.42 × 10^6). Among the various complexes tried with different ligands, bis-phenoxy-imine Ti/Zr/Hf catalysts (FI), in particular, were found to be highly active and versatile with a very high TOF especially for ethylene polymerisation. One could quite easily make UHMWPE by modifying the cocatalyst used. As many structural isomers are possible for these complexes, structural studies were carried out to find out the active isomer among the various structures. It was observed that the predominant active isomer was the one having *trans* O, *cis* N and *cis* Cl groups (Fig. 17.18, box) with minor amounts of another nonsymmetric isomer (*cis* O, *trans* N and *cis* Cl, Fig. 17.18). The crystal structure of the predominant isomer shows a distorted octahedral arrangement. A critical requirement for a high efficiency catalyst is that it must possess a pair of *cis* located sites for polymerisation which can be generated upon treatment with the cocatalyst. This is similar to the metallocene systems.[37, 38]

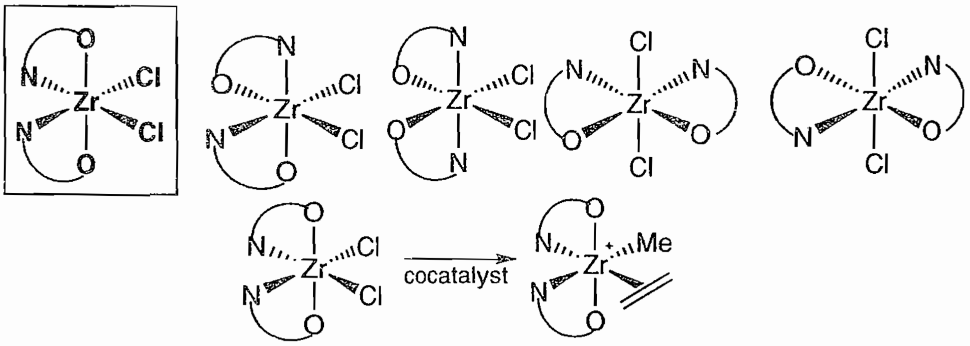
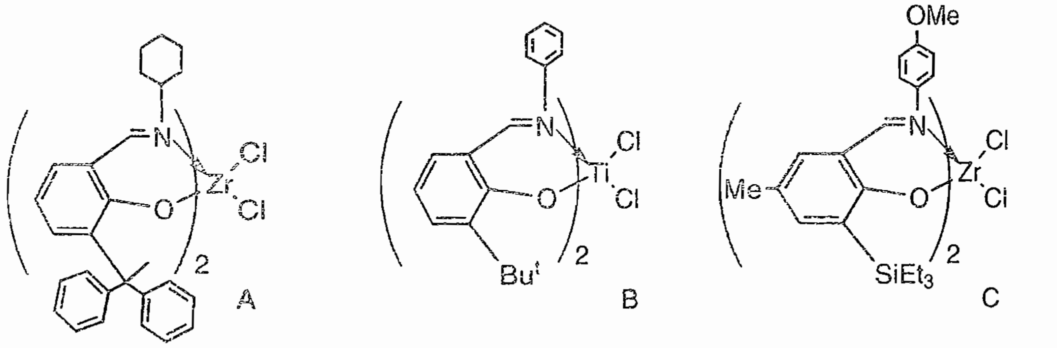


Fig. 17.18 Various isomers possible for FI catalysts and its mode of activation

The activity of 6552 kg PE/mmol cat/h, obtained with the zirconium FI catalyst A (Fig. 17.19) at 25°C for ethylene polymerisation works out to a TOF of 64,900/s/atm. Such activities are some of the highest exhibited TOF values for any homogeneous catalyst. Under identical reaction conditions, Cp_2ZrCl_2 gives only 20 kg PE/mmol cat/h. The titanium complex B along with the cocatalyst $Ph_3CB(C_6F_5)_4$/ *i*-Bu_3Al gives UHMWPE with a molecular weight value of M_v 5.05 × 10^6. This titanium catalyst is also quite efficient for making aPP. A zirconium FI catalyst C along with $Ph_3CB(C_6F_5)_4$/*i*-Bu_3Al gives exceptionally high molecular weight (1.02 × 10^7) ethylene propylene copolymer (propylene 20 mol%).[39]



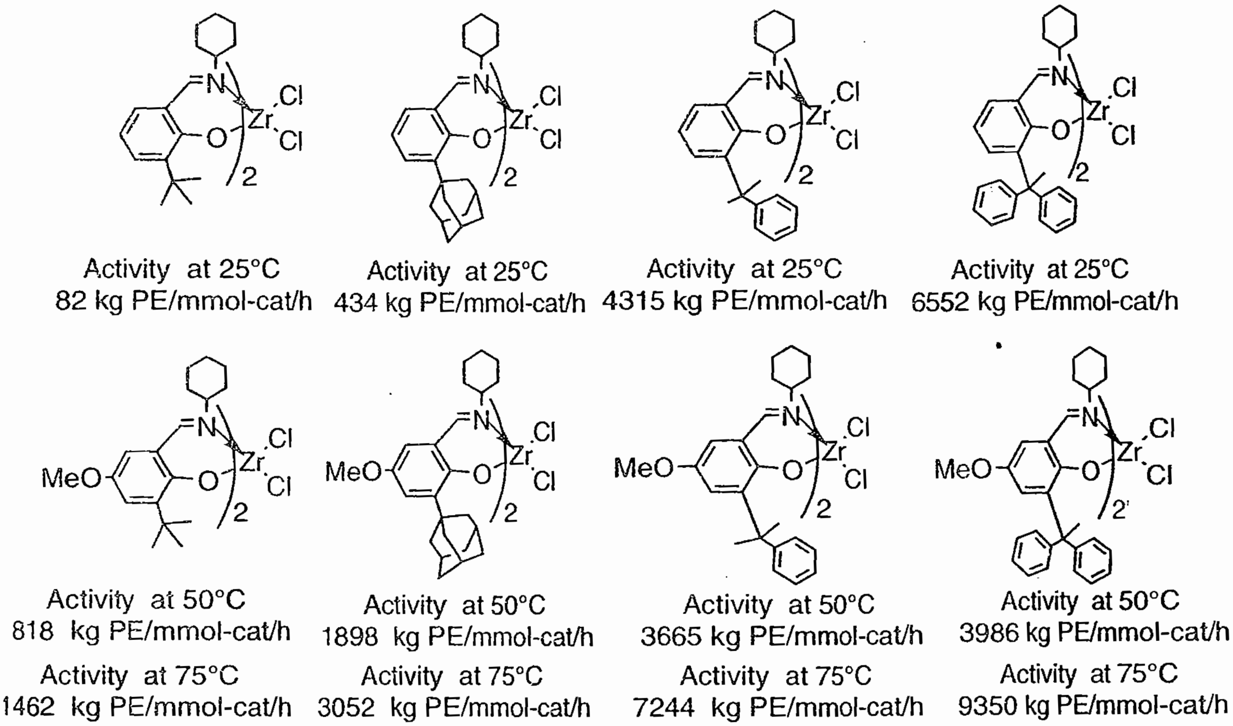
High activity at 25°C
6552 kg PE/mmol-cat/h
(ethylene)

Ultra high molecular weight
M 5.05 x 10^6
(ethylene)

Ultra high molecular weight
M_w 1.02 x 10^7
(ethylene–propylene)

Fig. 17.19 High activity and UHMW yielding FI catalysts

The activity of the catalyst was further found to depend significantly on the substituents present on the aryl ring as well as on the temperature of polymerisation. The data given in Fig. 17.20 illustrate these dependences.



Activity at 25°C
82 kg PE/mmol-cat/h

Activity at 25°C
434 kg PE/mmol-cat/h

Activity at 25°C
4315 kg PE/mmol-cat/h

Activity at 25°C
6552 kg PE/mmol-cat/h

Activity at 50°C
818 kg PE/mmol-cat/h
Activity at 75°C
1462 kg PE/mmol-cat/h

Activity at 50°C
1898 kg PE/mmol-cat/h
Activity at 75°C
3052 kg PE/mmol-cat/h

Activity at 50°C
3665 kg PE/mmol-cat/h
Activity at 75°C
7244 kg PE/mmol-cat/h

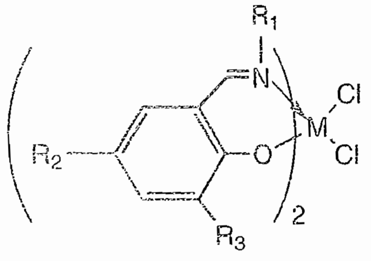
Activity at 50°C
3986 kg PE/mmol-cat/h
Activity at 75°C
9350 kg PE/mmol-cat/h

Fig. 17.20 Effect of substituents and temperature on activity of FI catalysts

The substituents on the aryl ring and on the nitrogen can be fine-tuned; when the metal is varied, the phenoxy-imine catalyst can give atactic, isotactic and syndiotactic polypropylene as well (Fig. 17.21). Unlike metallocene catalysts, phenoxy-imine catalysts with C_2 symmetry provide sPP and not iPP. This indicates that the mechanism of inducing stereospecificity is different for phenoxy-imine catalysts. The best syndiotacticity has been achieved by Ti complexes while Hf complexes provide quite high isotacticity.

Some of the Ti-phenoxy-imine catalysts having fluorine atoms *ortho* to the imine nitrogen are also quite efficient in the polymerisation of ethylene and propylene even at moderately high temperatures. The living nature of the polymer obtained is confirmed by very narrow M_w/M_n values (1.06).[40]

Catalyst



Polypropylene

Atactic PP: (M =Ti) R_1= Ph, R_2 = H, R_3 = Bu^t

Syndiotactic PP: (M= Ti)
R_1= C_6F_5, R_2 = H,R_3 = $SiMe_3$: [*rr*] 94%, T_m. 156 °C
R_1 =C_6F_5, R_2 = t-Bu, R_3=t-Bu: [*rrrr*] 96% T_m. 148 °C

Isotactic PP: (M= Hf)
R_1= Cy, R_2 = Me, R_3 = adamantane, [*mm*] 98 %, T_m. 164 °C

Fig. 17.21 Phenoxy-imine catalysts suitable for preparing atactic, syndiotactic and isotactic polypropylene

17.7 OLEFIN OLIGOMERISATION REACTIONS

In addition to polymerisation, oligomerisation of olefins using organometallic catalysts, especially to short and medium chain α olefins, is an industrially important process. Shell's SHOP process is undoubtedly the most important among olefin oligomerisation reactions.

17.7.1 Shell's Higher Olefin Process

This process accounts for 50% of linear α olefins produced worldwide by oligomerisation (scale of more than a million tons). The feedstock is ethylene and the process operates in three stages. Homogeneously catalysed ethylene growth reaction is the first stage and it uses a nickel hydride catalyst having a specific P, O based chelating ligand. This is followed by the next two stages, isomerisation and olefin metathesis. Both these processes are carried out in the industry using heterogeneous catalysts. The conditions are optimised to give olefins in the C11–C14 range which are later converted to detergent grade alcohols by hydroformylation. The importance of SHOP process can be seen from the prices of α olefins sold by some of the well known chemical suppliers. α Olefins with an even number of carbon atoms are relatively much cheaper than those with an odd number of carbon atoms. This is because the former is easily produced from ethylene by the SHOP process.[41]

Terminal olefin prices/100 ml in US dollars (2008)

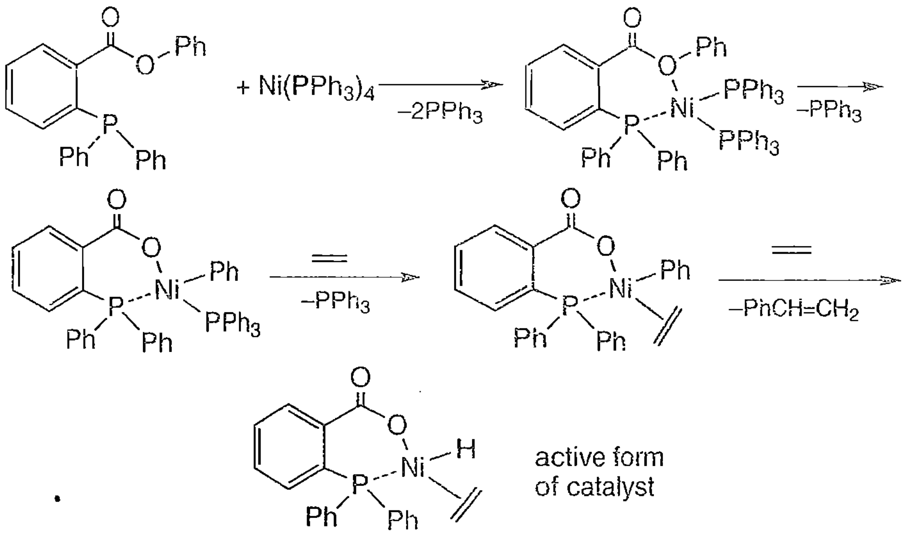
1- Hexene	$ 14
1- Heptene	$ 220
1- Octene	$ 25
1- Nonene	$ 820
1- Decene	$ 22
1- Undecene	$ 650

Catalyst generation

The oligomerisation reaction involves a nickel hydride catalyst which is generated in situ from the reaction of $Ni(PPh_3)_4$ with the phenyl ester of diphenylphosphino benzoic acid or an analogous aliphatic precursor. The sequence of steps requires phosphine dissociation from nickel and the transfer of the phenyl group to the metal. The active form of the catalyst is generated presumably by migratory insertion with the formation of styrene from the phenyl and ethylene bound nickel complex. Scheme 17.4 shows how the active form of the catalyst having a hydride and $CH_2{=}CH_2$ is generated in the catalyst cycle.

Ethylene growth reaction

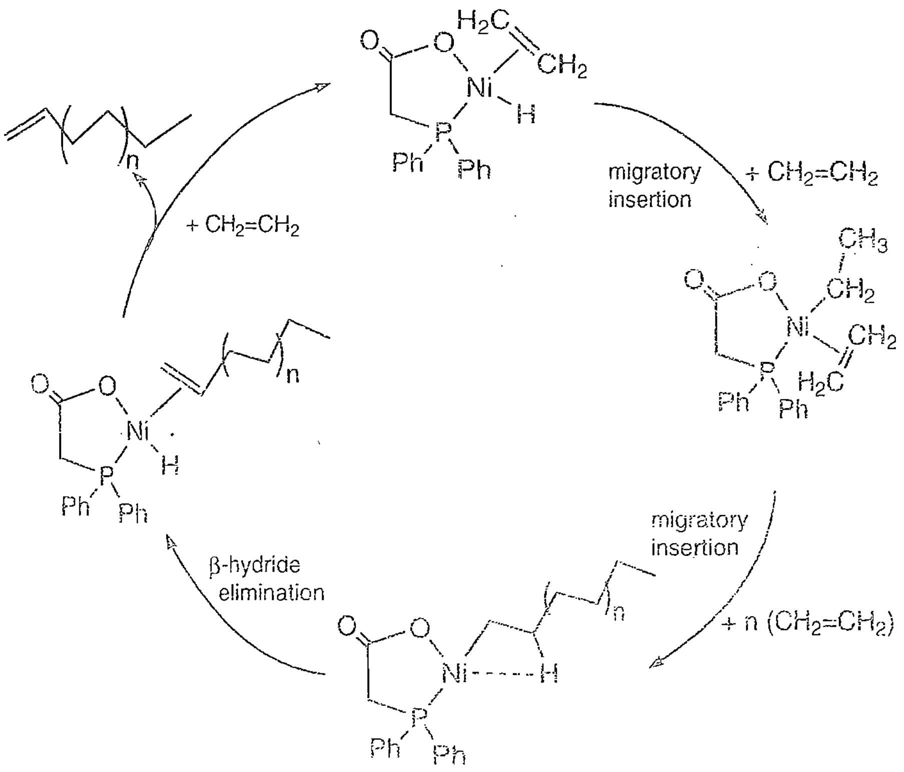
In this process, ethylene is selectively oligomerised to even number of carbon-containing linear α olefins in the presence of a nickel hydride catalyst. The active form of the hydride catalyst is generated from the precatalyst upon its reaction with the first molecule of ethylene (Scheme 17.4). The phosphorus and oxygen-containing chelating ligand is highly essential for the successful operation of this process for achieving high activities with low metal concentrations. The catalyst is also soluble in the polar solvent used (1,4-butanediol). So, the reaction mixture essentially consists of three phases—the solvent phase with catalyst, the α olefin phase and the ethylene gas phase. As the polar solvent is immiscible with the α olefins, it allows the facile separation of products from the catalyst. Also the lower solubility



active form of catalyst

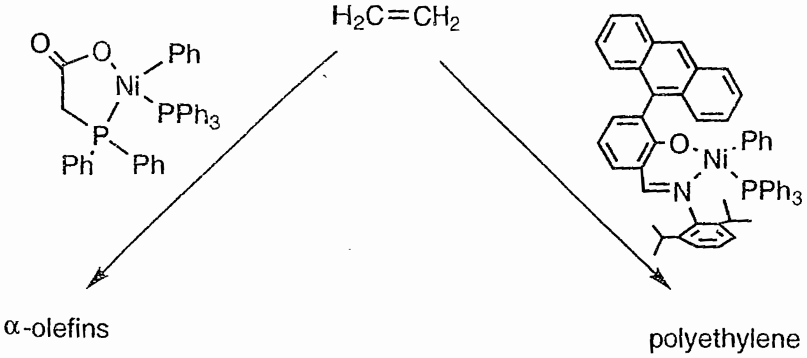
Scheme 17.4 Generation of active catalyst for the SHOP process

of the polar catalyst in the α olefin phase reduces the chances of isomerisation of the α olefins to the thermodynamically more stable products. The reaction conditions are 70–140 bar ethylene and 80–120°C. High partial pressure of ethylene ensures good rates of reaction and increased linearity of the α olefin product. Insertion of ethylene into the Ni-H bond yields a σ complex which can undergo further multiple ethylene insertions and propagate the oligomerisation, or the intermediate can undergo β elimination to release the α olefin. The proposed catalytic cycle (Scheme 17.5) involves migratory insertion steps and β hydride elimination followed by ethylene exchange with the α olefin product.[42]



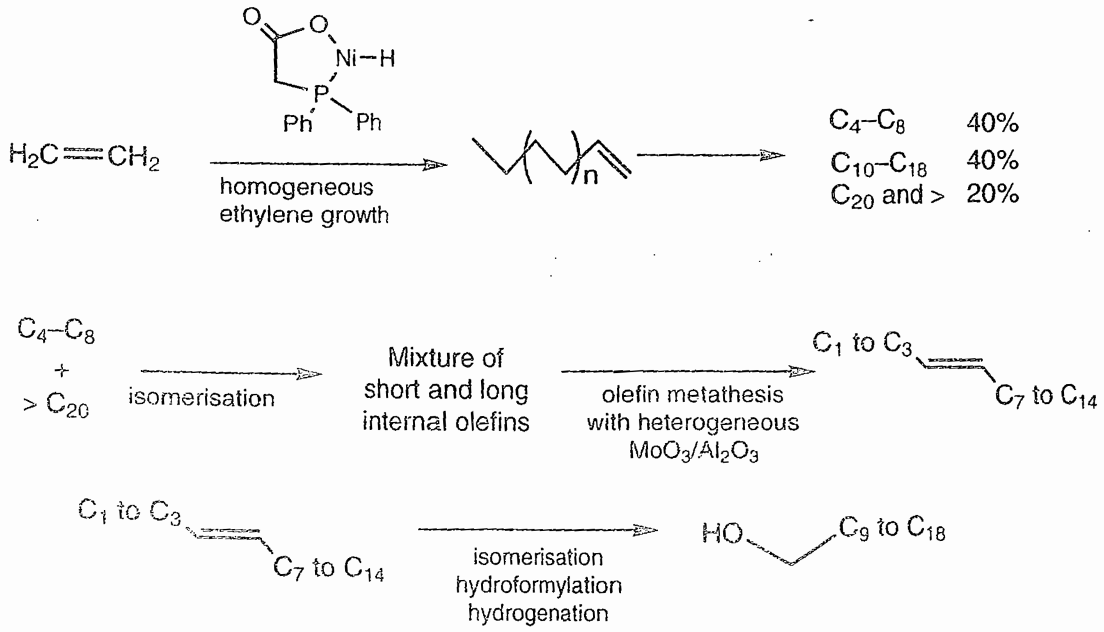
Scheme 17.5 Catalytic cycle for the SHOP process

As the scheme shows, the method can potentially lead to alkene terminated polyethylene as well. A fine control on the relative rates on migratory insertion versus elimination gives the low molecular weight olefins. Grubbs and coworkers have shown that by changing the P–O ligand to a bulky chelate, the nickel catalyst can be made to yield alkene terminated linear polyethylene with molecular weights up to 250,000. NMR studies carried out in situ support the evidence that the nickel hydride is the active form of the catalyst.



(17.5)

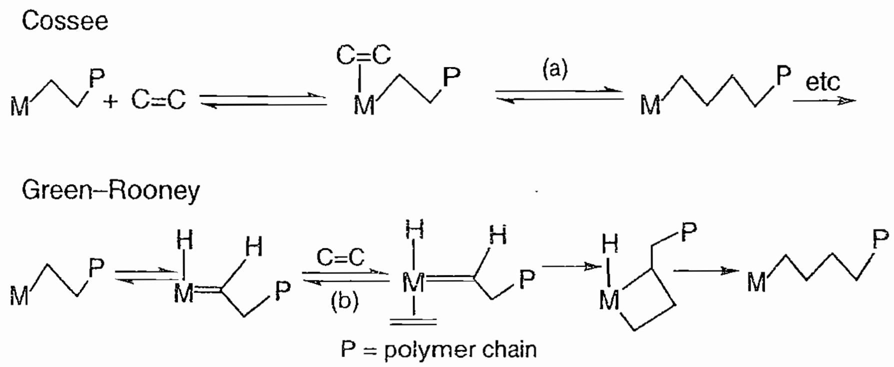
The SHOP process is also by far the largest application of metathesis in industry. The oligomerisation of ethylene results in α olefins in the range of C4 to C40. It is reported that around 3% of the products formed are internal olefins. The terminal C6–C18 olefins are separated out and used as comonomers or as feedstock for plasticisers and detergents after the hydroformylation reaction. Isomerisation of the light <C6 and heavy >C18 α olefins to internal olefins is carried out over a solid potassium/magnesium oxide catalyst.



Scheme 17.6 Industrial production of long chain alcohols starting with ethylene

Problems and Exercises

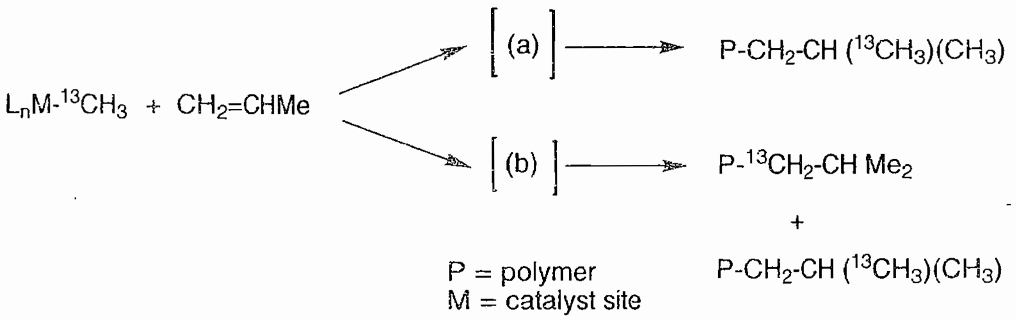
17.1. The carbon–carbon bond forming chain propagation step in metal catalysed olefin polymerisation follows two major pathways—four center migratory insertion (by Cossee) and carbene to metallacycle (by Green and Rooney) as shown below.



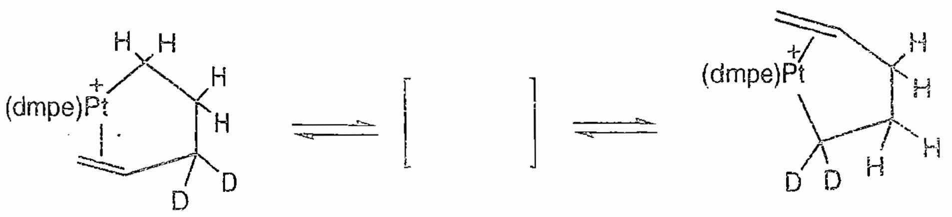
(a) Write one major important difference between these two pathways.

(b) Consider $^{*}Cp_2Lu\text{-}CH_3$ and $CH_2{=}CH(Me)$ as reactants and predict which of the above pathways is more appropriate for its reaction. Write the product and comment on the possible competing side reactions.

17.2. Write the structure of the intermediate in the reaction of $L_nM^{13}CH_3$ with $CH_2{=}CHMe$ using (a) Cossee and (b) Green's mechanisms.

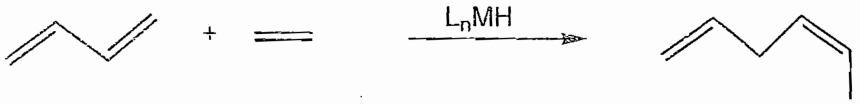


17.3. The following reversible alkyl–alkene insertion takes place in CD_3NO_2 at 125°C. Write the structure of the intermediate in this reaction and show how you reach that intermediate (*J. Am. Chem. Soc.*, 1984, Vol. 106, 6076).

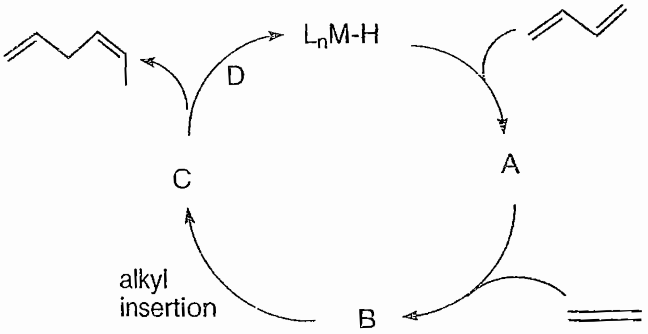


17.4. Regardless of the catalyst used, nearly all polymerisations and oligomerisations of conjugated dienes are thought to proceed via η^3-allyl metal complex intermediates. These intermediates can be formed either (a) by diene insertion into the metal hydride (or metal alkyl) bond and/or (b) by low valent metals like Ni(0) and Pd(0) reductively dimerising butadiene to the corresponding bis-(η^3-allyl) complex. Show the formation of these η^3-allyl intermediates by an appropriate general reaction in each case.

17.5. The oligomerisation of 1,3-butadiene with olefin leads to the formation of 1,4-hexadiene.



Identify the intermediates A, B and C in the given mechanism for this reaction.

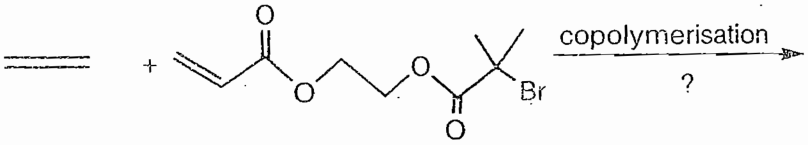


17.6. (a) What are the major drawbacks of MAO as cocatalyst in the polymerisation of ethylene and propylene using Kaminsky's catalysts?

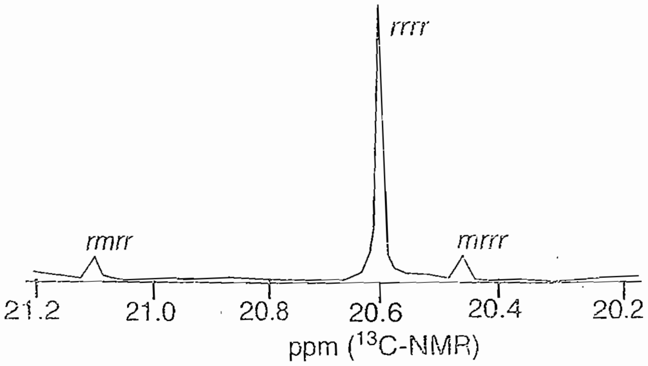
(b) How have the above problems been solved?

17.7. Write the basic differences and similarities between the active sites of metallocene based olefin polymerisation catalysts and FI catalysts.

17.8. Suggest a catalyst for copolymerisation of the following monomers. Comment on the density of the polymer prepared.



17.9. Given below is the rough sketch of ^{13}C-NMR and the pentad assignment from the microstructure analysis for polypropylene prepared by the polymerisation of propylene using a titanium bis-phenoxy imine catalyst along with MAO. Analyse the spectrum and determine (a) the tacticity, (b) the mechanism by which the polymerisation has proceeded. Justify your answer.



17.10. Two polypropylene samples A and B were subjected to polymer microstructure analysis and the results obtained are given in the table. Indicate the following.

(a) The tacticity of the polymers.

(b) The mechanism operating in the polymerisation of both the polymers.

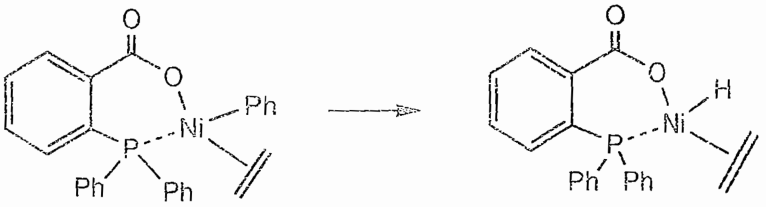
(c) One of the polymers was prepared using a metallocene catalyst. Identify the polymer and comment on the point group symmetry of the catalyst used.

Polymer	[*mmmm*] %	[*mmmr*] %	[*rmmr*] %	[*mmrr*] %	[*rmrr*] %	[*rmrm*] %	[*rrrr*] %	[*rrrm*] %	[*mrrm*] %
A	0.5	0	0	0	4	0	90	4.5	1
B	0	0	2	3	1	0	91	3	0

17.11. Write the products in the following table.

Catalyst used	**Reactant**	**Product**
Cp_2ZrCl_2	Ethylene	
$Cp_2ZrCl_2/R_3Al/H_2O$	Ethylene	
Cp_2ZrCl_2/MAO/No water	Ethylene	
$^*Cp_2ZrCl_2$/MAO	Propylene	
*CpCpZrCl(Me)	Propylene	
$CpTiCl_3$	Styrene	

17.12. In the formation of active catalyst for Shell's SHOP process, the following equation, although often shown as the final step does lack clarity. Elaborate the additional steps involved in the generation of the active catalyst in this consolidated step.



17.13. The (η^5-Cp)Ni(η^3-C_3H_5) complex catalyses the conversion of ethylene to 1-butene. The effective catalyst in this process is (η^5-Cp)NiH. Draw a catalytic cycle for this transformation.

Supplementary reading

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CHAPTER

18

FERROCENE: STRUCTURE, BONDING AND REACTIONS

Ferrocene is the most common and well studied metal sandwich compound due to its high stability, ease of preparation from inexpensive precursors and diverse nature of derivatives. It is one of the most important structural motifs in organometallic chemistry, materials science and especially catalysis. Chiral ferrocene derivatives are utilised in many industrial syntheses. Details of the discovery of ferrocene, currently available methods for its preparation, its physical properties and basic structural features have already been discussed in Chapter 7.

18.1 STRUCTURE AND BONDING OF FERROCENE

Ferrocene crystallises in a monoclinic unit cell at room temperature, in a triclinic form at <164 K and in an orthorhombic modification at <110 K. In the monoclinic form, a staggered conformation is arrived at from a disordered structure, while it is partially staggered in the triclinic form (with the angle between two vertices around 9°). The rings are fully eclipsed with D_{5h} geometry in the orthorhombic form and also in the vapour phase. The rotational barrier is very small (~ 4 kJ/mol) and the eclipsed form is lower in energy. The neutral complexes of ruthenocene (Cp_2Ru) and osmocene (Cp_2Os) in the solid state exhibit the eclipsed conformation similar to orthorhombic ferrocene.

The sequence of the chemically relevant frontier orbitals of metallocenes with axial symmetry can be easily obtained from a simple electrostatic model. As per this model, the

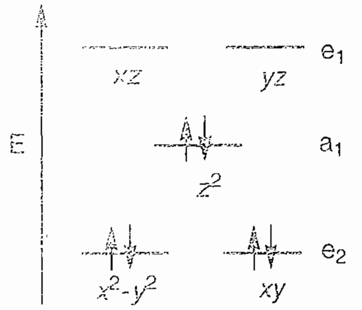


Fig. 18.1 Frontier orbital electronic configuration of ferrocene

crystal field generated by two negatively charged Cp rings splits the energy levels of the metal *d* orbitals. The splitting occurs as a result of unequal electrostatic repulsions between the metal *d* electrons and the charge loops (Fig. 18.1).

As shown in Fig. 18.2, the minimum electron–electron repulsion between the metal orbitals and the π electron density on the Cp ring will be for $d_{x^2-y^2}$ and d_{xy} as the lobes of these orbitals are not directed towards the Cp ring. The d_{z^2} orbital has one and the d_{xz}/d_{yz} orbitals have two lobes directed towards the Cp ring. Thus, the accurate electronic configuration of the frontier orbital region in ferrocene is $(e_2)^4(a_1)^2(e_1)^0$. This qualitative crystal field picture, however, does not do justice to the nature of metal–Cp interactions as it is highly covalent in character. The energy separation or the sequence of orbitals in the MO picture of ferrocene can vary depending on the quantum chemical method used (Fig. 18.3).[1,2]

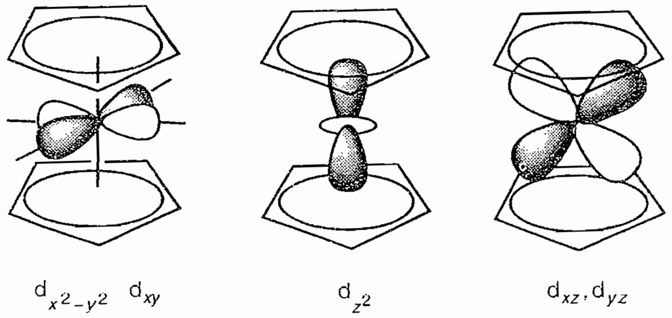


Fig. 18.2 Interactions of metal *d* orbitals with two Cp electron clouds

However, in the chemically relevant frontier orbital region, the order is $e_2 < a_1 < e_1$. It is the same order as deduced from the crystal field model. The energies of these frontier orbitals with reference to the basic orbitals can be regarded as bonding (e_2), nonbonding (a_1) and antibonding (e_1) (Fig. 18.4). Since the frontier orbitals are neither strongly bonding nor strongly antibonding, no significant change in the bond length is observed when ferrocene is oxidised to the ferrocenium ion. Also, the close proximity of the frontier orbitals among themselves indicate that metallocenes with 17, 19 or 20 electrons can also exist with stabilities not too far off from the 18 electron metallocenes.

The redox property of ferrocene can be understood in terms of its chemical structure and from the orbital point of view; oxidation corresponds to the removal of an electron from a nonbonding a_1 orbital. Therefore, one can correlate the bond lengths to the electronic occupancy in the bonding and antibonding orbitals. Ferrocene is fairly readily oxidised to the ferrocenium ion even by I_2, so the electrophile reacting with ferrocene should not be an oxidising agent.[3]

18.2 THE REACTIONS OF FERROCENE AND ITS DERIVATIVES

Among all organometallic compounds, ferrocene stands out as the one which is inexpensive, possessing high thermal stability and high tolerance to oxygen and moisture. Its behaviour as an electron rich aromatic compound in reactions, its facile metallation at one or both the rings and the unusual ability to stabilise carbocations at its benzylic-like position are properties which pave the way to prepare functionalised substituted ferrocenes. The ease of

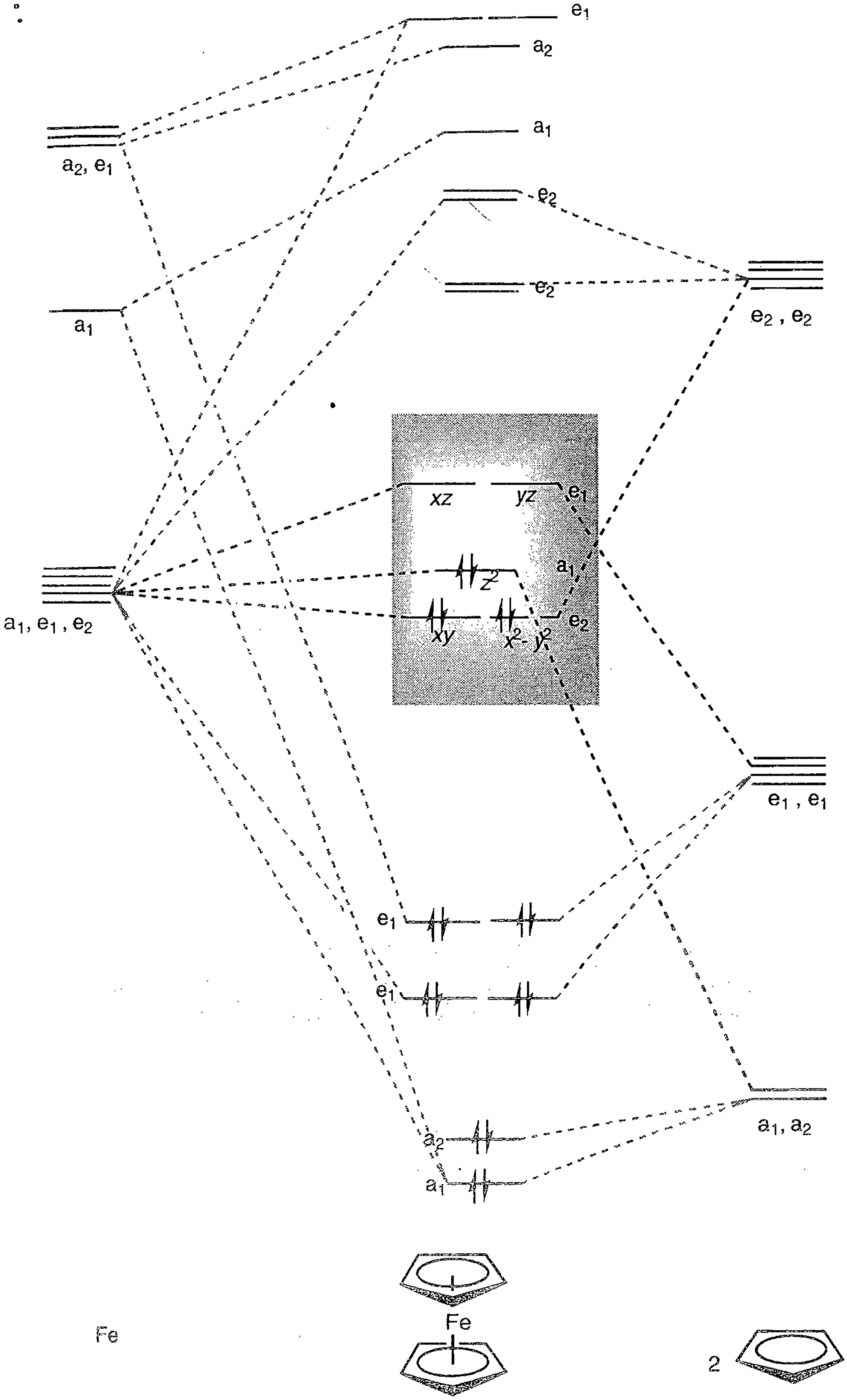


Fig. 18.3 Molecular orbital diagram of ferrocene (eclipsed form)

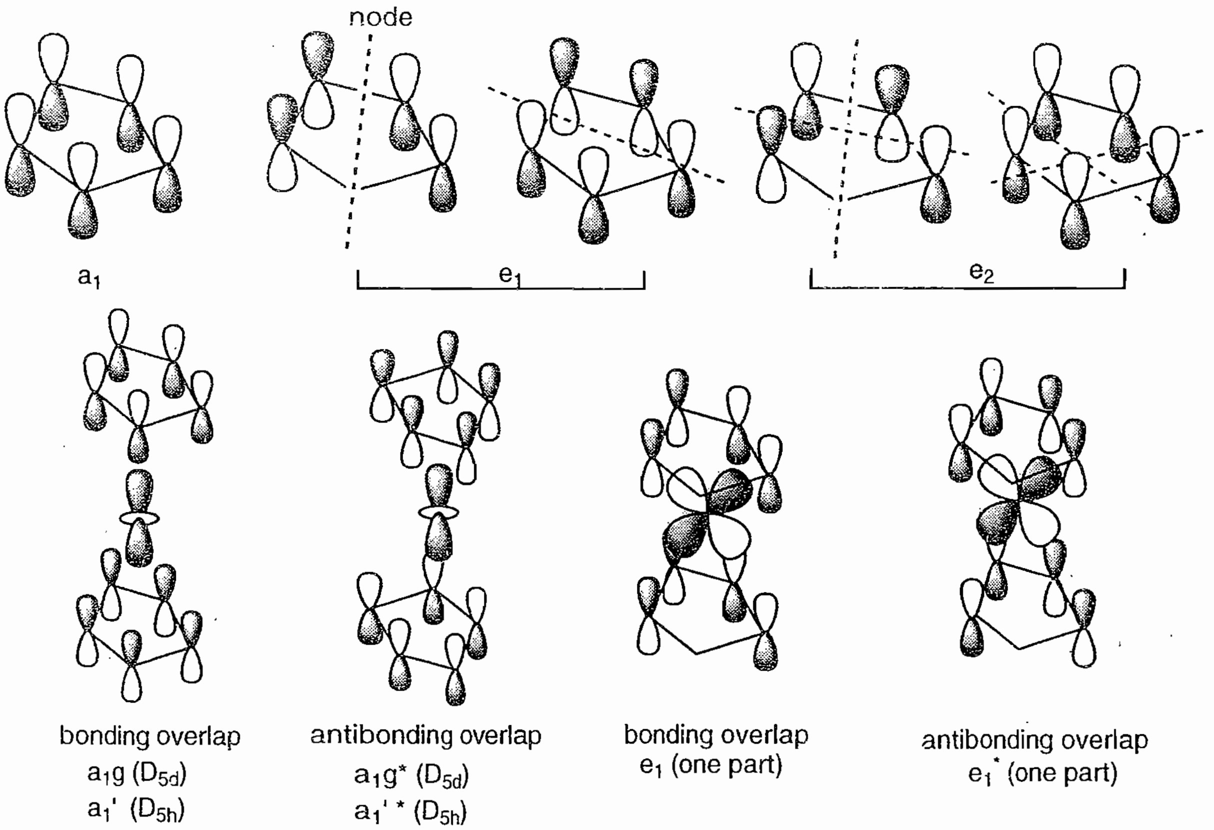


Fig. 18.4 Symmetry of the ligand group orbitals of Cp ligand and representative pictures of bonding and antibonding overlap with metal orbitals

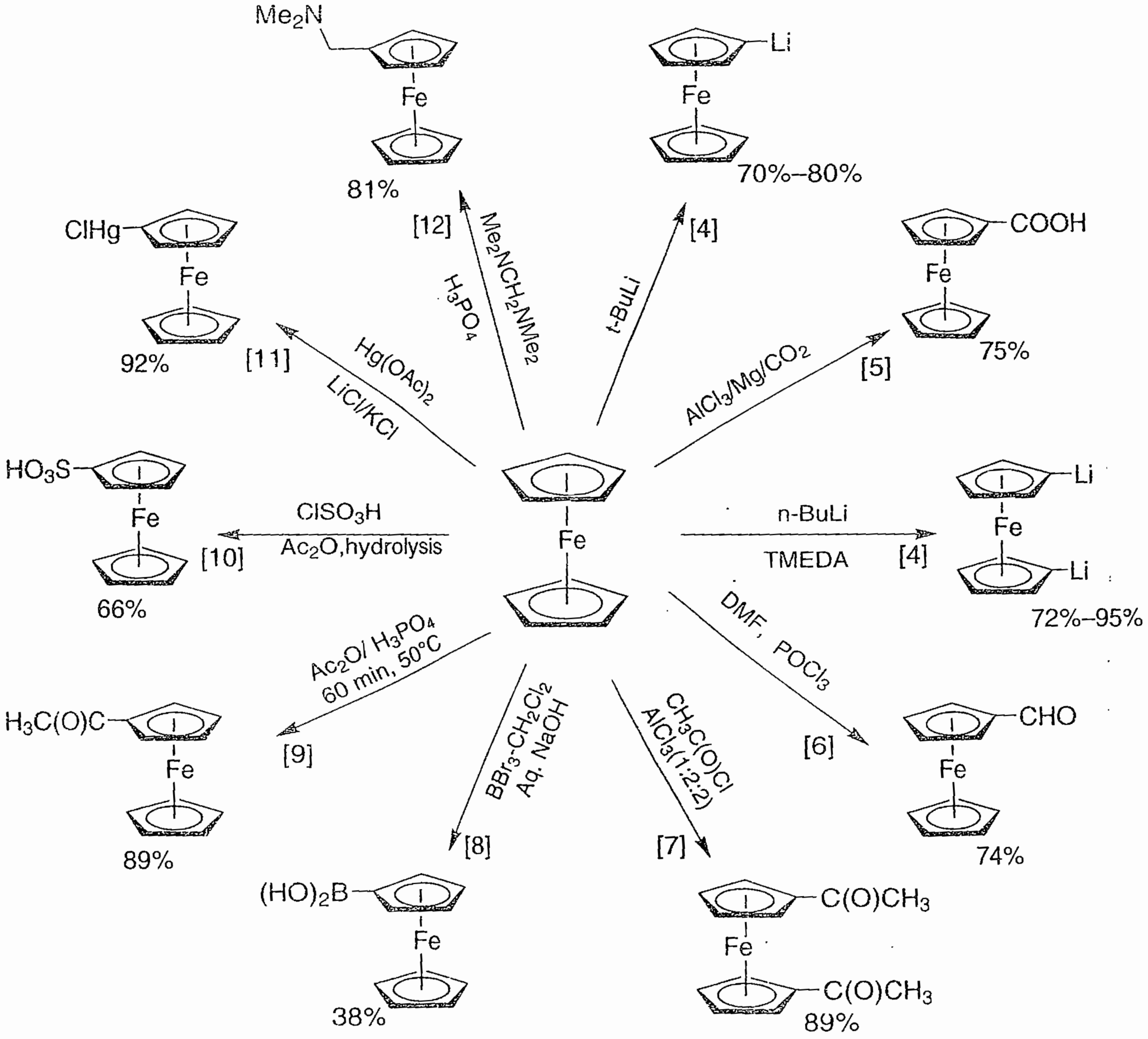
electrophilic substitution, the scope of having planar chirality, and the presence of a redox active iron atom in the soluble form, has facilitated the development of ferrocene chemistry in diverse directions. A major interest in ferrocene chemistry is centered around developing chiral chelating ligands with planar and lateral chirality and their use as prochiral ligands in asymmetric catalysis. The use of ferrocenophanes as precursors for ferrocene based polymers is another important application.

18.2.1 Basic Chemical Reactions of Ferrocene

Most of the reactions involving ferrocene revolve around the two Cp rings. Ferrocene is aromatic (similar to benzene) and the organic chemistry is important since in some cases (for example, electrophilic substitution reactions) its reactivity is superior to arenes. The resonance stabilisation energy in ferrocene is 56 kcal/mol. The basic reactions of ferrocene and moderate to high yielding reactions of some of its synthetically important derivatives are described in the following schemes.

18.2.2 Reactions of Acetyl Ferrocene and Formyl Ferrocene

In comparison to benzene, toluene or phenol, the 6π electron system of ferrocene is more electron rich and thus undergoes aromatic substitution reactions rather easily. In the Friedel-Crafts acetylation, ferrocene is 3.3×10^6 times more reactive than benzene and



Scheme 18.1 Basic chemical reactions of ferrocene with product yields[‡]

about 1 × 10^3 times more reactive than mesitylene. Friedel–Crafts acetylation using acetyl chloride and aluminum chloride results in the 1,1′-diacetyl compound. Only one isomer is formed which points to free rotation of the Cp rings around Fe. When excess of acetylating agent is used, 1,1′ and 1,2-derivatives (same ring substitution) are formed in a 60:1 ratio. This is because, deactivation of the Cp ring occurs once an acetyl group is substituted. Under milder conditions or when acetic anhydride and phosphoric acid are used, only mono-acetylation of ferrocene occurs. Acetyl ferrocene is the precursor for a variety of other useful compounds and is also the precursor for making a host of chiral derivatives. The widely used derivatives are alkynyl ferrocene and N,N-dimethyl-1-ferrocenylethylamine (Ugi's amine). This compound, first prepared by Ivar Ugi, opened up diverse synthetic routes for

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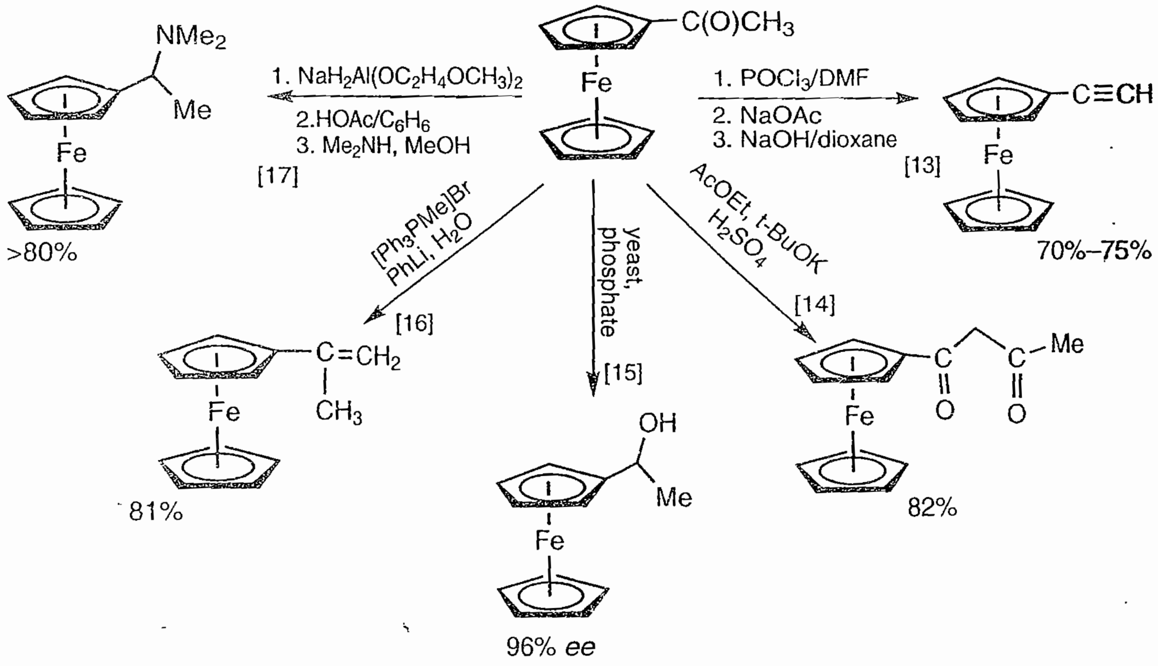
[‡] Numbers within square brackets denote the original reference of the reaction

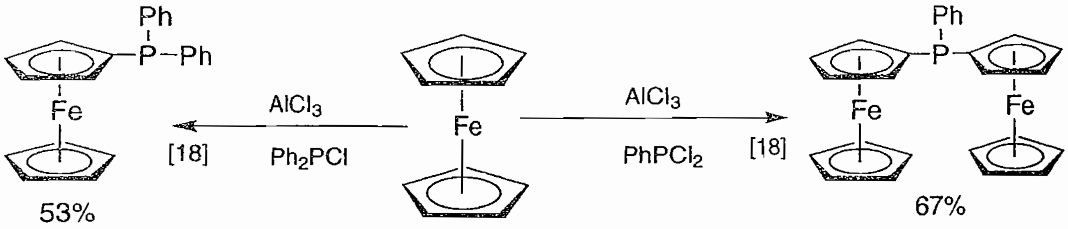
introducing both planar and central chirality on ferrocene derivatives. Enantioselective reduction of acetyl ferrocene and other similar ketones has been achieved not only by conventional reagents but also by microorganisms such as baker's yeast and enzymes such as horse liver alcohol dehydrogenase. Wittig reaction carried out on acetyl ferrocene using $(Ph_3PMe)Br$ resulted in good yields of 2-ferrocenylpropene (Scheme 18.2). The Vilsmeier reaction on ferrocene yields ferrocene carboxaldehyde (formyl ferrocene) which on Wittig reaction with Ph_3MePBr yields vinyl ferrocene in good yields. Ferrocene carboxaldehyde on reduction with $NaBH_4$ gives ferrocene methanol almost quantitatively.



Scheme 18.2 Reactions of acetyl ferrocene with product yields

Friedel–Crafts type reactions on ferrocene using $AlCl_3$ and phenylphosphorus chlorides results in air stable ferrocene derived tertiary phosphines. However, similar reactions with organosilyl chlorides have not been quite as successful due to the high rate of protolytic desilylation which is a competing reaction.

Ferrocene undergoes a wide variety of electrophilic substitution reactions. However, there is a restriction on the nature of the electrophile as it should not be oxidising in nature, since ferrocene is prone to oxidation and the oxidised Cp_2Fe^+ (ferrocenium cation) will repel the electrophile. Therefore, nitration, halogenation and similar reactions cannot be carried out directly on ferrocene. The 17-electron ferrocenium ion complex is an excellent radical trap. It is because of this unique property that ferrocene is able to strongly stabilise an adjacent carbocation centre. Although it is mostly prepared in situ by reagents such as I_2 or H_2SO_4, air stable ferrocenium salts with an intense blue colour can readily be isolated by the reaction of ferrocene with oxidants such as *p*-benzoquinone or $FeCl_3$ (Eqs 18.1, 18.2)[19].



Scheme 18.3 Preparation of mono- and di-ferrocenyl phenyl phosphines

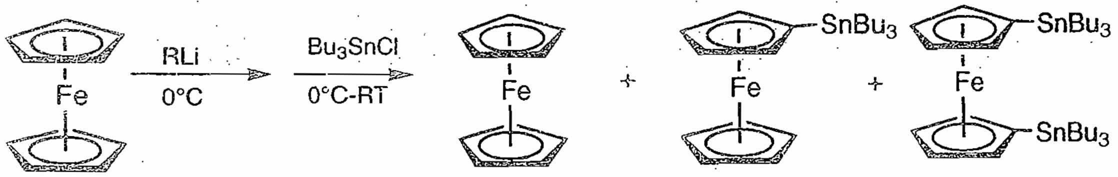
$$FeCp_2 + HBF_4.OEt_2 \xrightarrow[Et_2O]{p\text{-benzoquinone}} [FeCp_2][BF_4] \tag{18.1}$$

$$FeCp_2 + NH_4PF_6 \xrightarrow[H_2O/Acetone]{FeCl_3} [FeCp_2][PF_6] \tag{18.2}$$

18.2.3 Lithiated Ferrocenes and their Reactions

Lithiated ferrocenes are useful precursors for preparing a host of new ferrocene derivatives. Exclusive preparation of the monolithiated ferrocene in high yield has been quite cumbersome. The reaction of ferrocene with n-BuLi leads to the mono- and dilithiated products in a ratio of 70:30 and the overall conversion is only around 35%. Pure monlithiated ferrocene can be formed exclusively but in poor yield (25%) when the reaction is carried out in diethylether at low temperature and then brought to room temperature after 5–6 hours (known as Goldberg's procedure). The use of t-BuLi increases the yield of monolithiated product substantially (70%–86%) but some dilithiation also occurs. Kagan and coworkers have carried out a detailed study on lithiation with various lithium reagents under similar conditions (Table 18.1).

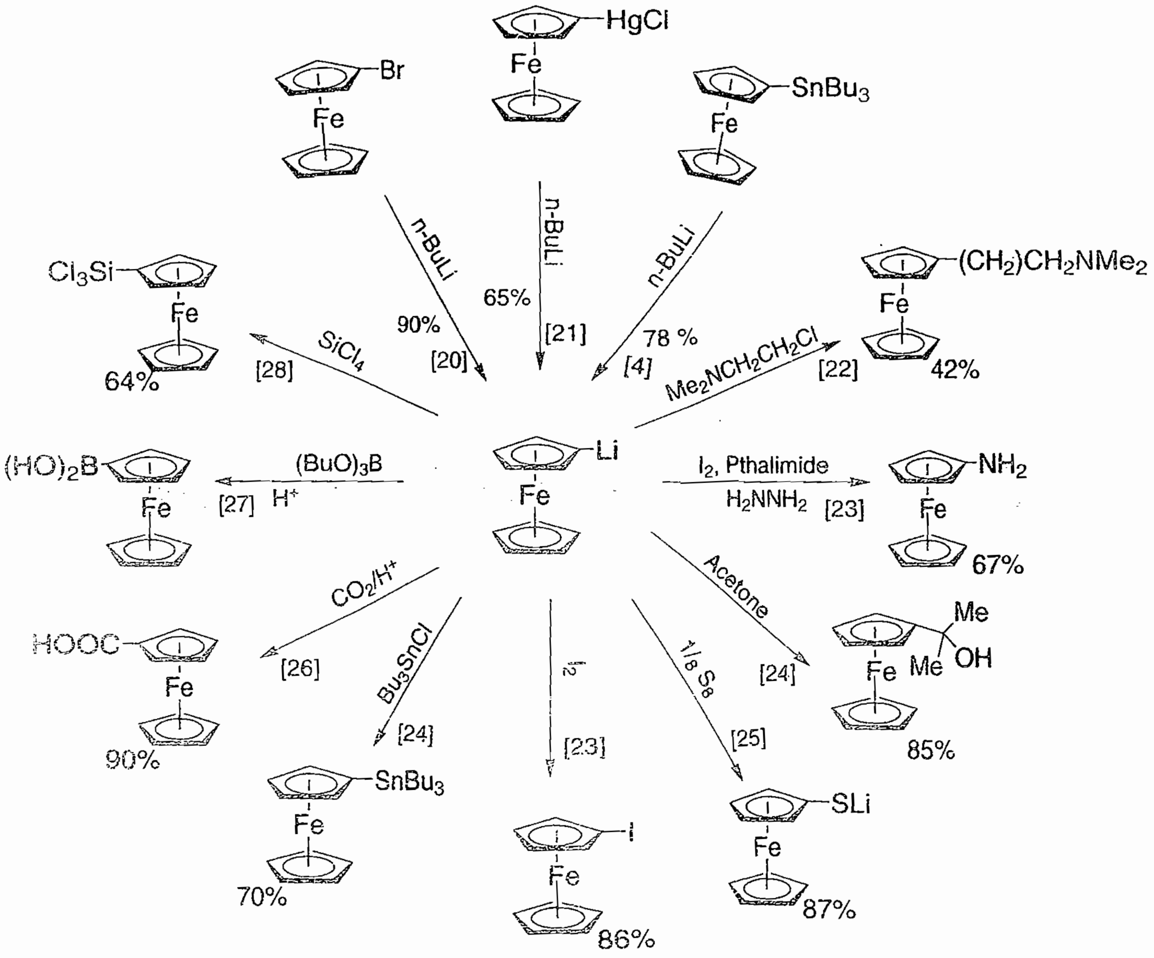
Table 18.1 Extent of ferrocene monolithiation using alkyllithium reagents



RLi	Solvent used	Unreacted ferrocene	Monosubstituted ferrocene	Disubstituted ferrocene
MeLi / LDA	THF	100	0	0
n-BuLi	THF	78	16	6
s-BuLi	THF/Et_2O	59	34	7
t-BuLi	THF/Hexane	33	60	7
t-BuLi	THF/Et_2O	26	63	11

LDA = Lithium diisopropylamide

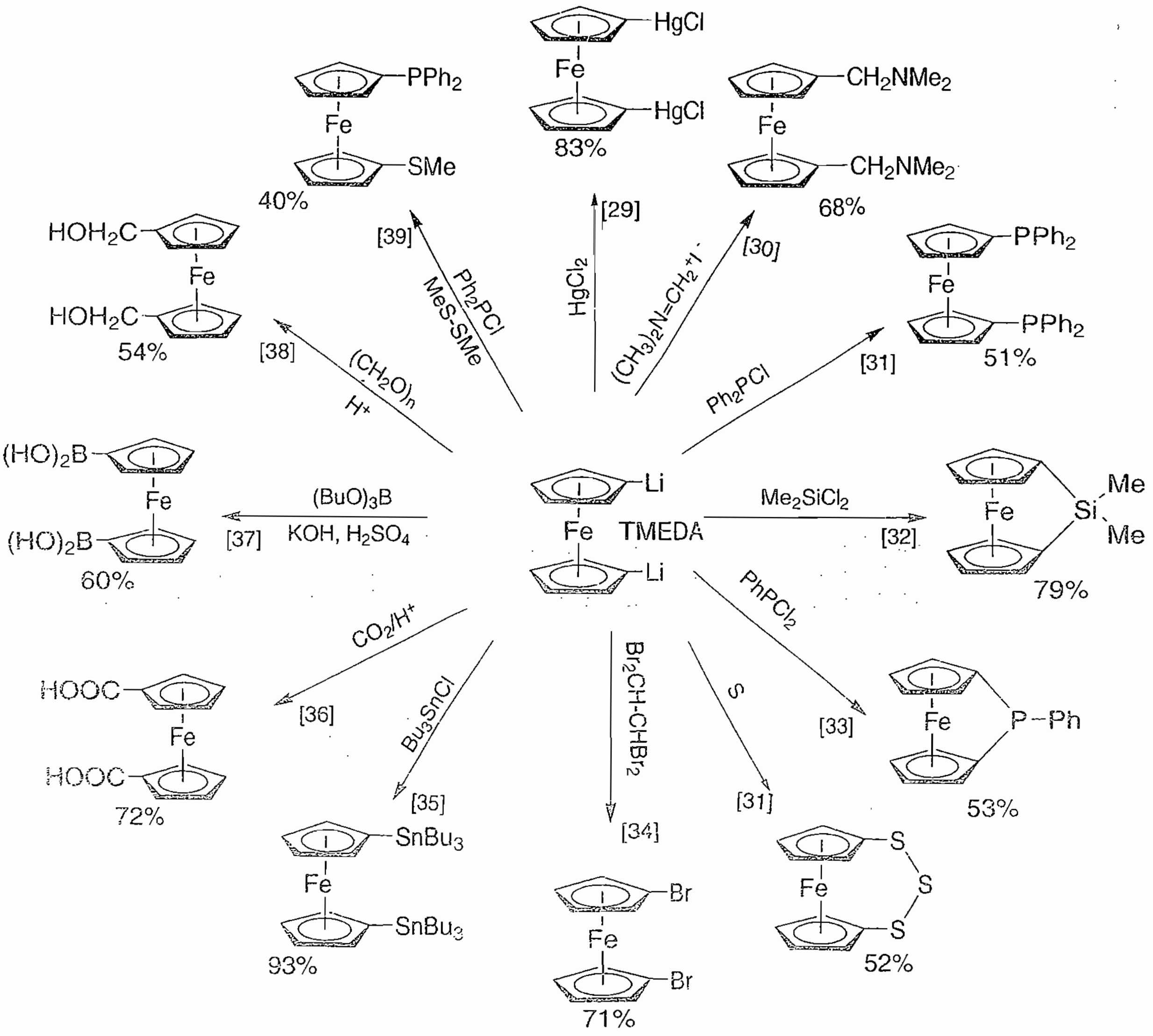
Mono and dilithiated ferrocenes are precursors for a wide variety of ferrocene derivatives as shown in Schemes 18.4 and 18.5. Dilithiated ferrocene can be obtained in almost quantitative yields by the reaction of n-BuLi with ferrocene in the presence of TMEDA. Although monosubstituted ferrocene derivatives have been prepared by reactions of monolithiated ferrocene with a variety of reagents, the yields are very poor in many cases (for example, nitroferrocene from N_2O_4 is 2%; aminoferrocene from $MeONH_2$ is 8%) and therefore such reactions are of no synthetic value. The requirement of t-BuLi, instead of the common and easily available n-BuLi, to get some appreciable yield of monolithiated ferrocene has also hampered the synthesis of derivatives by that route. In order to avoid the formation of disubstituted products in the lithiation reaction, n-BuLi can be reacted with ferrocene derivatives such as tributylstannyl, chloromercury or bromo ferrocenes. Insertion of chalcogens and carbon dioxide into the Fc–Li bond followed by hydrolysis has been an attractive high yielding method to prepare thiols, selenols and carboxylic acids. Silicon based ferrocene compounds are also prepared by the lithiation route as direct Friedel–Crafts reaction does not lead to these compounds in high yield. Iodoferrocene, which cannot be prepared by direct iodination of ferrocene, is obtained in good yields by the lithiation route (Scheme 18.4).



Scheme 18.4 Synthesis and reactions of monolithiated ferrocene with product yields

The reaction of $SiCl_4$ with monolithiated ferrocene resulted in good yields of trichlorosilylferrocene. This compound finds use in the synthesis of electroactive and surface-attached ferrocene materials. Iodoferrocene on further reaction with pthalimide and hydrazine gives aminoferrocene in reasonable yields. A variety of tethered ferrocene compounds especially polymer and dendrimer precursors have been synthesised by reactions of lithiated ferrocene with long chain molecules having haloalkane residues. Reaction of lithioferrocene with simple ketones, aldehydes and esters such as acetone, ethyl acetate and benzaldehyde results in the corresponding substituted alcohols in good yields.

The easy and high-yield synthesis of the TMEDA adduct of dilithiated ferrocene (structural studies indicated a complex adduct of dilithiated ferrocene and TMEDA in the ratio of 2:3) using n-BuLi has been a boon for the synthesis of 1,1′-disubstituted ferrocene derivatives (Scheme 18.5). A variety of chelating ligands such as dppf are prepared from $FcLi_2$ including chiral compounds. The ferrocenophanes, obtained by bridging the two

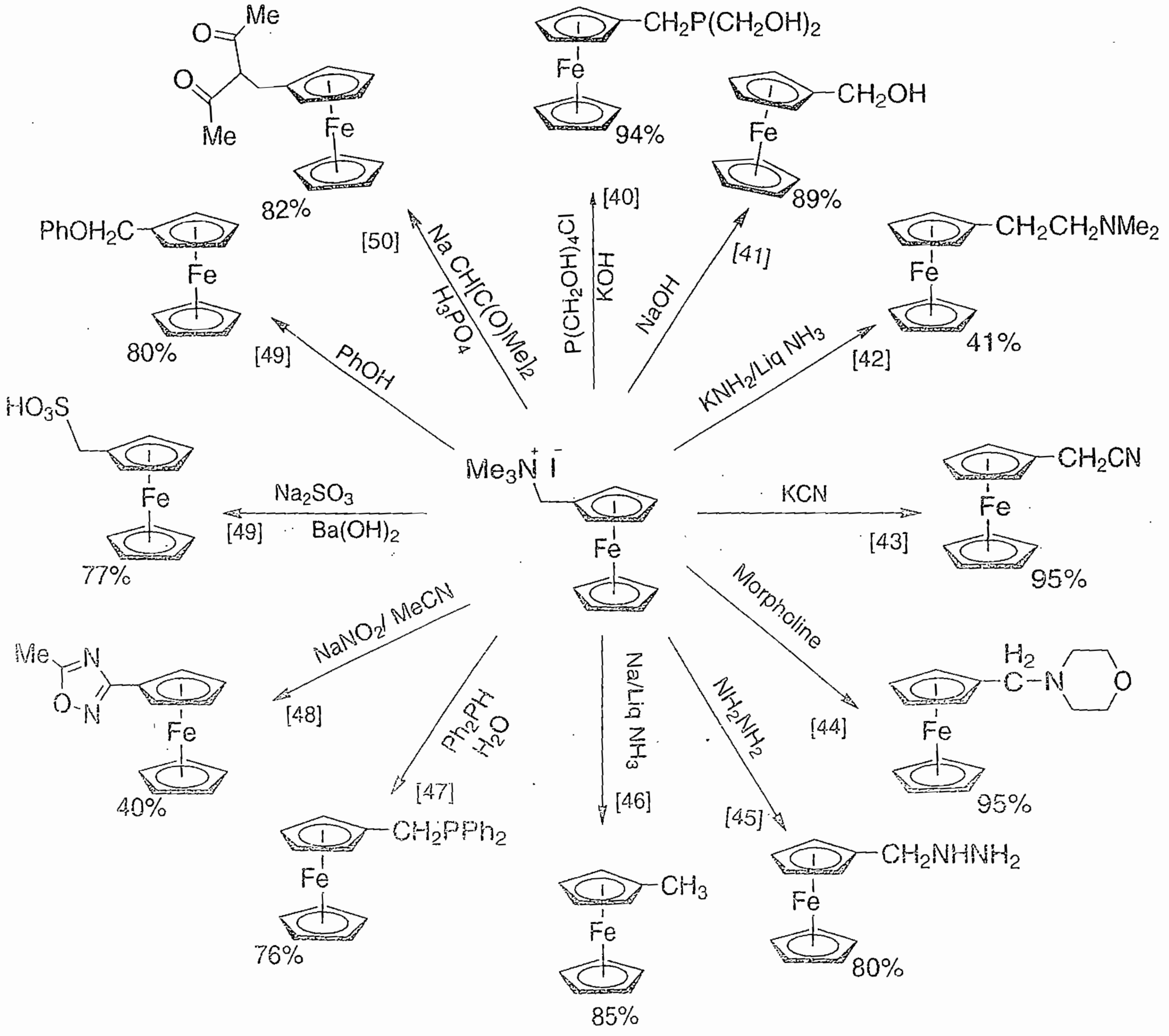


Scheme 18.5 Selected reactions of dilithiated ferrocene with product yields

Cp units, are often strained and are important precursors for the preparation of a host of ferrocene based polymers which have been achieved by ring opening polymerisation (see Section 19.2.3). Reaction of mono- and dilthiated ferrocene with tributylborate followed by hydrolysis is a convenient method for the synthesis of ferrocene mono- and diboronic acids. Bis(hydroxymethyl)ferrocene, a well known monomer of ferrocene derived condensation polymers, is easily prepared by the reaction of paraformaldehyde with dilithiated ferrocene.

18.2.4 (Dimethylaminomethyl)ferrocene and its Methiodide Salt

(Dimethylaminomethyl)ferrocene is easily prepared by the Mannich reaction in high yields. Interestingly, this reaction does not occur with benzene. The methyl iodide salt of this amine is obtained almost quantitatively from a reaction of the amine with MeI. This salt is the precursor for a host of novel ferrocene derivatives having a spacer between the Cp ring and functional group as shown in Scheme 18.6. These reactions are of importance as the related chiral

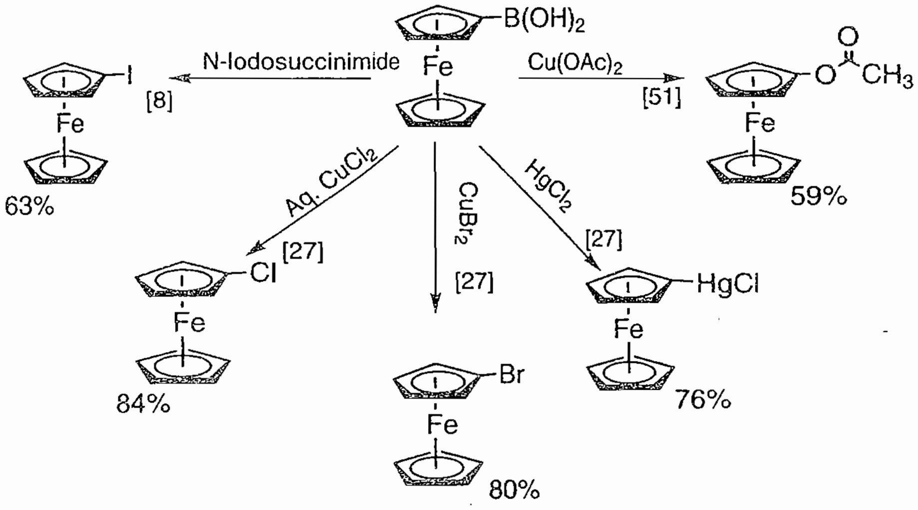


Scheme 18.6 Selected reactions of (dimethylaminomethyl)ferrocene methiodide

(dimethylaminoethyl)ferrocene has been one of the best precursors for preparing many chiral ferrocene compounds. The ferrocenyl methyl and ethyl carbocations [$FcCH_2^+$, $FcCH(Me)^+$] are resonance stabilised by the cyclopentadienyl ring and are intermediates in these substitution reactions. The amino methyl group is *ortho* directing and can stabilise *ortho* metallation on the same Cp ring by complexation of the metal (Li, Na, Pd and others) with the amino group. Such metallated compounds are useful for the synthesis of planar chiral compounds. Attempts to prepare 1,1′-bis (dimethylaminomethyl)ferrocene by Mannich reaction resulted in poor yields (17%). However, a better method for the same is to use Eschenmoser's salt (N,N-dimethylmethyledene ammonium) iodide on dilithiated ferrocene (Scheme 18.5).

18.2.5 Ferrocene Boronic Acid and Haloferrocenes

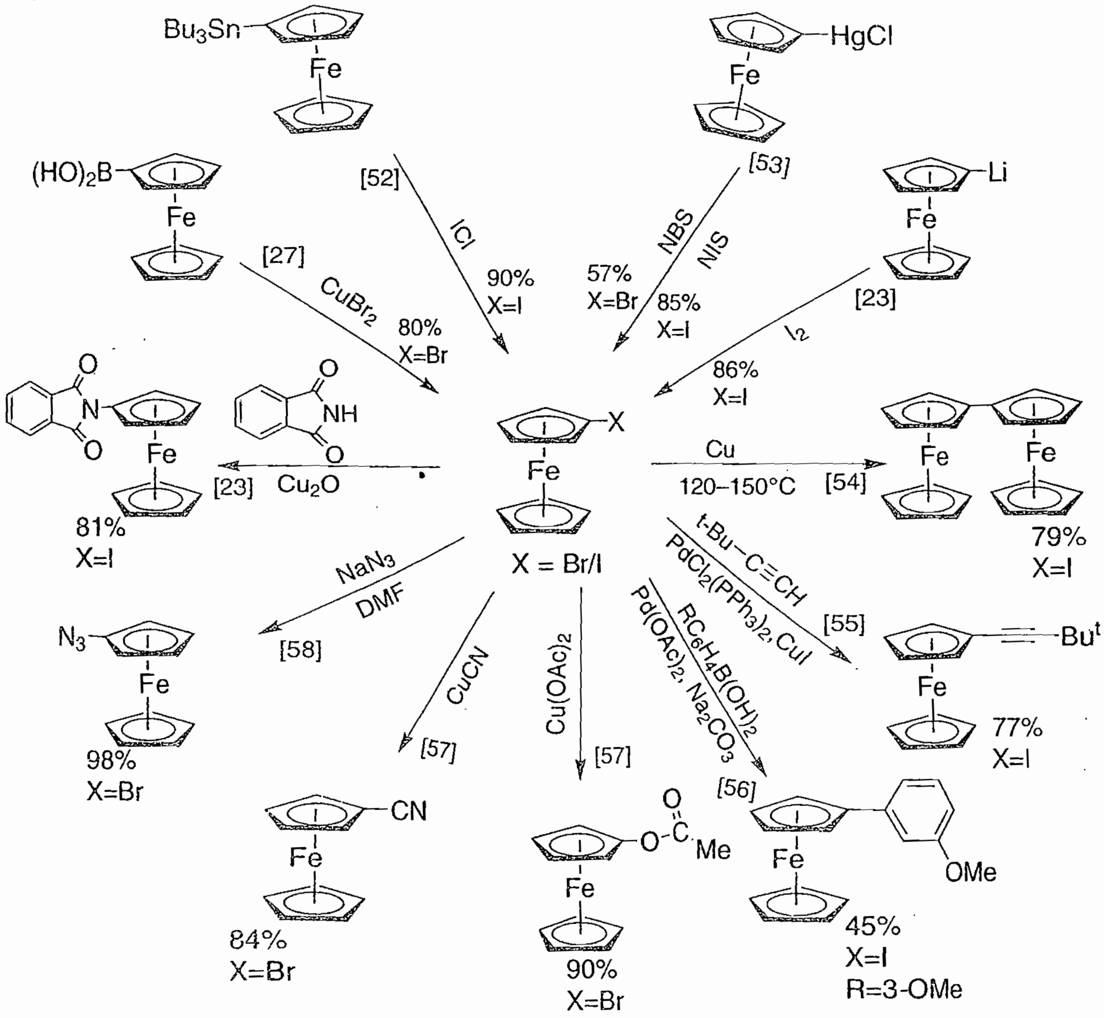
Boronic acid of ferrocene is an important precursor for the preparation of halo, acetyl and chloro mercury derivatives of ferrocene in good yields (Scheme 18.7). The recent spurt of activity on Suzuki cross coupling reactions also makes this molecule a useful reagent for cross coupling with aryl halides to generate ferrocenyl aryl compounds. Haloferrocenes – especially the bromo- and iodoferrocenes – are also highly useful for making ferrocenyl aryl, alkenyl and alkynyl compounds using palladium catalysed cross coupling reactions (Scheme 18.8). Haloferrocenes also offer good scope for realising azido and cyanoferrocene derivatives by their reaction with metallated reagents (such as NaN_3, CuCN) and amino ferrocene from N-ferrocenyl phthalimide (by the Gabriel synthesis using N_2H_4/EtOH) which cannot be easily prepared using other ferrocene based reagents.



Scheme 18.7 Reactions of ferrocene boronic acid

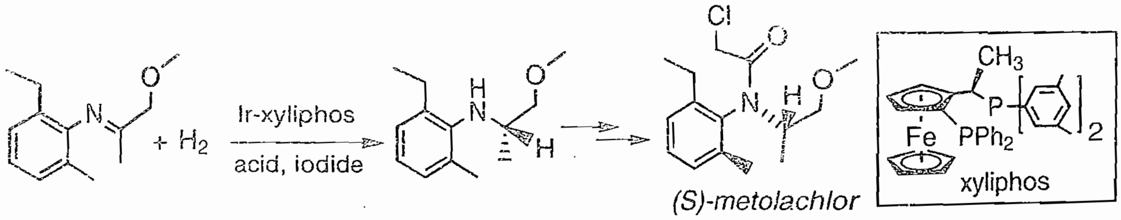
18.3 FERROCENE DERIVATIVES IN ASYMMETRIC CATALYSIS

A unique class of ferrocene derivatives – which is of particular interest to the pharmaceutical industry – involves chiral ferrocene based chelating ligands. These are useful reagents for



Scheme 18.8 Synthesis and reactions of bromo- and iodoferrocenes

the industrial preparation of many optically active compounds. A remarkable example of their utility is in the synthesis of a precursor of the herbicide (S)-*metolachlor* by an iridium–xyliphos catalysed asymmetric hydrogenation reaction (Scheme 18.9). This process constitutes one of the largest industrial scale enantioselective catalytic processes with TONs of 2,000,000 and TOFs of around 600,000 h^{-1}, at more than 10,000 tons per annum.



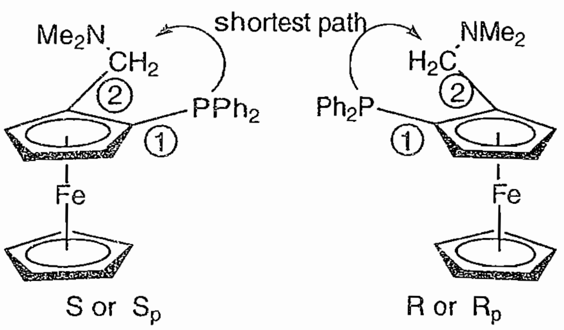
Scheme 18.9 Industrial synthesis of (S)-*metolachlor* using iridium–xyliphos catalyst

18.3.1 Chirality in Ferrocene Derivatives

Basically three different kinds of chirality (planar, lateral and axial) are observed in ferrocene based ligands.

Planar chirality

Planar chirality is unique for compounds such as metallocenes, paracyclophanes and half sandwich compounds; it is obtained by the loss of a plane of symmetry in the metallocene molecule. Thus, mirror images of ferrocene having two different substituents on the same Cp ring are not superimposable. One of the advantages of planar chirality is that it does not undergo racemisation. The Cahn–Ingold–Prelog rules for assigning planar chirality in ferrocene are shown in Fig. 18.5.



The molecule is viewed from the top of the Cp ring having two different substituents.
If the *shortest path* from the substituent with the highest priority *to that following in hierarchy* is clockwise, the planar chirality descriptor is R or R_p, if opposite it is S or S_p.

Fig. 18.5 Method of assigning planar chirality descriptors (according to Schlögl; 1964)

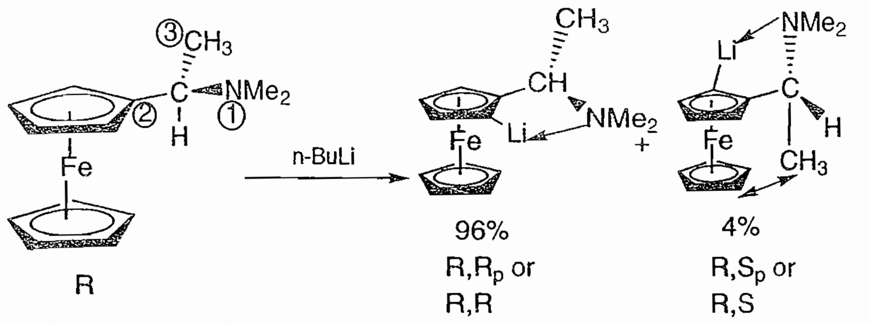
Central chirality

Central chirality, also known as lateral chirality, is the second type of chirality found in ferrocene and similar compounds. It is basically due to a chiral carbon centre directly connected to the Cp ring. Ivar Ugi was the first to achieve the synthesis of a useful lateral chiral ferrocene derived amine in 1970. The Ugi's amine, [(R)-N,N-dimethyl-1-ferrocenylethylamine] can be made to undergo a resolution step in which the Cp ring of aminoethyl ferrocene, having a chiral carbon atom bound to it, is lithiated. Selectivity is observed (Fig. 18.6); the lithiated product, having the methyl group on the chiral carbon, projecting away from the second Cp ring, is formed in large excess in this reaction. The disubstituted product is formed when lithium is replaced in an electrophilic substitution reaction. This process is highly diastereoselective and since the Me_2N group can be easily replaced by a variety of derivatives, specific chiral configurations can be produced.

Axial chirality

Axial chirality is the third type of chirality and is present specifically in 1,1′ unsymmetrically disubstituted ferrocenes. Chelating ferrocene-based ligands having two different groups at the 1 and 1′ positions do not possess planar chirality. However, when they coordinate to a metal as a chelate, two rotamers (1) and (2) are produced which are non-superimposable due to the rotation of the Cp rings in opposite directions. This type of chirality is known as axial chirality (Fig. 18.7).

Stereoselective lithiation by Ugi's method



When both lateral and planar chirality are present in a molecule, the first chiral descriptor indicates the lateral chirality

Fig. 18.6 Method of assigning planar chirality descriptor along with central chirality

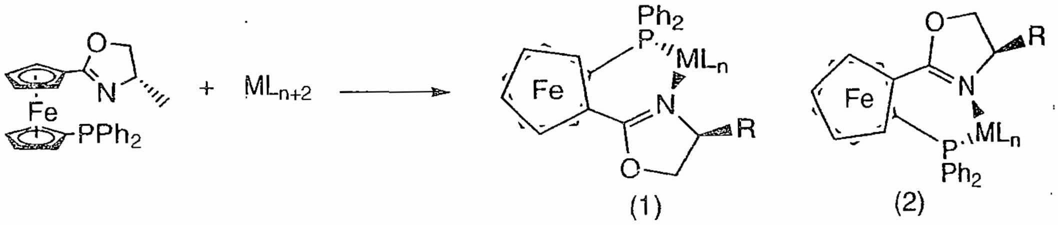
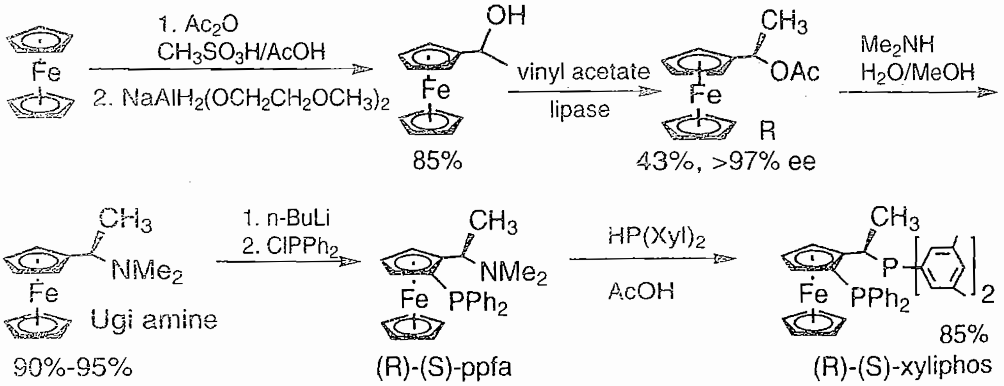


Fig. 18.7 Representation of axial chirality

18.3.2 Synthesis of Chiral Ferrocene Based Compounds

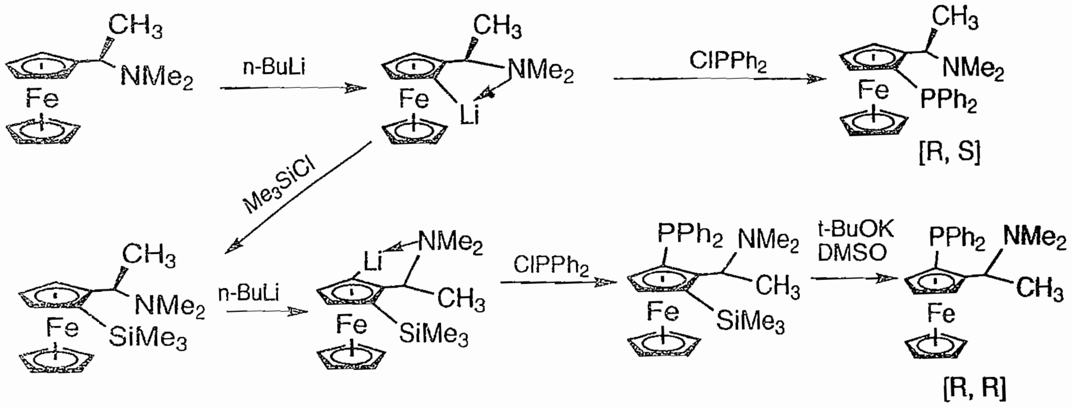
There are ferrocene compounds that have one or more of the above types of chiralities present in the same molecule. The ligand ppfa [(R)-N,N-dimethyl-1-(2-diphenyl phosphino) ferrocenylethylamine] (Scheme 18.10), obtained from the reaction of the lithiated Ugi's amine with Ph_2PCl, is the first reported example of a planar chiral enantiomerically pure ferrocenyl phosphine. Later, a series of 1,2-disubstituted chiral ferrocene derivatives were prepared using this strategy based on the Ugi's amine. In addition, two more widely used synthetic strategies are available currently for the preparation of enantiomerically pure 1,2-disubstituted ferrocenes—the oxazoline approach which is based on the easy preparation of ferrocenyl phosphino oxazolines and the sulphoxide based method which makes use of a cyclic sulphite as the precursor.[59, 60, 61]



Scheme 18.10 Synthesis of the Ugi amine and Xyliphos ligands

Synthesis based on Ugi's amine

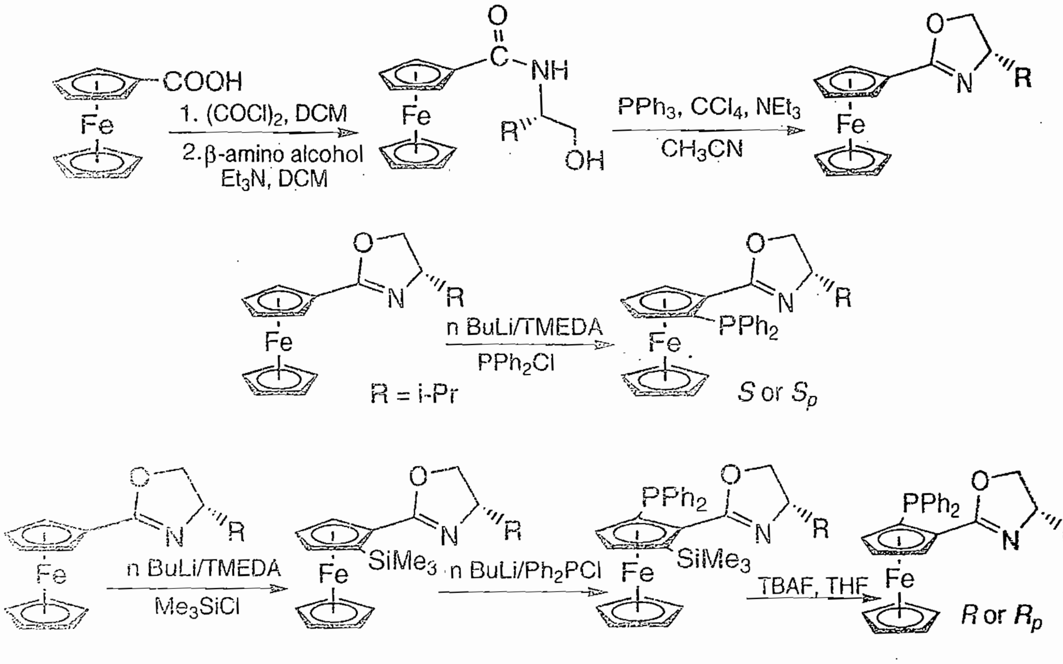
Industrial synthesis of the chiral ligand Xyliphos, used in metolachlor manufacture has been carried out using the Ugi's amine (Scheme 18.10). Chiral resolution was carried out on the precursor alcohol using the enzyme lipase in this industrial synthesis although many other methods for chiral resolution are also available. As shown in the final step, the Ugi's amine method allows a further sterospecfic S_N1 type reaction on the aminomethyl moiety with different species such as phosphines and amines, carried out with retention of configuration. An important feature of this methodology is that the formation of both the optical antipodes of the Ugi's amine are equally feasible (Scheme 18.11).



Scheme 18.11 Synthesis of [R,S] and [R,R] diphenylphosphino derivatives of the Ugi's amine

Synthesis based on oxazolines

Ferrocenyl oxazolines are easily prepared from ferrocene carboxylic acids and amino acids (Scheme 18.12). These are known to be good *ortho* directing groups for lithiation on the



Scheme 18.12 Synthesis of chiral oxazoline derivatives of ferrocene

Cp ring. Similar to the Ugi's amine, planar chiral phosphine derivatives of both R_p and S_p configuration can be prepared from the ferrocenyl oxazolines. Oxazoline is a component in many 1,1′-disubstituted ferrocene based bidentate ligands as well. Fc-Phox is a well known chiral phosphine based on ferrocenyl oxazoline (Fig. 18.8).[62]

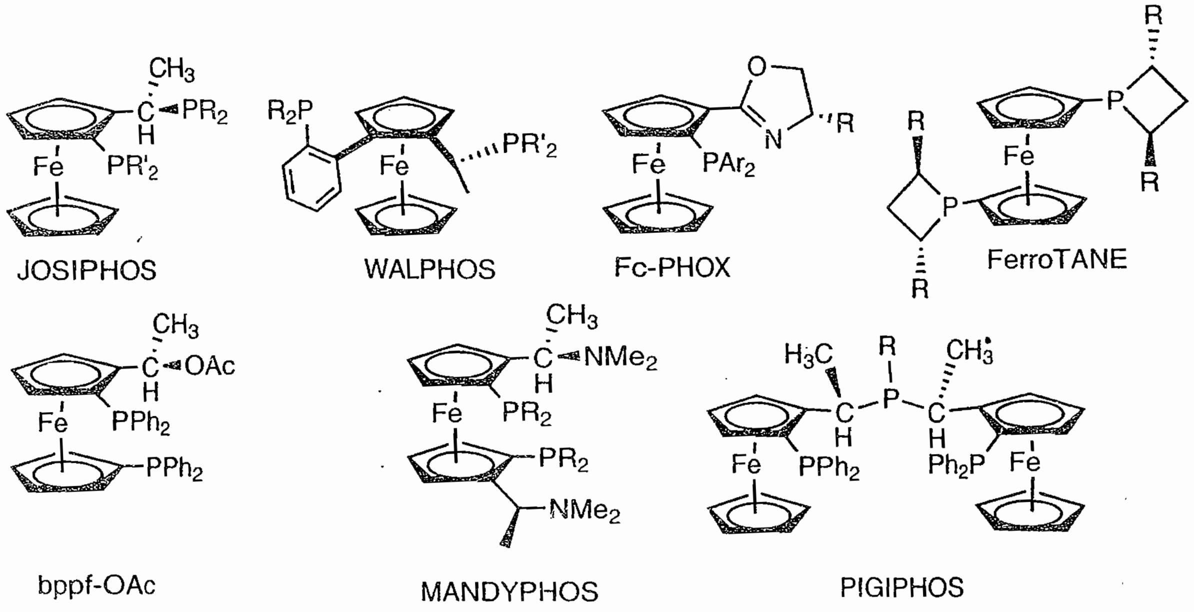


Fig. 18.8 Examples of ferrocene derived multidentate phosphine ligands

Synthesis based on sulphoxide

A third method to prepare 1,2-disubstituted ferrocenyl compounds having planar chirality is based on an efficient asymmetric synthesis of a ferrocenyl sulphoxide and it does not require the conventional chiral resolution step. In this 'sulphite route' an enantiomerically pure cyclic sulphite (a) is converted to a sulphinate (b) which is then transformed to a ferrocenyl sulphoxide (c). The enantiomerically pure t-butyl sulphinate (b) on reaction with ferrocenyllithium gives t-butylferrocenyl sulphoxide. This and other similar sulphoxides prepared by the sulphite method were found to be enantiomerically pure. After a diasteroselective *ortho* metallation step, the sulphinylated *ortho* directing group can be either reduced to a thioether (Fesulphos ligand) or it can act as a removable group by C–S cleavage when reacted with t-BuLi (Taniaphos ligand) (Scheme 18.13).

Ferrocene derived chiral phosphines are used industrially on a large scale in many processes. In addition to the *metolachlor* synthesis by Ciba, Lonza in Switzerland uses the Josiphos class of compounds to catalyse the stereoselective hydrogenation step in the synthesis of *biotin* (Scheme 18.14). The growing research in planar chiral ferrocene derivatives will be of special interest to chemical companies, especially the pharmaceuticals, in future. A large portion of drugs are chiral and their syntheses stereoselective in nature, the need for better chiral catalysts to improve efficiency in chemical reactions is definitely the top priority for such industries.

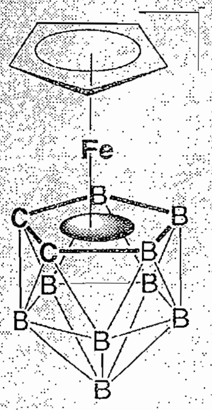
In addition to the 1,2-disubstituted ferrocene based chiral phosphines, a host of other 1,1′-disubstituted, 1,1′,2-trisubstituted and 1,1′,2,2′-tetrasubstituted phosphines on the ferrocene have been found to be useful in asymmetric catalysis and many of them are commercially available. A few well known examples of such ferrocene based phosphine ligands covering the different types of substitution are shown in Fig. 18.8.[63]

Variations on the ferrocene theme: Carbollide and bucky ferrocenes

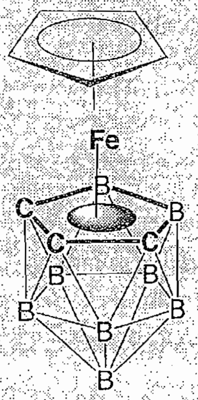
The stability, reactivity and electroactivity of ferrocene have stimulated the imagination of chemists across the world and many attempts have been made to prepare hybrids of ferrocenes with other ligands which resemble the cyclopentadienyl group. The most well known among these are the ferrocene carbollide discovered as early as 1965 by M F Hawthorne and the relatively recent *bucky ferrocene* discovered by E Nakamura in 2002.[64-67]

Ferrocene carbollides

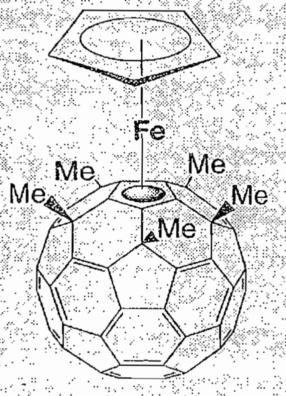
The reaction of the dicarbollide ion $[1,2\text{-}C_2B_9H_{11}]^{2-}$ with $FeCl_2$ along with Cp^- followed by reduction with sodium amalgam resulted in the formation of ferradicarbollide $(\eta^5\text{-}Cp)Fe(\eta^5\text{-}1,2\text{-}C_2B_9H_{11}]^-$ (A) which is stable and obeys the 18 electron rule. The structure of the ferradicarbollide showed a classical sandwich geometry with the Fe...C_2B_3 and Fe...C_5 distances equal to 1.437 and 1.663 Å respectively, the latter value close to that of ferrocene (1.660 Å). The planar C_2B_3 and C_5 rings are nearly eclipsed and almost parallel to each other. A similar neutral ferra-tricarbollide $[1\text{-}Cp\text{-}1,2,3,4\text{-}FeC_3B_8H_{11}]$,(B) was reported in 2005; it was prepared from a photolytic reaction between $NMe_4^+[7,8,9\text{-}C_3B_8H_{11}]^-$ and $CpFe(C_6H_6)]^+BF_4^-$.



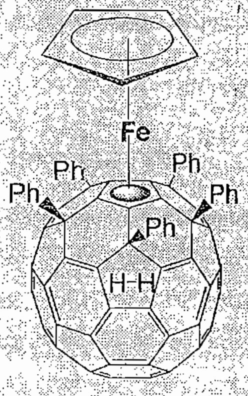
$[1\text{-}Cp,1,2,3\text{-}FeC_2B_9H_{11}]$
A



$[1\text{-}Cp,1,2,3,4\text{-}FeC_3B_8H_{11}]$
B



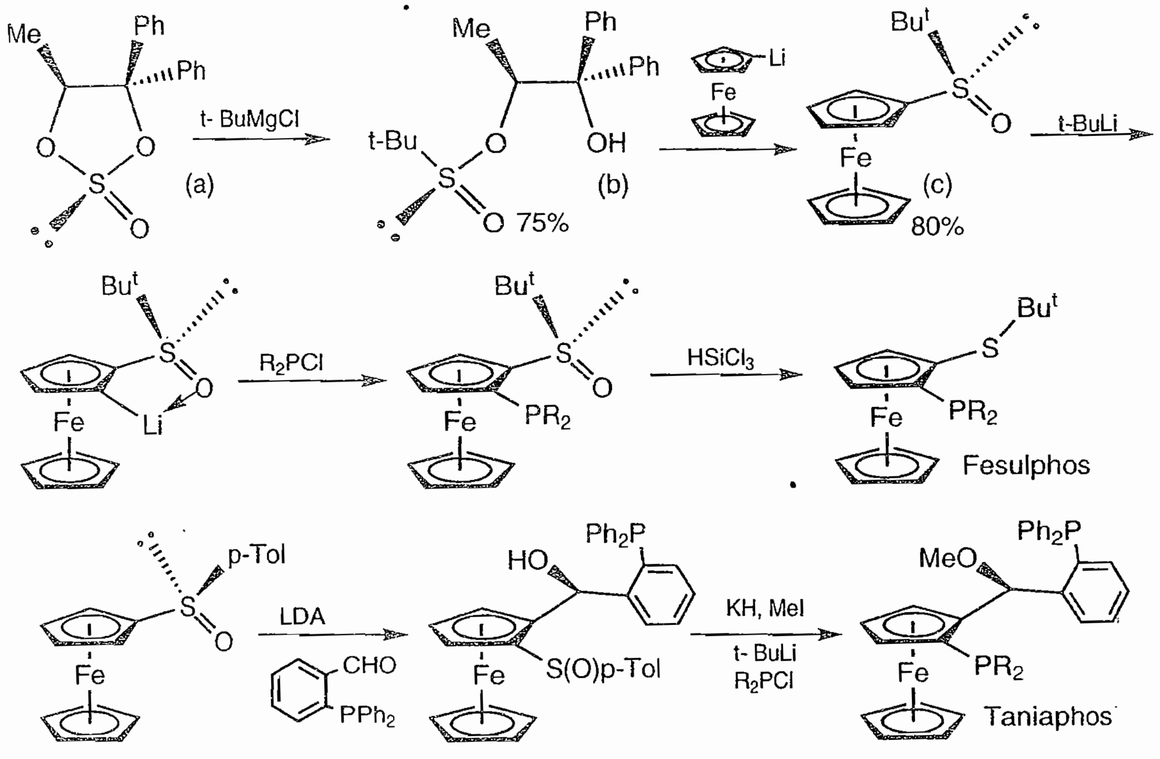
$Fe(C_{60}Me_5)(Cp)$
C



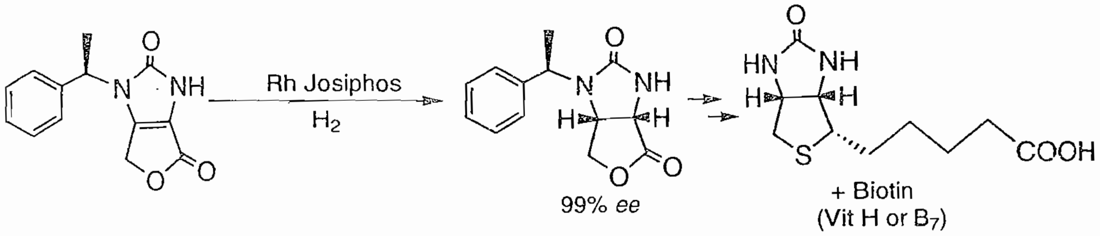
$Fe(H_2@C_{60}Ph_5)(Cp)$
D

Bucky ferrocenes

The idea of combining ferrocene and C_{60} through face to face fusion of the two molecules has been in the mind of chemists since the discovery of C_{60}. However, for a long time only η^2-fullerene–metal complexes were being discovered. The breakthrough in making a stable η^5-derivative of fullerene was achieved by using derivatives of C_{60} and C_{70} which were pentasubstituted by methyl or aryl groups around the outer periphery of a five membered ring. Heating $C_{60}Me_5H$ and $[FeCp(CO)_2]_2$ at 180°C resulted in the neutral hybrid ferrocene compound $Fe(C_{60}Me_5)Cp$ (C). Later on, the hydrofullerene analogue $Fe(C_{60}H_5)(Cp)$ was also prepared. Another variation of this compound was one having a H_2 molecule encapsulated inside the C_{60} unit (D). The compounds were structurally characterised and the H_2 encapsulated molecule $Fe(H_2@C_{60}Ph_5)(Cp)$ also showed a unique chemical shift in its ^{1}H-NMR for the encapsulated H_2 unit at $\delta = -10.39$ ppm as opposed to $\delta = -1.44$ for $H_2@C_{60}$.



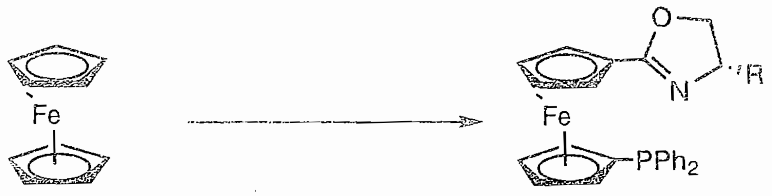
Scheme 18.13 Synthesis of Fesulphos and Taniaphos planar chiral ligands



Scheme 18.14 Use of rhodium--Josiphos catalyst in the synthesis of biotin

Problems and Exercises

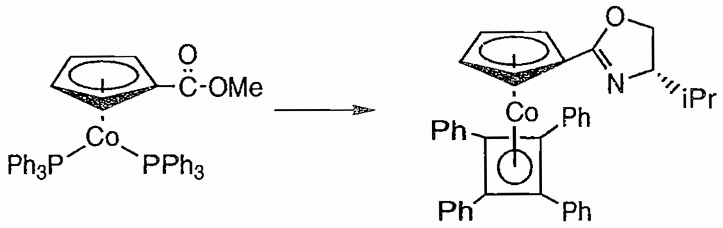
18.1. Given that 1,1′-ferrocene dibromide on reaction with s-BuLi and followed by CO_2 and hydrolysis gives the monocarboxylated product, show stepwise how ferrocene is converted to oxazolinyldiphenyl phosphinoferrocene in the following transformation.



18.2. Using a crystal field diagram, indicate the HOMO of cobaltocene and the electron occupancy of the metal orbitals. Label the orbitals and show their Mulliken symbols.

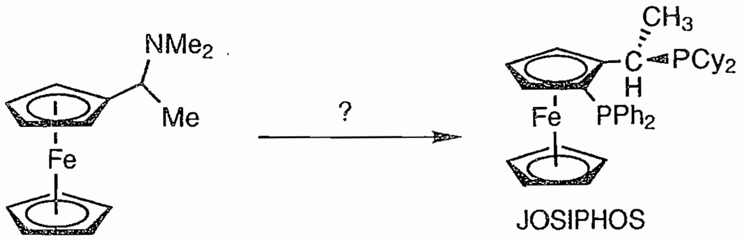
18.3. The observed magnetic moments of Cp_2Mn, Cp_2V, Cp_2Co and Cp_2Ni are 5.81, 3.84, 1.76 and 2.86 respectively. Using the MO picture of ferrocene, draw the valence shell electronic configuration of these metallocenes. Assume the metallocenes to be staggered.

18.4. Starting from the given half sandwich compound, show the steps involved in the preparation of the metallocene oxazolidene derivative.

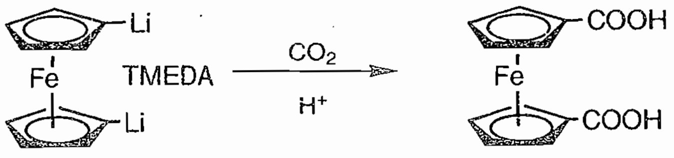


18.5. Show the steps involved in the preparation of ferrocenyl acetylene, starting from ferrocene by (a) palladium catalysed cross coupling reaction and (b) via acetyl ferrocene. Which one of these two methods is better and why?

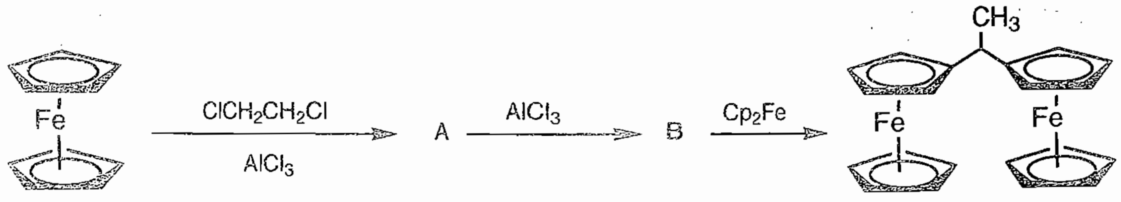
18.6. Show how the following Josiphos catalyst can be synthesised starting from chiral Ugi's amine.



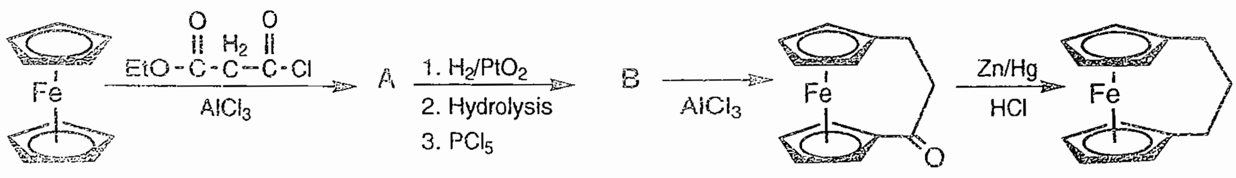
18.7. 1,1′-ferrocene dicarboxylic acid is synthesised by the following reaction. Will you expect the molecule to have an eclipsed or a staggered conformation? Explain.



18.8. Write the structure of compounds A and B in the following reaction scheme.

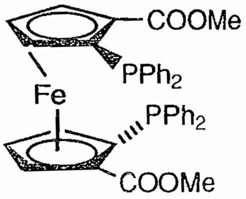


18.9. Write the structure of intermediate compounds A and B in the following reaction scheme.

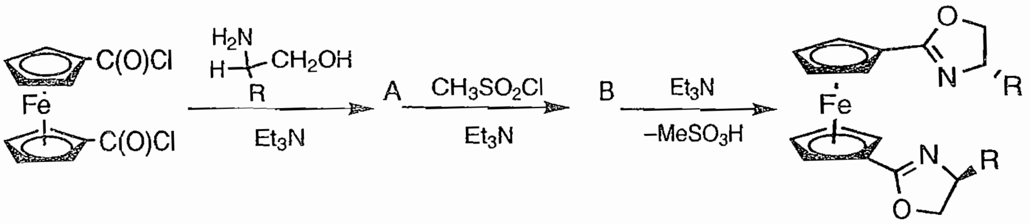


18.10. Between η^5-CpMn(CO)$_3$ and ferrocene, which will undergo electrophilic substitution faster and why?

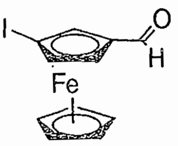
18.11. Indicate the type of chirality shown by the given molecule. Draw the structure of the product formed when this compound is treated with PdCl$_2$(CH$_3$CN)$_2$.



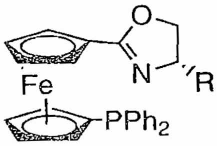
18.12. Draw the structures of the intermediate compounds A and B in the following synthesis of oxazoline derived ferrocene.



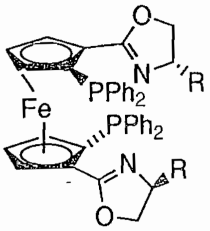
18.13. Which among the following compounds will show planar chirality? Assign the planar chirality descriptor for the following chiral compounds.



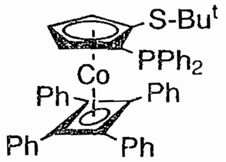
(a)



(b)

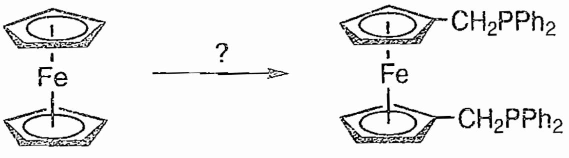


(c)



(d)

18.14. Similar to dppf, dpmf [bis(diphenylphosphinomethyl)ferrocene)] is a useful chelating biphosphine ligand. Suggest two synthetic schemes each with a minimum number of steps, for the preparation of this compound. Ph$_2$PH can be used as one of the reagents.



Supplementary reading

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ORGANOMETALLIC POLYMERS

CHAPTER 19

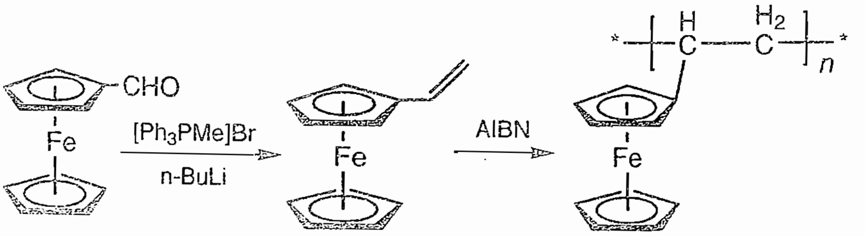
The first organometallic polymer was reported in 1955 by Arimot and Haven who prepared it by the polymerisation of vinyl ferrocene using a free radical initiator.[1] Significant strides have taken place in the development of organometallic polymers from 1990 onwards. The presence of transition metal atoms as part of a polymer chain can provide access to many interesting physical and catalytic properties which are characteristic of metal complexes, organometallics and solid state metal containing compounds. The soluble polymeric systems containing transition metals in the main chain yield novel materials which exhibit both the rheological characteristics of conventional polymers and technologically interesting electronic and photophysical properties associated with transition metal complexes.[2, 3]

The well known organometallic polymers can be broadly classified as:

- polymers having organometallic moieties as pendant groups,
- polymers having organometallic moieties directly incorporated in the main chain, and
- dendrimers or cascade molecules having organometallic moieties (at the core, periphery or branching points).

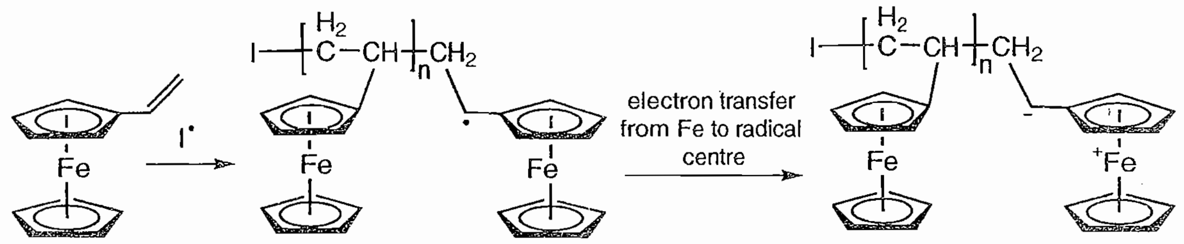
19.1 POLYMERS WITH ORGANOMETALLIC MOIETIES AS PENDANT GROUPS

Polymers having organometallic moieties such as ferrocene units as pendants were the first examples of organometallic polymers to be reported. Polyvinyl ferrocene and a host of its copolymers were the first among such polymers prepared by addition polymerisation. Vinyl ferrocene is prepared in high yield by the Wittig reaction of ferrocene carboxaldehyde with $(Ph_3PMe)Br$.[4]



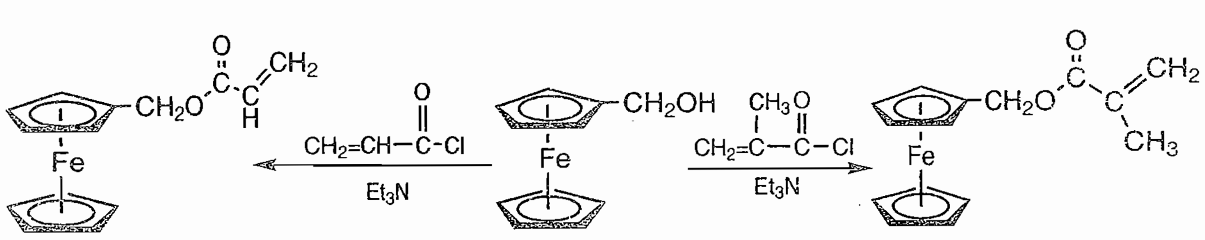
(19.1)

Polyvinyl ferrocene with molecular weights (M_n) in the range of 5,000–12,000 has been prepared by polymerisation of vinyl ferrocene using AIBN as a free radical initiator. It is soluble in solvents such as THF and shows electronic absorptions (λ_{max} = 440 nm) similar to ferrocene. Electrochemical studies on polyvinyl ferrocene indicate that the pendant ferrocene units do not interact with each other as revealed by a single oxidation potential. As such it is an insulator and upon doping with iodine, the polymer shows a conductivity of around 10^{-8} to 10^{-6} S/cm. The major impediment in the development of these polymers was the observation that free radical initiated addition polymerisation reactions, especially of vinyl substituted organometallic species, yielded low molecular weight polymers. Kinetic studies revealed that an internal electron transfer from iron to the radical centre generated an anionic chain-end which was quickly quenched resulting in an abrupt termination of chain growth (Scheme 19.1).



Scheme 19.1 Abrupt termination of chain growth of polyvinyl ferrocene

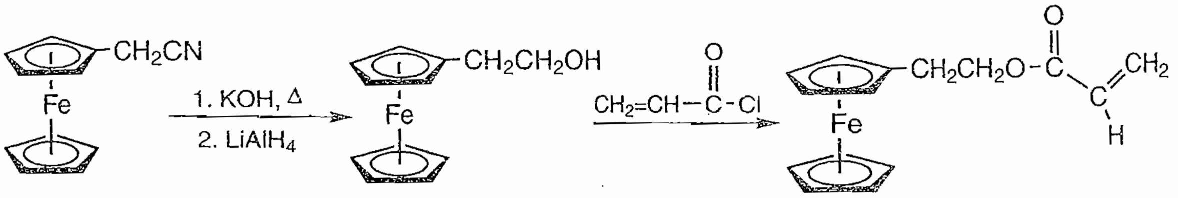
This problem was solved by devising acrylic monomers that had the propagating radical centre positioned away from and out of conjugation with the iron centre (Scheme 19.2). Radical initiated addition polymerisation of the monomers resulted in relatively high molecular weight polymers (polyferrocenyl methylacrylate: M_n = 20,130, M_w = 82,300; polyferrocenyl methyl methacrylate: M_n = 35,500, M_w = 211,000).[5]



Scheme 19.2 Synthesis of acrylic and methacrylic ferrocene derived monomers

However, the stable ferrocenylmethyl cation $FcCH_2^+$, generated during the polymerisation of the above monomers, made the polymer susceptible to hydrolysis in polar ionising solvents. This obstacle was overcome by designing 2-ferrocenylethyl derived acrylic monomers and homopolymerising them (Scheme 19.3).[6]

The pendant ferrocene moiety sharply increased the glass transition temperature (T_g) of these polymers in comparison to its non-organometallic analogues such as polystyrene and polymethyl acrylate. For example, polyvinyl ferrocene with molecular weights (M_n) ir the range of 5560–11400 has a T_g of 184–194°C while atactic polystyrene has a T_g of 95



Scheme 19.3 Synthesis of 2-ferrocenylethyl derived acrylic monomer

Similarly poly(methyl acrylate) and poly (methyl methacrylate) have T_gs of 3° and 105°C while poly(ferrocenyl methylacrylate) and poly(ferrocenyl methyl methacrylate) have T_gs in the range of 197–210°C and 188–195°C respectively.

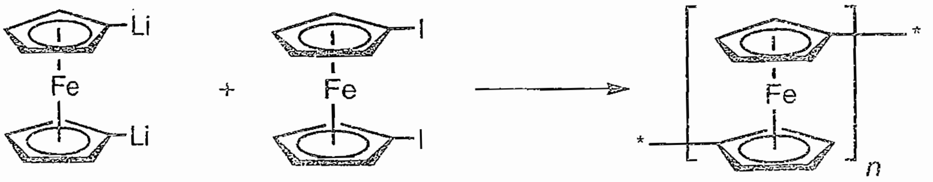
19.2 POLYMERS WITH ORGANOMETALLIC MOIETIES IN THE MAIN CHAIN

There are two types of polymers with organometallic moieties in the main chain. These polymers are obtained by condensation and by ring opening polymerisation methods.

The major types of organometallic condensation polymers known as of now are mostly based on ferrocene or are the platinum group metal based rigid rod polyynes.

19.2.1 Ferrocene Based Condensation Polymers

The synthetic strategy involved in preparing main chain ferrocene polymers through condensation is by using suitable 1,1′-disubstituted ferrocenes. Since ferrocene can be easily diacetylated and dilithiated, this property was used to make suitable monomers for condensation reactions. Early successful methods include reactions of 1,1′-dilithioferrocene with 1,1′-diiodoferrocene leading to polyferrocenylene. Extremely pure starting materials are required for this process and the molecular weights approach only about $M_n = 4000$. Condensation polymerisation of dilithiated ferrocene and Me_2SiCl_2 in polar solvents leads to polymers with molecular weights around 2000. Polymers with low molecular weights tend to have low transition temperatures and mechanical properties and generally do not have many useful commercial applications.

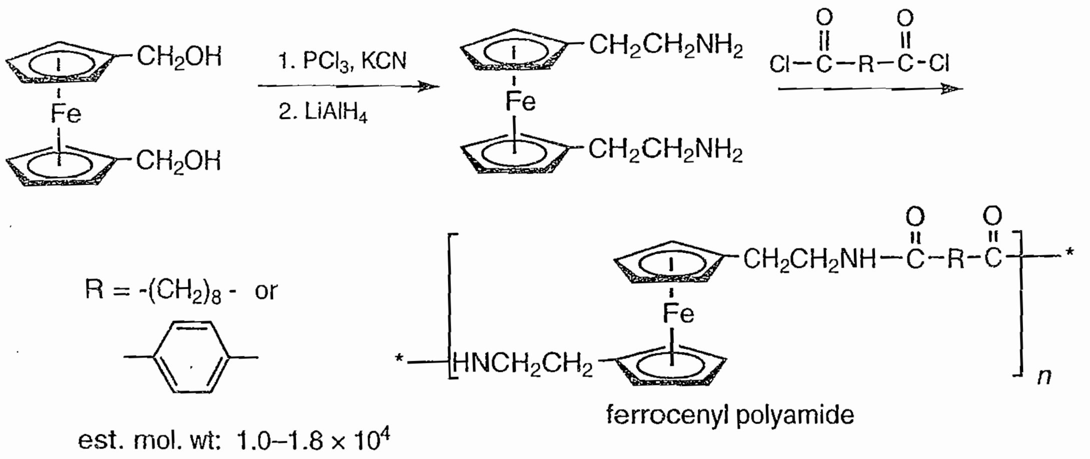


(19.2)

Ferrocene based difunctional reagents containing spacer groups were found to be more effective in preparing higher molecular weight polymers. For example, a polyamide (molecular weights between 10,000 and 18,000) was prepared by a condensation reaction between $Fc(CH_2CH_2NH_2)_2$ and diacid chloride as shown in Eq. 19.3.[7]

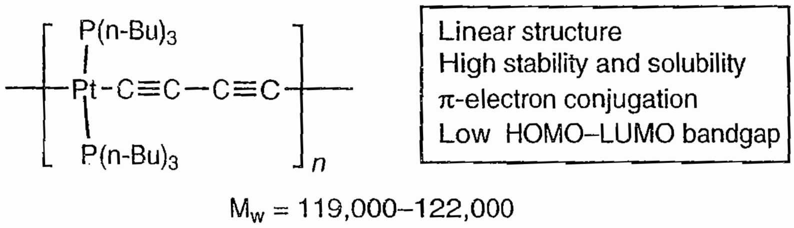
19.2.2 Condensation Polymers Based on Rigid Rod Polyynes

Introducing a metal complex or a metallocene unit into a conjugated polymeric chain bring in a range of novel properties in the polymer. Condensation polymers that are



(19.3)

rod-like and possessing platinum group metals directly bonded to alkyne moieties were first reported by Hagihara and coworkers in 1975 (Fig. 19.1).[8,9]



Linear structure
High stability and solubility
π-electron conjugation
Low HOMO–LUMO bandgap

Fig. 19.1 Properties of Hagihara's first platinum based rigid rod polyyne

The rigid rod oligomeric and polymeric compounds with metal units in the conjugation have shown promising electronic and structural properties which include third order nonlinear optical effects, liquid crystalloid nature, photoconductivity and luminescence. These stable and soluble polymers had metal ions [mainly Pt(II) and Pd(II)] in the main chain in square planar geometry and the metal had two $P(n\text{-}Bu)_3$ ligands coordinated in *trans* geometry (Fig. 19.2). The n-butyl groups on the phosphine help to solubilise the polymer by enhancing interactions between the solvent and polymer chain segments and reduce intramolecular interactions between the polymer chains. The preferred use of $P(n\text{-}Bu)_3$ over other alkyl phosphines in these polymers is due to the fact that the solubility of the alkyl groups on a phosphine decreases in the order n-Bu>n-Pr>Et>Me.

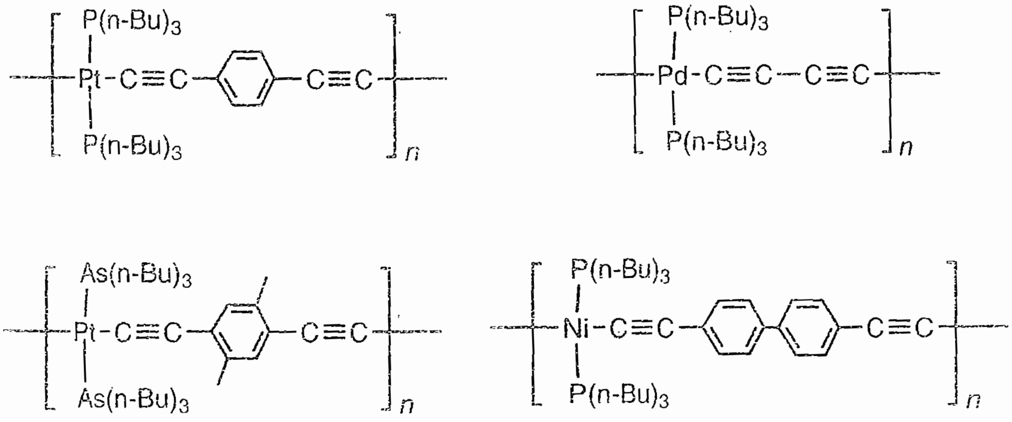


Fig. 19.2 Selected examples of polymers based on rigid rod polyynes

$P(n\text{-}Bu)_3$ although classified as pyrophoric, is considered borderline pyrophoric unlike the ethyl and methyl analogues. Hagihara's polyynes had butadiyne and diethynylbenzene bridging units connecting the metal centres and these were air stable orange–yellow solids with average molecular weights (M_n) below 7500. Further improvement in the molecular weight ($M_w > 10^5$) was achieved by the same researchers in 1977. Currently a variety of rigid rod polyynes are known whose properties have been explored in detail.[10–14]

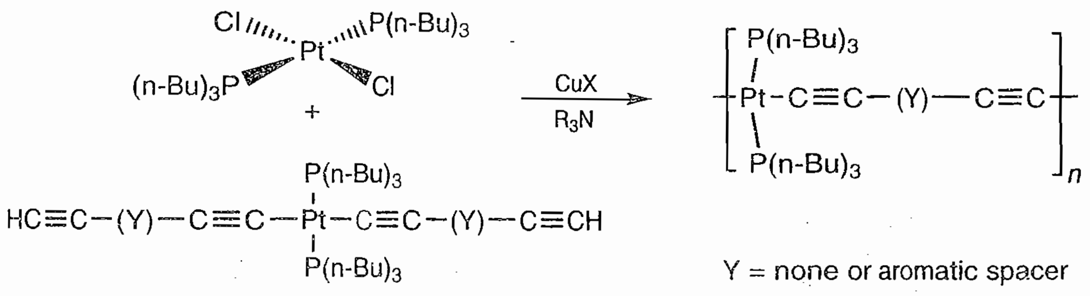
Synthesis of organometallic polymers based on rigid rod polyynes

Copper catalysed synthetic routes are available for the preparation of platinum and palladium based rigid rod polyyne polymers. The routes are:

- dehydrohalogenation (in the presence of CuI and amines),
- oxidative coupling in the presence of Cu(I) halides and O_2 (also known as Hay coupling),
- alkynyl ligand exchange reactions, and
- amine-free reactions using trimethyltin derived dialkynes.

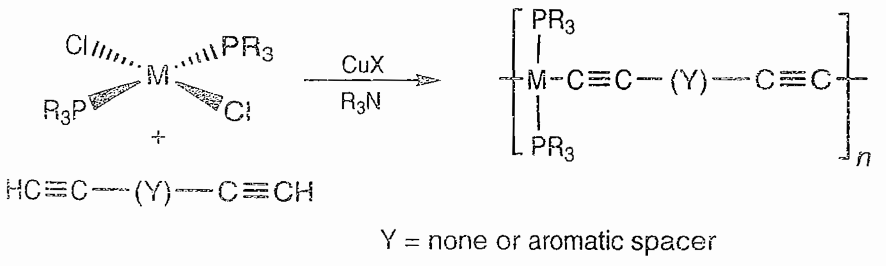
Dehydrohalogenation

This involves the equimolar reaction of a *trans* $MCl_2(PR_3)_2$ (M = Pt and Pd) complex with a terminal dialkyne using cuprous halides as catalysts. Use of an amine is essential in these reactions and it acts both as an acid acceptor and as solvent. Polymerisation often proceeds even at room temperature. The preliminary reactions carried out by Hagihara and coworkers (Eq. 19.4) were cumbersome as they first involved preparing a dialkyne complex and then reacting it with the phosphine coordinated metal–halide complex.



(19.4)

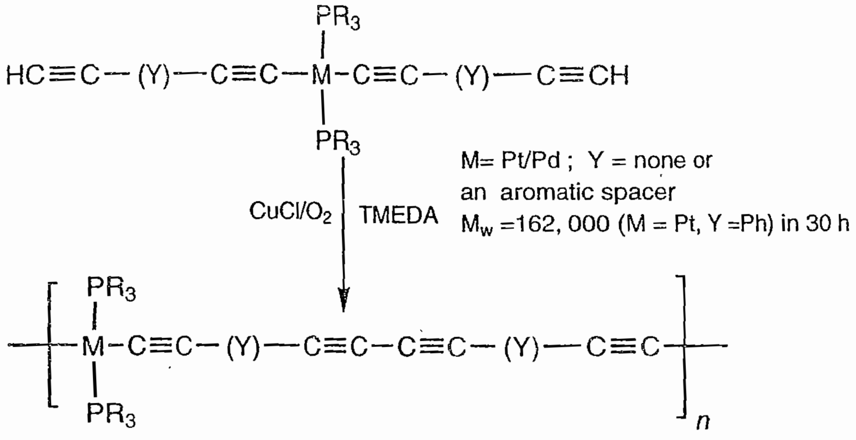
Later on, dehydrohalogenation reactions were simplified (Eq. 19.5).



(19.5)

Oxidative coupling

Unlike dehydrohalogenation, there is no restriction of stoichiometry in this method. The method is the same as Hay's coupling which uses catalytic amounts of cuprous halide along with O_2 for coupling of terminal alkynes.



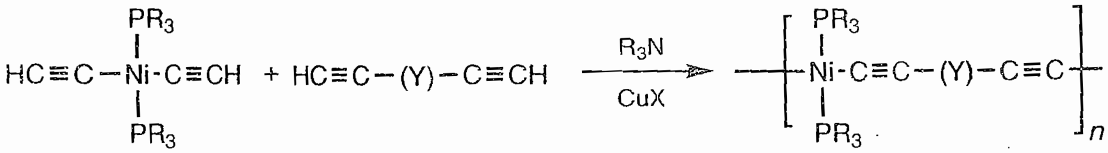
M= Pt/Pd ; Y = none or an aromatic spacer M_w =162, 000 (M = Pt, Y =Ph) in 30 h

(19.6)

Alkynyl ligand exchange

In general, preparing nickel containing rigid rod polyynes by methods involving amines is difficult because the decomposition of dihalonickel complexes occurs in amine solvents and the nickel centres react with the oxidative coupling reagents. Also, these methods cannot be extended to group 8 and 9 metal complexes because they are either insoluble in amines and if soluble, decompose rapidly in such basic solvents.

The alkynyl ligand exchange method avoids metal halides and uses a metal complex having alkynyl ligands already bound to it (Eq. 19.7). The method is best suited for nickel based rigid rod polyynes.

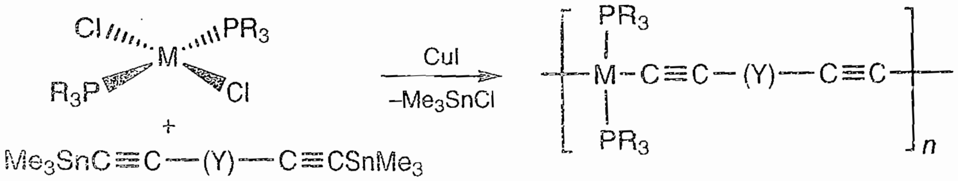


(19.7)

Y = none or an aromatic spacer group

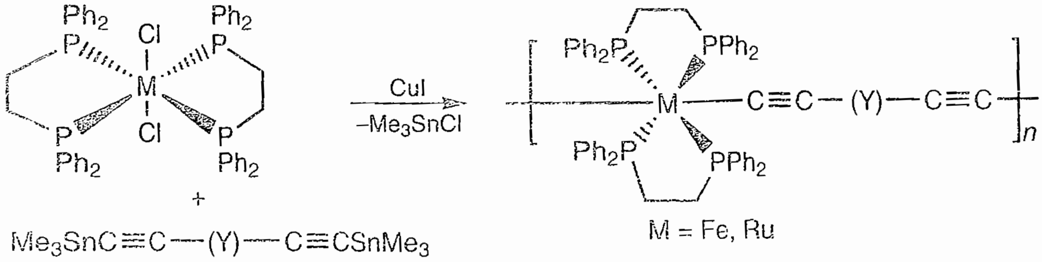
Amine-free reactions using trimethyltin derived dialkynes

Lewis and coworkers have come up with a convenient and more general metathesis reaction involving trimethyltin substituted alkynyl reagents which does not involve amines as solvents and yields rigid rod polyynes of high molecular weights (Eqs 19.8, 19.9).



(19.8)

M = Ni, Pd, Pt



(19.9)

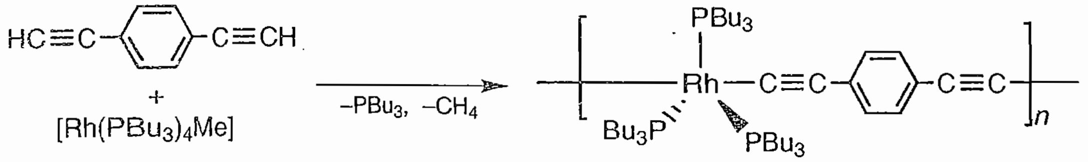
M = Fe, Ru

Y = none or aromatic spacer

Equimolar amounts of bis(trimethylstannyl)acetylene are reacted with metal halide complexes using CuI as catalyst. The method is more general and provides platinum based polymers with slightly higher molecular weights compared to those obtained by the dehydrohalogenation method. The great advantage of this method is that it does not require amines as solvents. The molecular weights obtained for platinum based polymers were also much higher {$[Pt(n\text{-}Bu_3P)_2C{\equiv}C\text{–}C{\equiv}C]_n$; $M_w = 210{,}000$}. This method also works well with group 8 and 9 metal complexes.

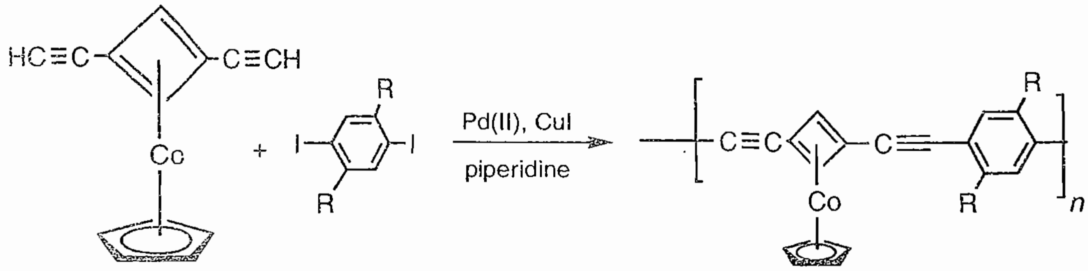
Other miscellaneous methods

The following synthetic method involves the reaction of unsubstituted diynes with a methyl rhodium complex. The polymer is formed along with reductive elimination of methane and the loss of a phosphine unit.



(19.10)

In another method, cyclobutadienyl cobalt sandwich compounds have been incorporated into rigid rod polyynes by Sonogashira coupling of cyclobutadiene-based *trans* diynes and 1,4-diiodo arenes.



(19.11)

R = hexyl, $M_w = 4.7 \times 10^3$, PDI = 3.5

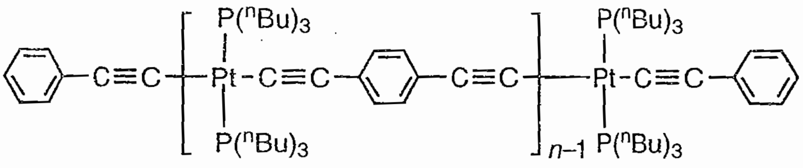
Properties of polymers having transition metal based rigid rod polyynes

Polyyne polymers show unique and interesting properties due to the conjugation present in the polymer chain. Polymers containing group 10 metal atoms show good stability in air and in the solid state but slowly decompose in solution phase. Within group 10, platinum based polymers show considerably more stability than palladium and nickel analogues. Many of these polymers are soluble in organic solvents such as benzene, toluene, THF and dichloromethane and the solubility has been attributed mostly to the presence of n-butyl groups on the phosphines.[15]

Optical spectroscopic studies

The metal–polyyne based polymers show metal to ligand charge transfer transitions and the optical band gap corresponding to the lowest energy transition varies depending on the metal centres and their coordination geometry. Optical transitions have been investigated as a function of chain length for a series of platinum based polymers as shown in Table 19.1 and a red shift is observed as the chain length increases. It was also observed that these polymers

Table 19.1 Optical transitions of polyyne polymers with varying chain lengths



n	λ_{max} (nm)
2	363
3	371
4	376
5	378
131	380

exhibit strong metal-to-ligand charge transfer (MLCT) absorptions. Another unique feature is that the platinum based polyynes have a much smaller HOMO–LUMO band gap than the corresponding dialkynyl monomer complexes, which is indicative of increased π electron conjugation along the polymer chain. The band gaps are approximately around 3 eV but much smaller values close to those of conjugated organic polymers have been obtained for some polyynes (Table 19.3).

Nonlinear optical properties

Polymers with extended π-conjugation play a significant role in third order nonlinear optics and large nonlinearities have been achieved by increasing the π-delocalisation length of the polymer chain. Many platinum polyynes exhibit large hyperpolarisabilities (γ) that are comparable to inorganic semiconductors such as InSb (170×10^{-35} esu) and Ge (130×10^{-35} esu). The type of metal, the presence of an arene spacer and the length of conjugation do significantly affect the third order nonlinear optical hyperpolarisabilities of these polyynes (Table 19.2).

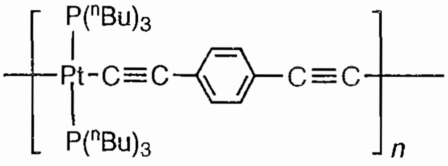
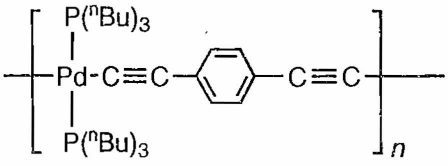
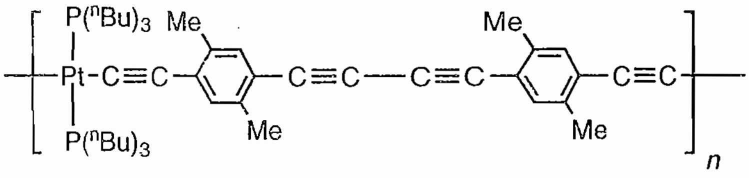
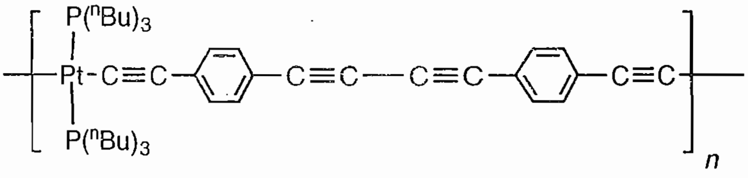
Liquid crystalline properties

Palladium containing polyyne polymers were the first examples of lyotropic liquid crystalline polymers that involve transition metals. It is expected that concentrated solutions of Pt and Pd based polyynes would form nematic liquid crystals in trichloroethane. For example, NMR studies have indicated that often polymers with diethynyl aromatic bridges are aligned parallel to an applied magnetic field while those composed of only dialkynyl units are arranged perpendicular to the magnetic field (Fig. 19.3).

Luminescence

Many platinum (II) alkynyl complexes show luminescence and the emissive state has Pt → π* (C C) metal to ligand charge transfer character. For example, the dinuclear platinum (II) complex $[Pt_2(\mu\text{-}C{=}CHPh)(C{\equiv}CPh)(PEt_3)_3Cl]$ which shows red-orange luminescence at 77 K has been the first luminescent platinum complex prepared in 1989. The related platinum

Table 19.2 Hyperpolarisabilities of metal–polyyne polymers

Compound	γ (× 10^{-35} esu)
	102
	390
	181
	856

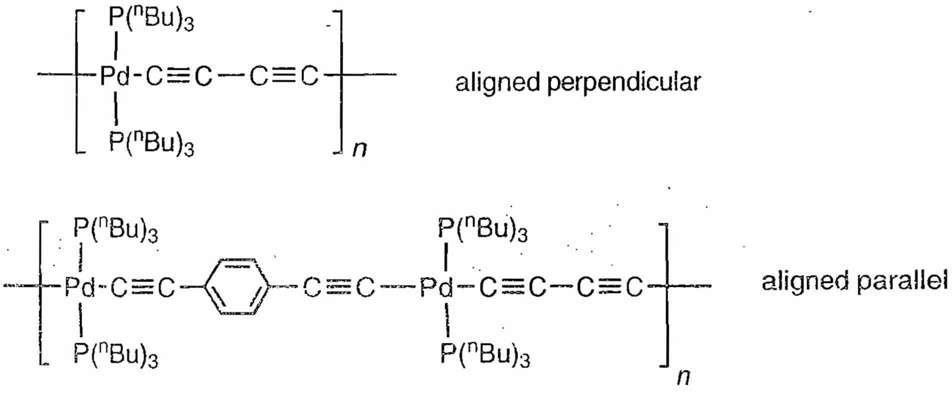


Fig. 19.3 Liquid crystalline metal–polyyne polymers

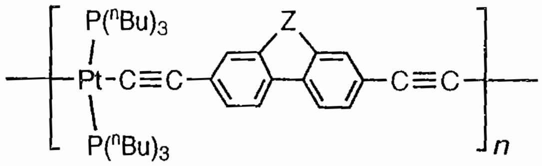
based polyyne polymers also show vibronically structured emission bands which originate from $\pi \rightarrow \pi^*$ excited states that are localised on alkynyl moieties.

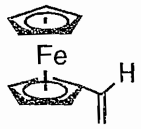
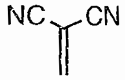
Absorption and emission data for some fluorene based luminescent platinum polyynes are given in Table 19.3. These compounds show promise as active components in polymeric light emitting diodes (PLEDs).

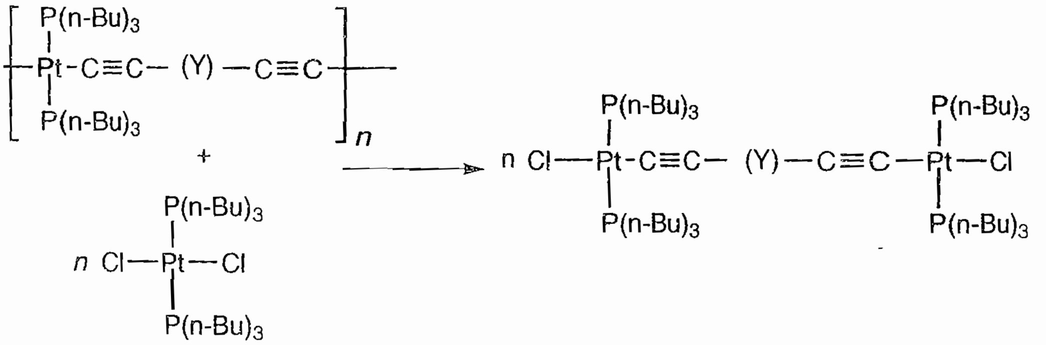
Depolymerisation

Depolymerisation of rigid rod polyynes often happens under reflux conditions in the presence of metal-halide complexes. This is a characteristic property which needs to be considered during the synthesis of these polymers.

Table 19.3 Absorption and emission data for luminescent platinum polyynes



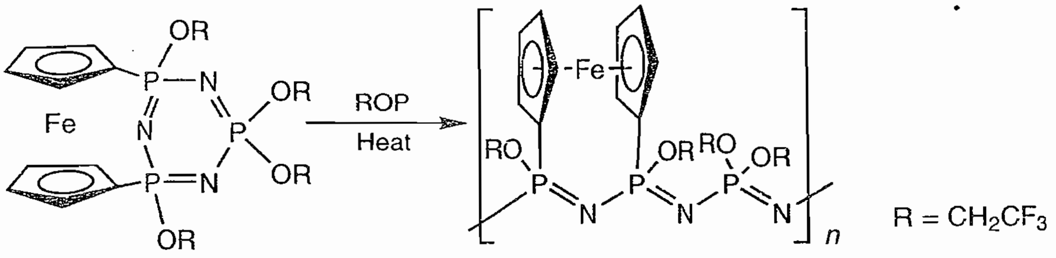
Z	Largest λ_{max} (nm) film	Band gap (eV)	Colour	λ_{em} (nm) film (290 K)
C=O	503	2.10	red	641
	382	2.10	red	565
	661	1.58	deep blue	421



(19.12)

19.2.3 Polymers Prepared by Ring Opening Polymerisation Process

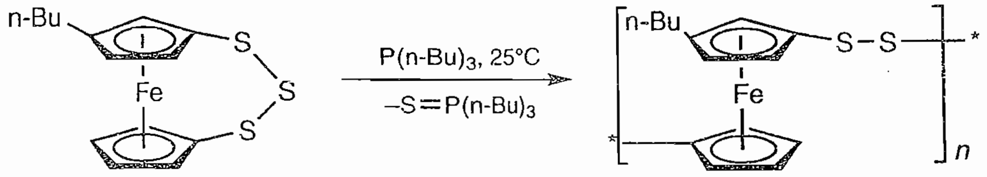
Many interesting polymer properties are accessible only when the molecular weight of the polymer exceeds a certain value. Polycondensation methods in organometallic polymer synthesis, as described earlier, have in many cases failed to make high molecular weight metallopolymers. The problem arises because of the difficulty to achieve precise stoichiometry between the monomers and inability to have high purity reactive organometallic species. Unlike condensation methods, chain growth processes such as ring opening polymerisation (ROP) enables one to synthesise high molecular weight polymers due to the high reactivity of the propagating species. ROP has been successfully employed to make high molecular weight inorganic polymers such as polysiloxanes and polyphosphazenes. ROP has also been used in ferrocene chemistry, for example, the reaction of dilithiated ferrocene with fluorinated cyclophosphazene forms a transannular substituted phosphazene molecule. This compound or its alkoxy derivatives undergo ROP upon heating. The driving force for this reaction is the release of strain on the cyclophosphazene upon ring opening.[16]



(19.13)

The syntheses of ferrocene–backbone polymers by condensation polymerisation give low molecular weight polymers. However, the same polymer when prepared by the ring opening polymerisation of [1]ferrocenophanes give polymers with molecular weights of up to 4,000,000. Since [m]ferrocenophanes are key precursors to the high molecular weight polymer formation, their general properties and syntheses are discussed in the following sections.

Derivatives of ferrocene in which the two cyclopentadienyl rings are linked by one bridging group are known as [m]ferrocenophanes, where m denotes the number of atoms in the bridge. The inter-ring separation of ferrocene is 3.32 Å and therefore bridges shorter than this would be expected to cause molecular distortion by tilting the planes of the Cp rings. While [3]ferrocenophanes are easy to make, the synthesis of [1] and [2] ferrocenophanes has proved difficult. Rauchfuss and coworkers showed that a ferrocene with the Cp rings bridged by a trisulphur bridge ([3]ferrocenophane) upon treatment with tributyl phosphine opens up and forms a ferrocene based polymer along with the removal of phosphine sulphide. The presence of the n-butyl group on the Cp ring is required to obtain a soluble polymer.[17, 18]



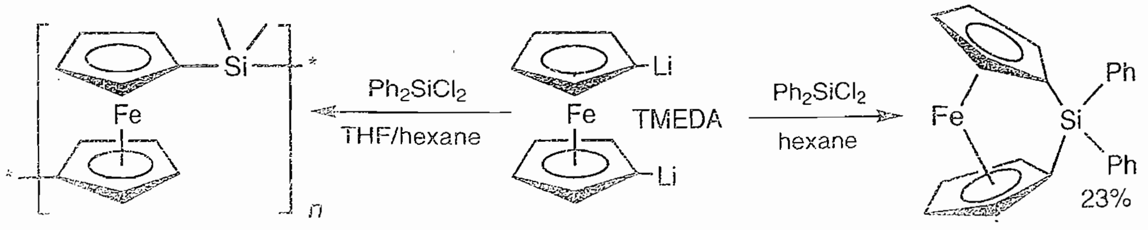
$M_n = 3.1 \times 10^5$, PDI = 1.1

(19.14)

These studies have formed the prologue for the use of [1] and [2]ferrocenophanes as precursors for ferrocene based polymers, with ferrocene as part of the main chain. This concept was developed by Manners and coworkers starting from 1992.

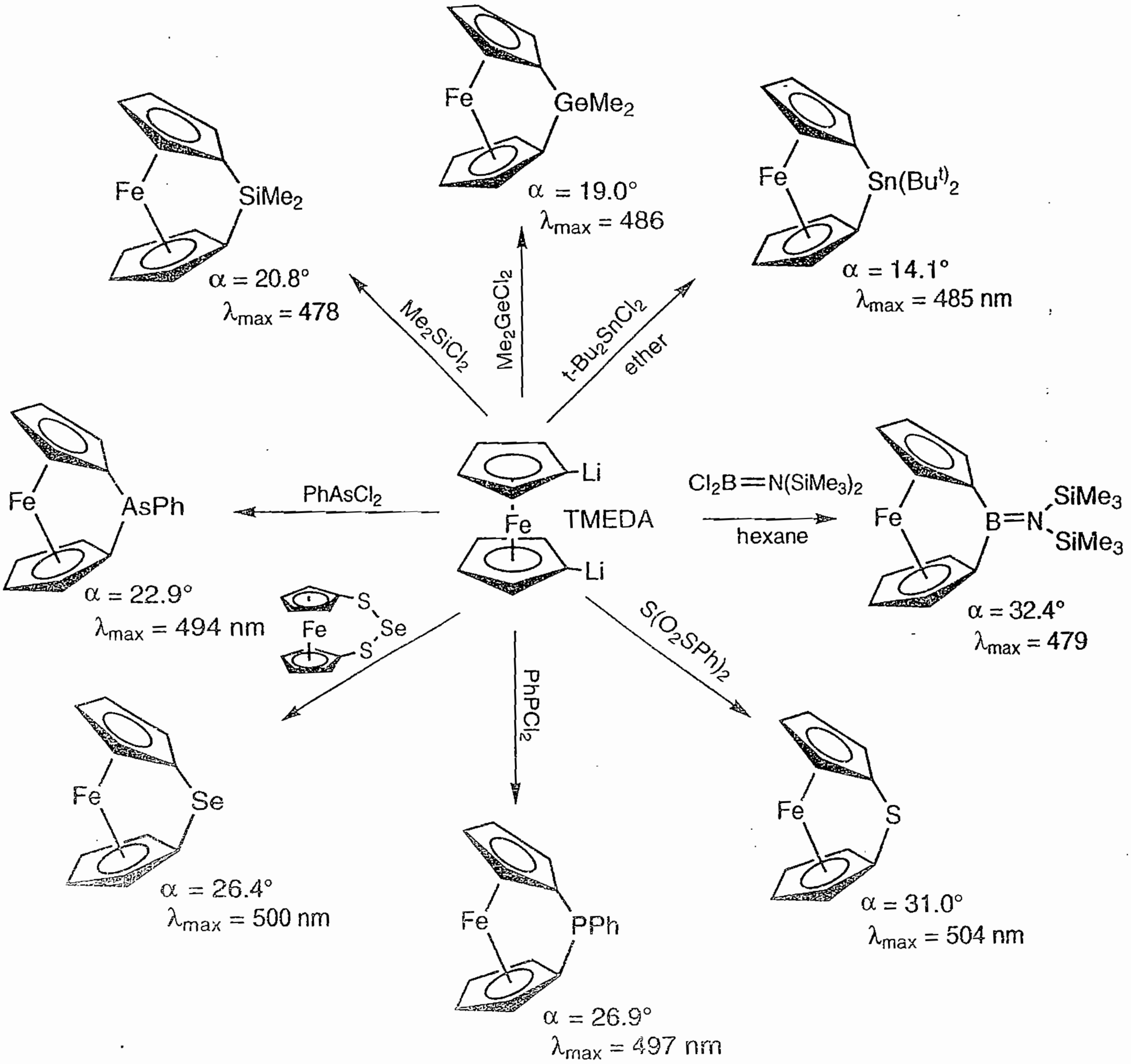
Synthesis of [1]ferrocenophanes

The reactions of dilithiated ferrocene with Ph_2SiCl_2 in THF/hexane mixture, carried out by Rosenberg in the early 1970s, did not show the formation of any [1]ferrocenophanes. However, Osborne and Whiteley could isolate [1]ferrocenophanes in low yields when only hexane was used as the solvent. In 1979, Wrighton and coworkers prepared the dimethylsilyl analogue in 60% yield.[19, 20]



(19.15)

Since then, various synthetic methods have been adopted to prepare strained [n] ferrocenophanes. These involve a metathesis reaction of dilithioferrocene (tmeda) and an organoelement dihalide, or a 'fly trap' approach which is basically a reaction of a bridged Cp based dianion $(C_5H_4\text{-}Z\text{-}C_5H_4)^{2-}$ with Fe(II) halides. Scheme 19.4 summarises the synthesis of a host of [1]ferrocenophanes along with two of their unique characterisation data [tilt angles (α) and UV-Vis absorption maxima].[21]



Scheme 19.4 Synthesis of [1]ferrocenophanes, their tilt angles (α) and λ_{max} (UV-Vis)

Most of the [1]ferrocenophanes are air stable compounds and are well characterised by UV-Vis and NMR spectroscopy. The 440 nm peak in free ferrocene has undergone a bathochromic shift in these compounds up to ~ 500 nm. The ^1H NMR spectrum consists of two well separated unsymmetrical triplets, characteristic of ring tilted ferrocenes. The synthetic strategy was later extended to phosphorus (III) and (V), arsenic (III), sulphur, boron and carbon bridged ferrocenophanes. The degree of ring tilt is usually expressed in terms of the tilt angle, α, which is the dihedral angle between the two cyclopentadienyl rings units is a decisive factor for a metallocenophane to qualify for ring opening polymerisation (Fig. 19.4). Table 19.4 compares a few examples of [1] and [2]ferrocenophanes. Four parameters determine which one will undergo ring opening polymerisation. The most decisive among these is the tilt angle and in general, it has been observed that a tilt angle above 15.0° for a ferroceonophane makes it quite likely to undergo thermal ring opening polymerisation. Exceptions do exist when sterically bulky substituents on the bridging element prevent ring opening polymerisation in spite of the fact that the molecule has a favourable tilt angle.[22, 23]

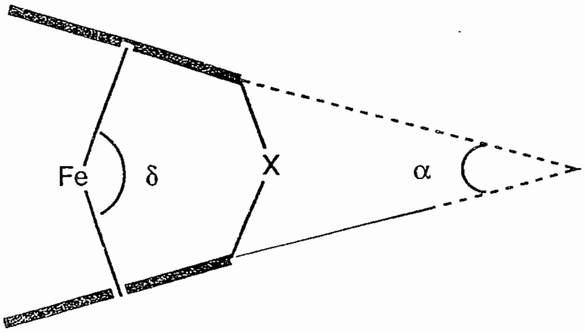
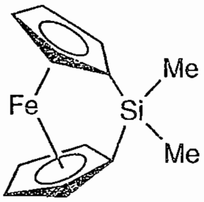
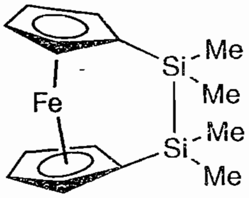
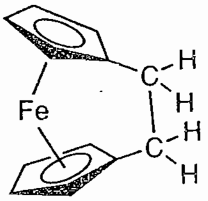
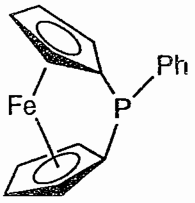


Fig. 19. 4 Depiction of tilt angle in ferrocenophanes

Table 19.4 Comparison of selected [1] and [2]ferrocenophanes with respect to polymerisation feasibility

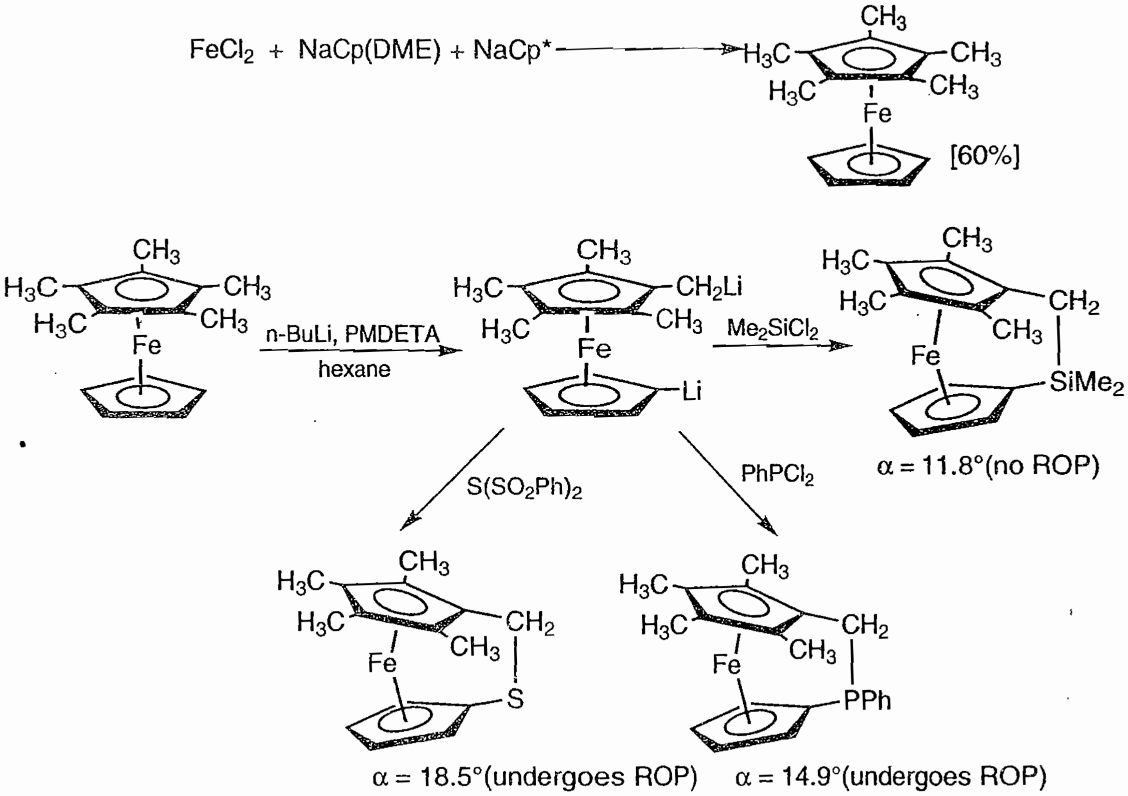
Parameter				
Tilt angle (α)	20.8°	4.2°	21.6°	26.9°
Angle around Fe (δ)	164.7°	176.5°	164.1°	159.8°
λ_{max} (ε)	478 nm (450)	444 nm (88)	474 nm (450)	497 nm
^{13}C-NMR (*ipso* carbon)	33.5 ppm	72.4 ppm	91.2 ppm	18.6 ppm
Thermal ROP	Undergoes at 130°C	Does not undergo ROP	Undergoes at 300°C	Undergoes at 120–130°C

Synthesis of [2]ferrocenophanes

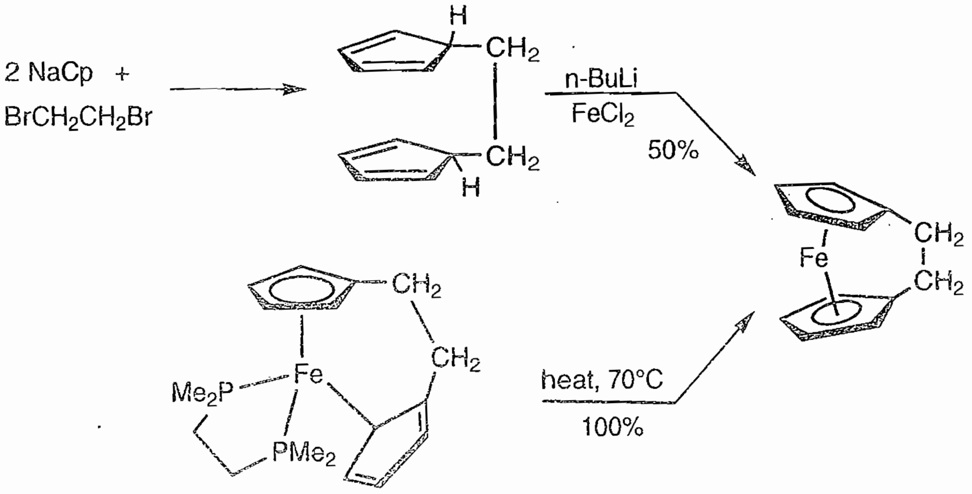
These were prepared using the methods shown in Schemes 19.5 and 19.6.[24]

Ring opening polymerisation of ferrocenophanes

The relief of ring strain when ferrocenophanes with tilted Cp rings open up and revert back to planar Cp rings has been the driving force for ring opening polymerisation of



Scheme 19.5 Synthesis of [2]ferrocenophanes having $-CH_2-R-$ bridges



Scheme 19.6 Synthesis routes for [2]ferrocenophane having a $-CH_2CH_2-$ bridge

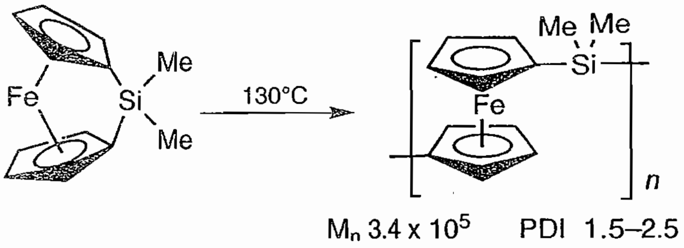
ferrocenophanes. Silicon bridged [1]ferrocenophanes are the most well studied systems and three main synthetic approaches have been reported for their ring opening polymerisation reactions.

- Thermal ring opening polymerisation,
- Anionic ring opening polymerisation,
- Transition metal catalysed ring opening polymerisation.

The tilt angle gives a good indication on the feasibility of ferrocenophanes undergoing the ring opening polymerisation reaction. This reaction is less likely to proceed when the tilt angle is small.

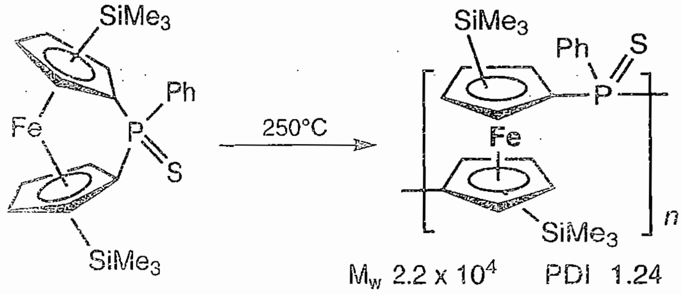
Thermal ring opening polymerisation

The temperature required for ring opening polymerisation varies over a wide range and depends on the substituents on the silicon as well as on the Cp rings. $Fe(\eta^5\text{-}C_5H_4)_2SiMe_2$ upon polymerisation in a sealed pyrex tube at 130°C results in a high molecular weight polymer ($M_w = 5.2 \times 10^5$; $M_n = 3.4 \times 10^5$). This polymer exhibits excellent thermal stability to weight loss up to 350–400°C.

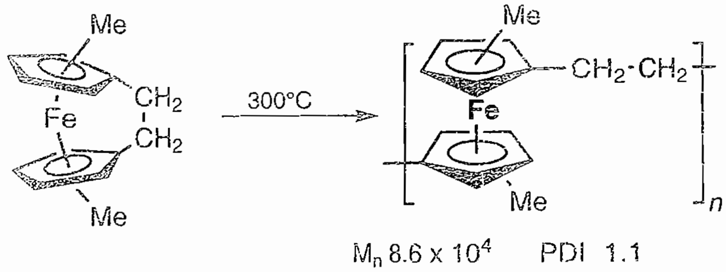


(19.16)

The size of the bridging atoms also affects the tilt angle and the tendency for thermal ROP. This is indicated by the fact that [2]ferrocenophane, bridged by $Me_2SiSiMe_2$, does not undergo ROP (when heated up to 340°C) while ring opening polymerisation goes well when it is bridged by CH_2CH_2. While ROP is favoured in many [1]ferrocenophanes with a high tilt angle, poor solubility of the polymer formed often becomes an impediment in characterisation and fabrication. Groups such as Me_3Si or CH_3 are introduced on the cyclopentadienyl ring to overcome this problem (Eqs 19.17 and 19.18).

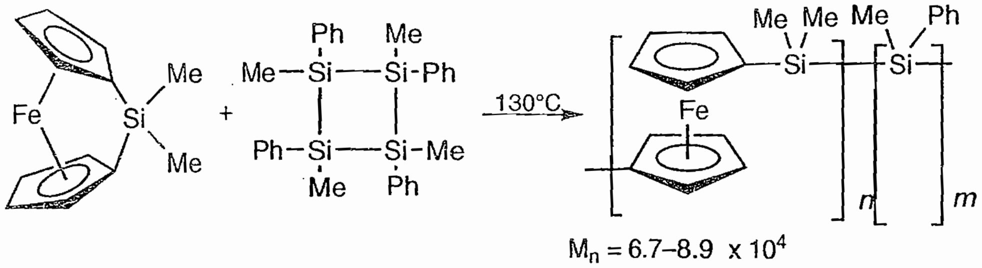


(19.17)



(19.18)

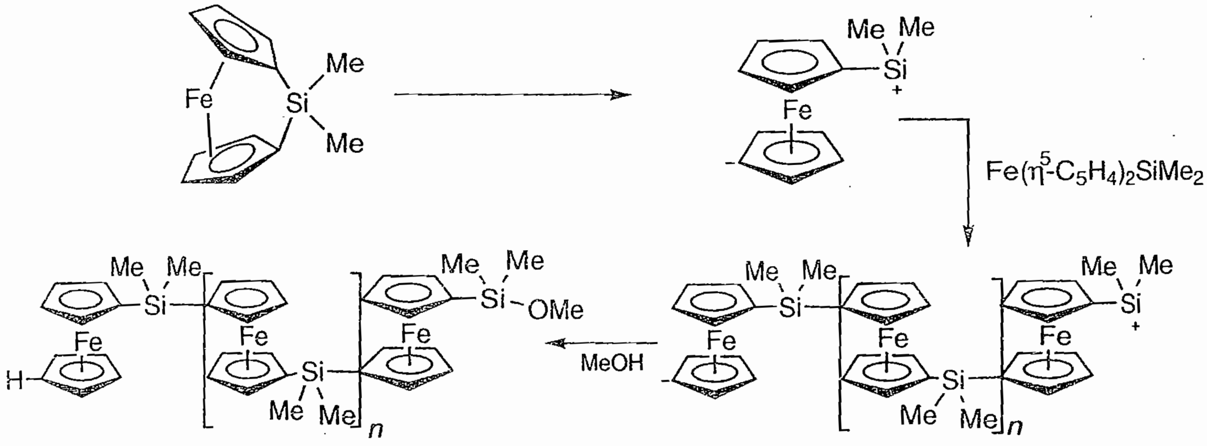
Thermal ROP can also be utilised for copolymerising cycloferrocenylsilane with other strained rings such as cyclotetrasilanes.[25]



(19.19)

The mechanism of thermal ROP has been explored in the complex Fe(η^5-C_5H_4) (η^5-C_5Me_4) $SiMe_2$ and has been found to be a chain growth process. The first step is the heterolytic cleavage of the Si–Cp or Si–(η^5-C_5Me_4) bond leading to a positive charge on the silicon atom. Propagation is possibly through the attack of the silicon centred cation on another ferrocenophane molecule. The polymerisation is easily quenched by protic solvents such as water or methanol. The mechanism is supported by the isolation of dimeric strain-free cyclic molecules from some reactions.

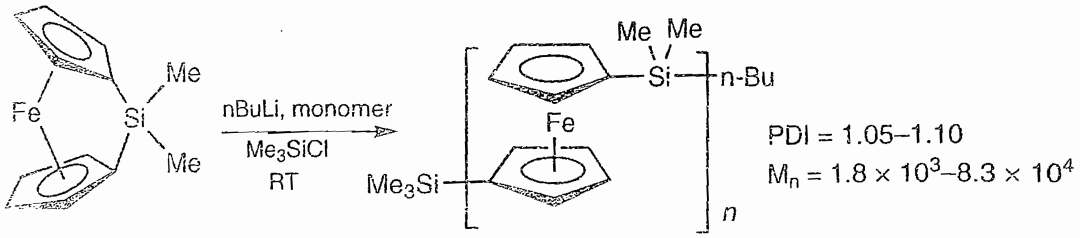
The mechanism of thermal ring opening polymerisation of [Fe(η^5-C_5H_4)$_2$$SiMe_2$] is given in Scheme 19.7.



Scheme 19.7 Thermal ring opening polymerisation of [Fe(η^5-C_5H_4)$_2$$SiMe_2$]

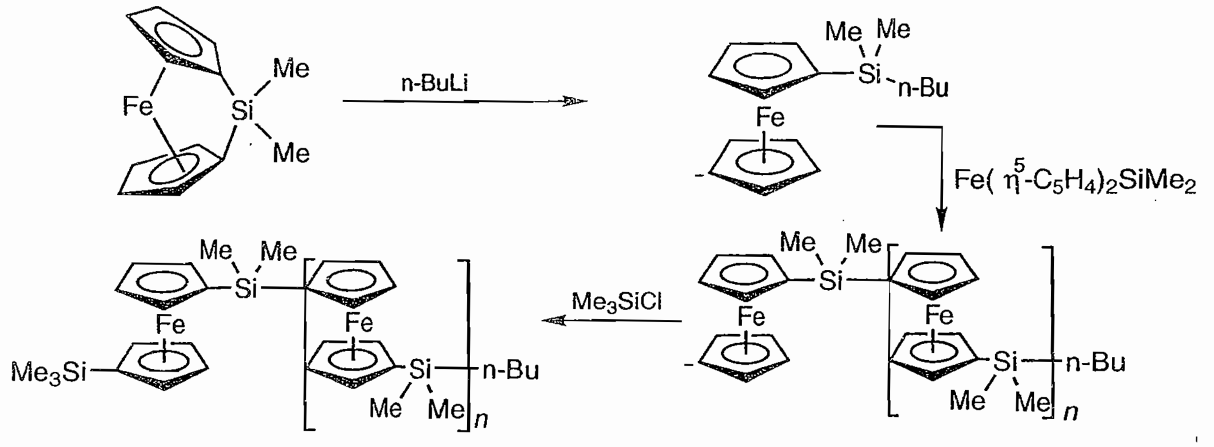
Anionic ring opening polymerisation

Anionic initiators such as n-butyllithium, ferrocenyl lithium and phenyl lithium can bring about ambient temperature polymerisation of [1]ferrocenophanes affording living polymers. The advantage of this process is the control of molecular weights leading to a very low polydispersivity index (PDI). The main requirement for this polymerisation is the very high purity of the starting materials and they have to be free from water and acidic impurities.[26, 27]

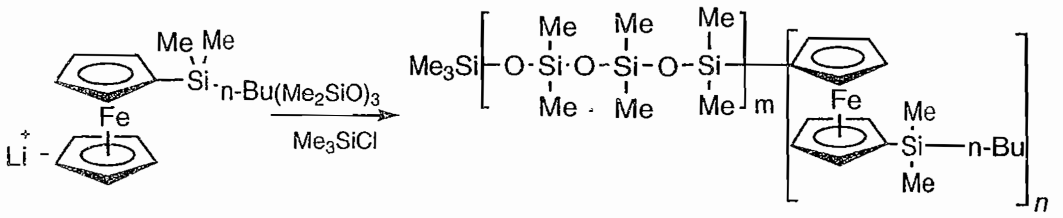


(19.20)

The anionic polymerisation mechanism involves the generation of a Cp centered anionic initiator which attacks another precursor molecule and propagates the polymerisation. The reaction can be terminated by the addition of trimethylchlorosilane (Scheme 19.8). Block copolymers can also be prepared by this method (Eq. 19.21).



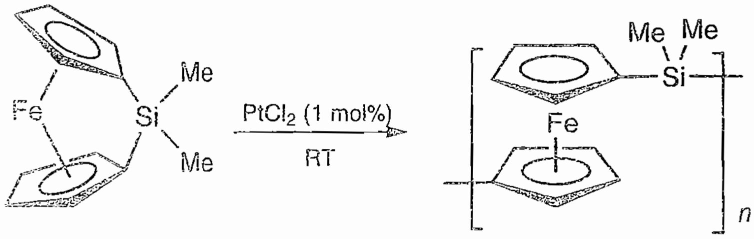
Scheme 19.8 Anionic ring opening polymerisation of $[Fe(\eta^5-C_5H_4)_2SiMe_2]$



(19.21)

Transition metal catalysed ring opening polymerisation

Ambient temperature polymerisation of a variety of silicon based [1]ferrocenophanes have also been achieved by using transition metal salts or complexes as catalysts. Mostly Rh(I), Pt(II), Pd(II), Pd(0) and Pt(0) based metal complexes have been utilised. Stringent requirements involving purity of precursors are not required for this type of polymerisation. Control of molecular weight is generally achieved by the addition of hydrosilanes such as Et_3SiH.

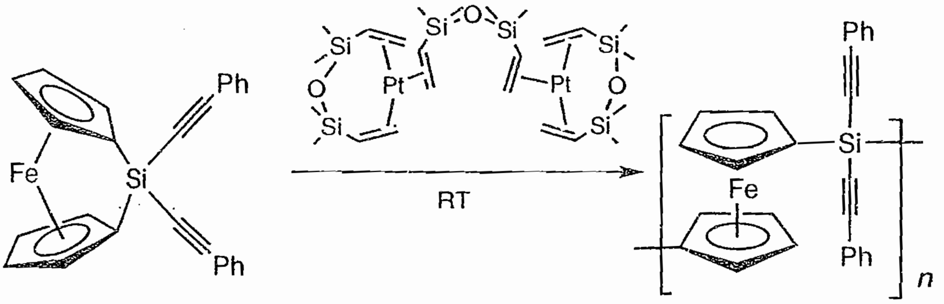


PDI = 1.1–2.3
$M_n = 4.5 \times 10^4$

(19.22)

This polymerisation methodology is general and has been applied to a variety of silicon based ferrocenophanes having different substituents on the silicon centre, for example, silicon substituted with alkynyl substituents has also been polymerised using Karstedt's catalyst.[28]

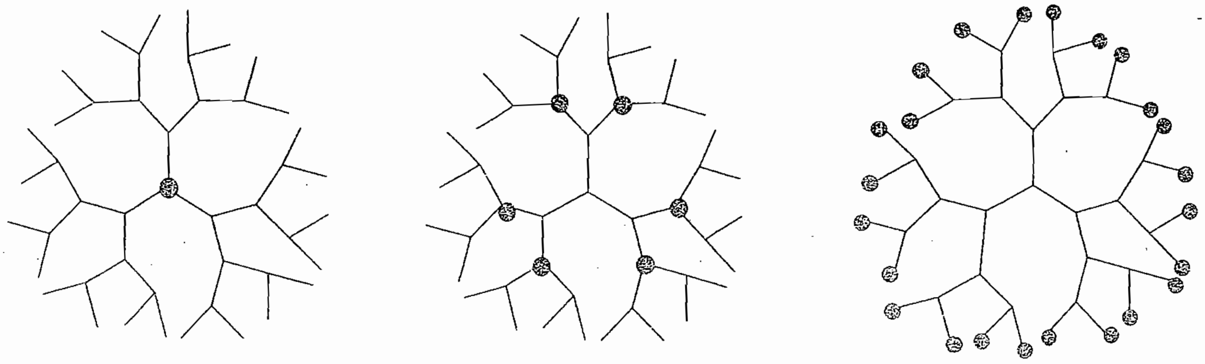
The mechanism of transition metal catalysed ROP of silyl ferrocenophanes has been investigated and it suggests that the insertion of the transition metal between the Cp and Si bond is the initiation step which is followed by successive insertion reactions leading to the polymer.



(19.23)

19.3 ORGANOMETALLIC DENDRIMERS

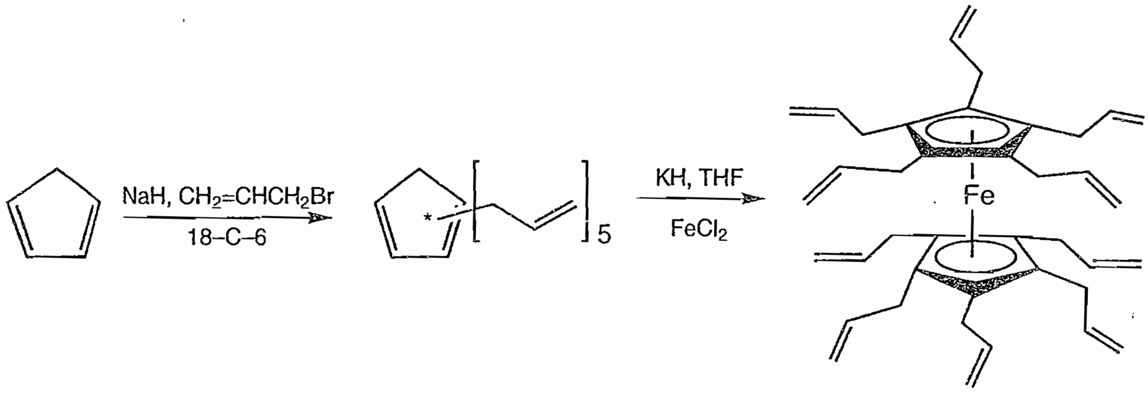
Dendrimers, originally referred to as cascade molecules, are a class of three dimensional highly branched macromolecules. In general, these molecules originate from a core and like a tree, grow and split up into branches till steric forces prevent further reaction. Each subsequent branching unit is termed as a generation. Unlike normal polymers having molecular weights spread over a range, dendrimers have fixed molecular weights which can be determined by mass spectral methods. Thus dendrimers are nanosized well-defined macromolecules with a polydispersivity (PDI) equal to 1.0. Many dendrimers have been prepared which have metallocenes and organometallic complexes positioned at the centre, at specific branching points or at the periphery of dendrimers (Fig. 19.5).



Metal at the core Metals at specific branching points Metals at the periphery

Fig. 19.5 Major types of organometallic dendrimers

When dendrimers were being discovered in the mid 1980s, they were just molecular curiosities. The application potential of these macromolecules was discovered later and now dendrimers with a variety of applications are known. Catalysis appears to be one of the most promising areas since the dendritic architecture can be controlled to ensure the appropriate size, constitution and shape to make macromolecules with multi-site catalytic centres. The shapes of dendrimers become globular after a few generations, close to that of biological units such as viruses and neurons. A lysine based dendrimer having 24 units of complexed gadolinium at its periphery has been found to show quantitative renal elimination and higher intravascular retention when used as a contrast material in magnetic resonance imaging (MRI) studies. Other applications of dendrimers are in making sensors and macromolecules that show luminescence. Most of the examples of organometallic dendrimers either possess a metal atom at the centre, or metal atoms at the periphery of the dendritic architecture. Decaallyl ferrocene is an interesting molecule for the synthesis of dendrimers with ferrocene as the core (Scheme 19.9).[29]



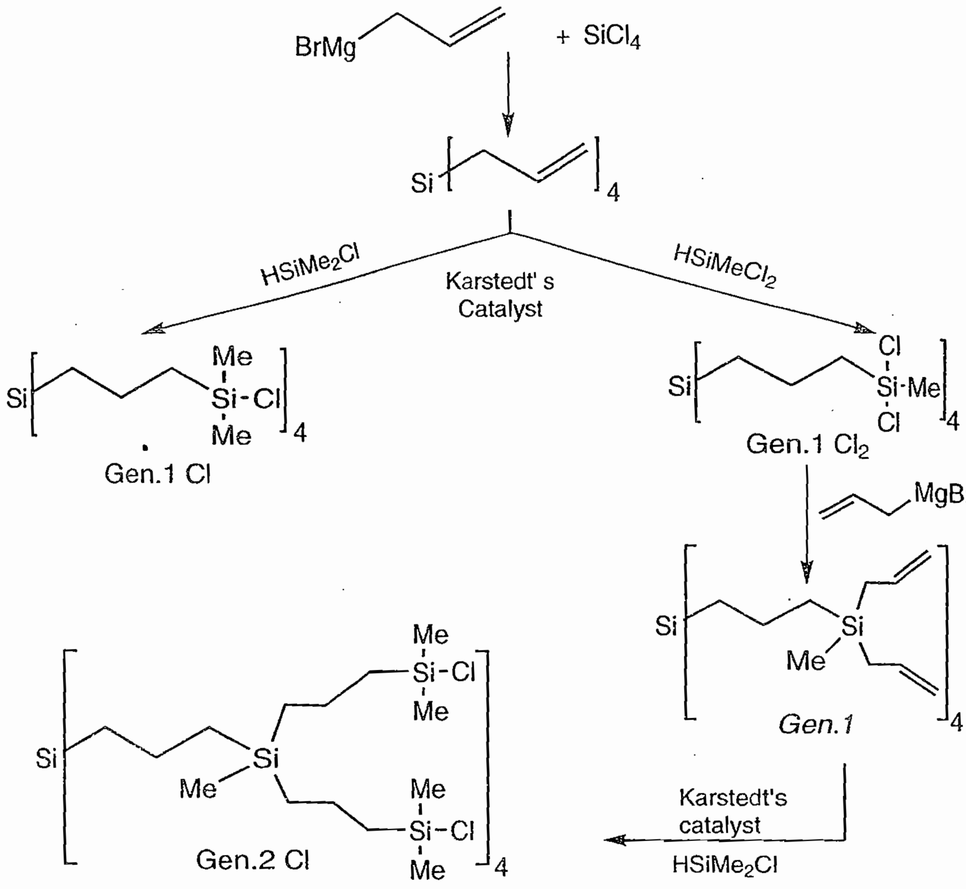
Scheme 19.9 Synthesis of decaallyl ferrocene

Hydrosilylation is a very common reaction carried out in dendrimer synthesis to build upon and extend the branches of a dendrimer. This is illustrated in the synthesis of dendrimers given in Schemes 19.10 and 19.11.

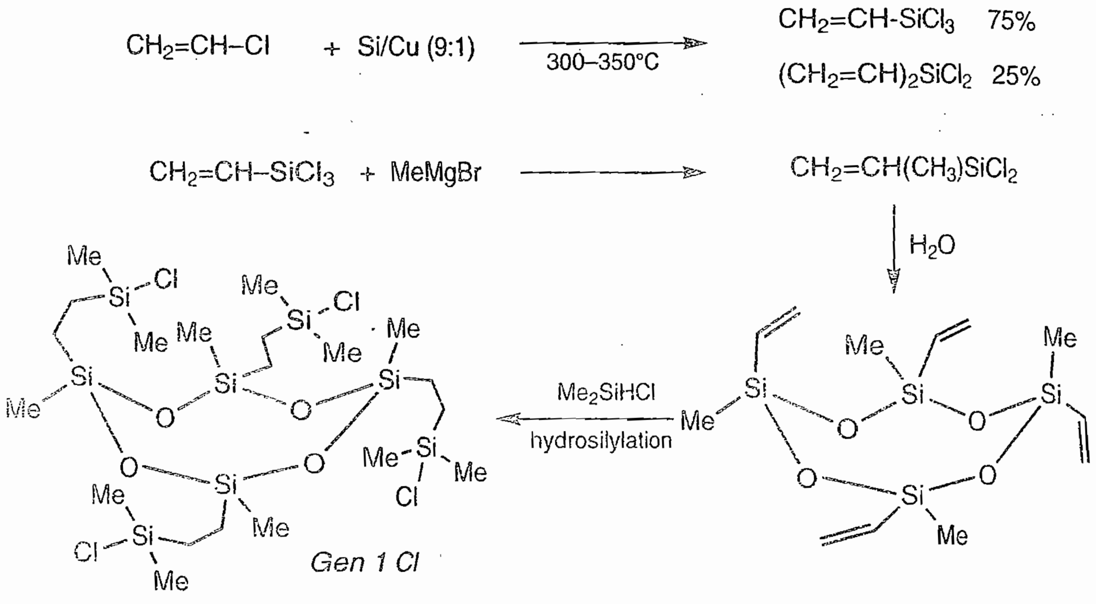
19.3.1 Synthesis of Dendrimers: Divergent and Convergent Methods

Two fundamentally different synthetic methods exist for the synthesis of dendrimers. These are (i) the divergent method and (ii) the convergent method. The divergent method, first reported by Vögtle in 1978, is a synthesis in which one branching unit after another is successively attached to the core. The molecule can ultimately reach a spherical shape and the number of peripheral units possible depends on the branching multiplicity. One of the common problems associated with the divergent approach is that as generations increase, there is a higher chance of incomplete reactions leading to nonuniformity at the periphery. With a view to overcome this drawback, convergent synthesis was demonstrated by Frecht in 1990. In this method, the skeleton is constructed stepwise from the end groups towards the inside and finally such units are linked to a core to yield the dendrimer.[30]

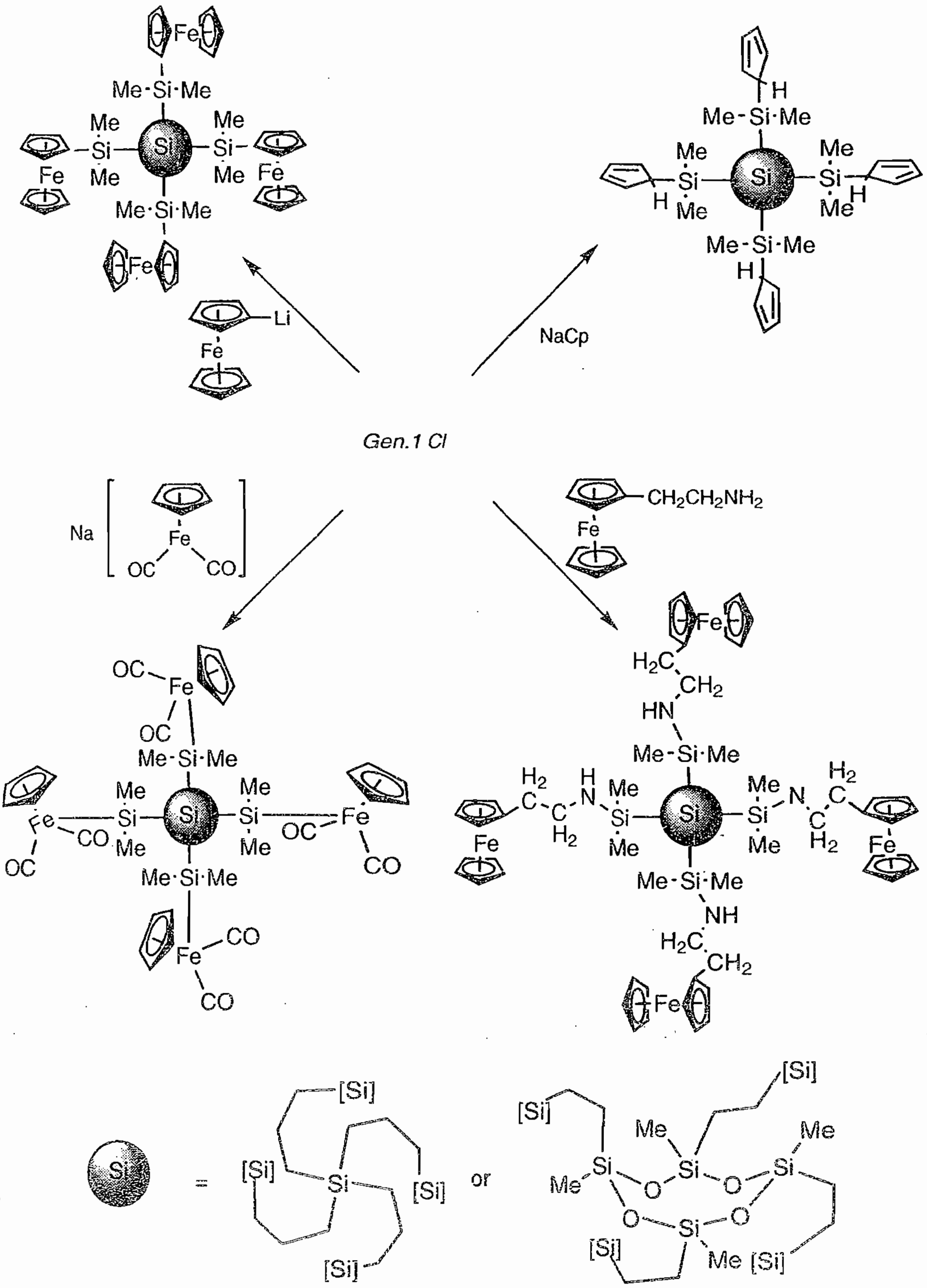
For dendrimers with ferrocene at the core, the dendrons act as a nonpolar sheath that effectively encapsulates the Fe core and prevents ion penetration to the core. This effectively hinders the oxidation of the central ferrocene unit and often destabilises the formation of the ferrocenium ion which is indicated by anodic shifts in the redox potential of the compound.[31]



Scheme 19.10 Synthesis of reactive first and second generation silicon based cores for divergent synthesis



Scheme 19.11 Steps involved in the synthesis of reactive cyclosiloxane based dendrimer core for divergent synthesis



Scheme 19.12 Examples of first generation dendrimers synthesised by divergent synthesis starting from Gen.1 Cl cores

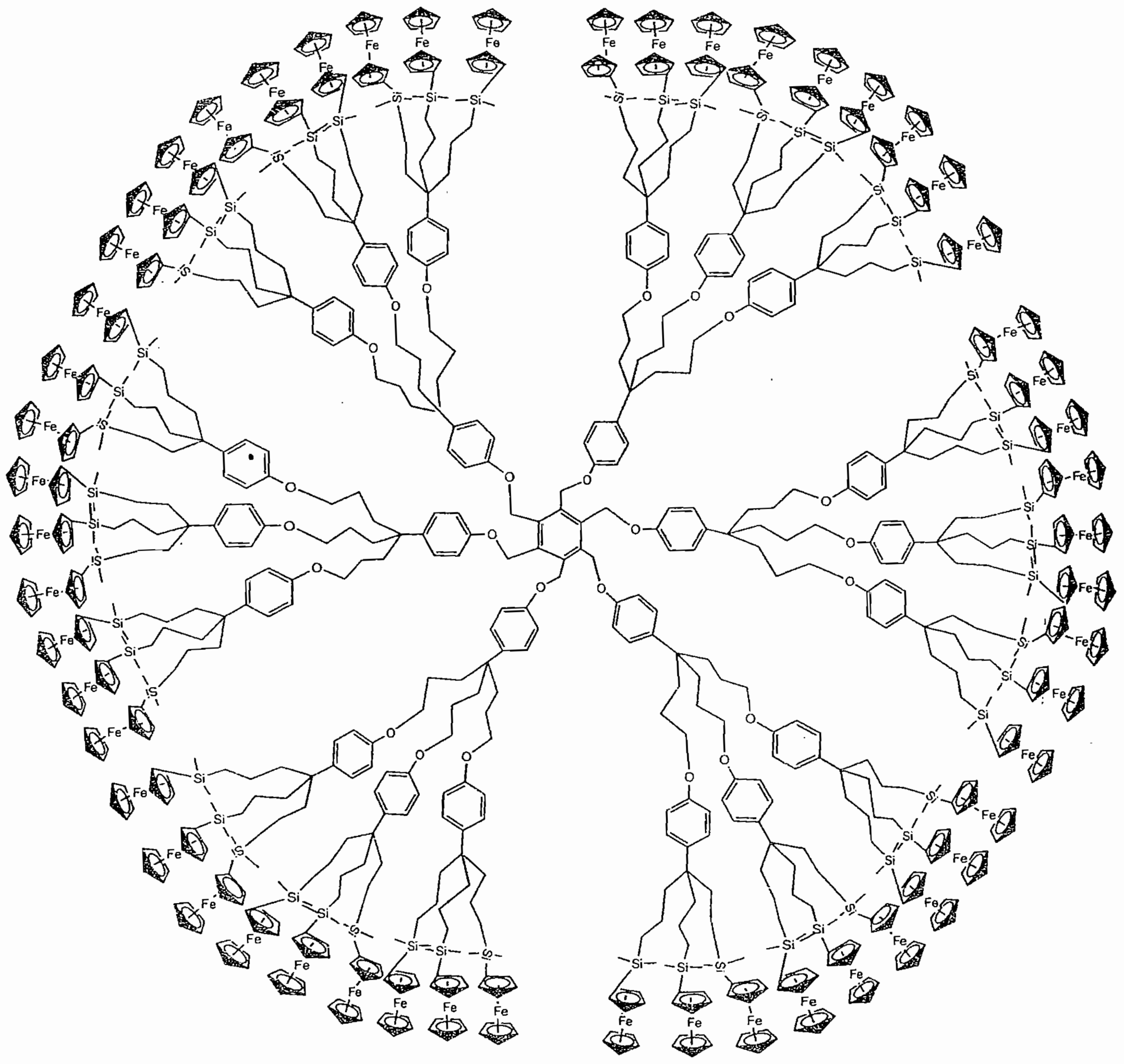
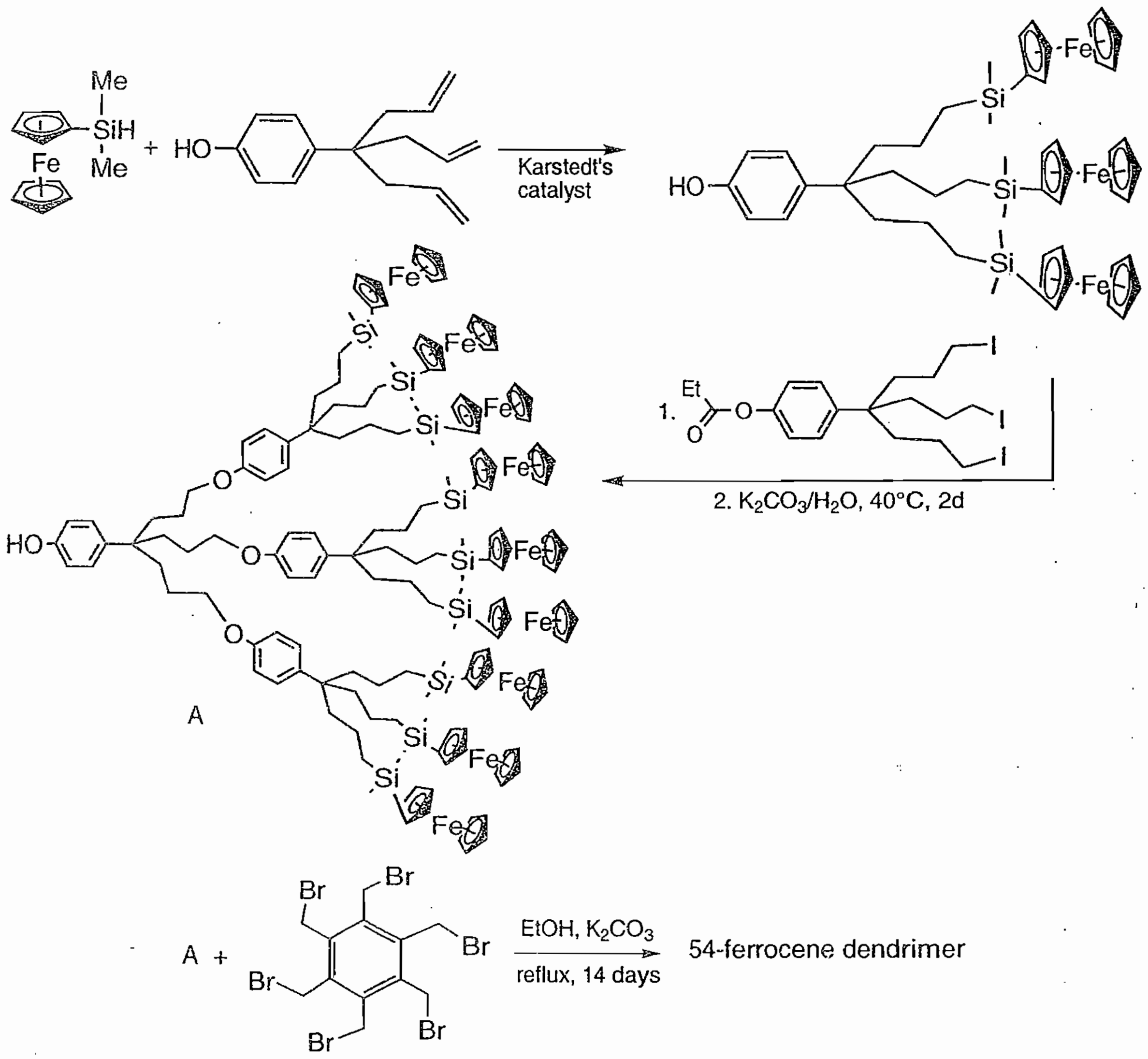


Fig. 19.6 Dendrimer with 54 ferrocene units at the periphery

When ferrocene or its derivatives are at the periphery, the dendrimer can act as a multi-site catalyst and shows interesting electroactivity. Cyclic voltammetric studies on the compound given in Fig. 19.6 prepared by Astruc, showed a 54 electron wave which could be reversibly oxidised indicating that all the ferrocene units are independent and do not interact with one another. This compound was prepared by convergent synthesis (Scheme 19.13) and such compounds find use in modifying electrodes, as catalysts, as sensors and in molecular batteries.

A useful example of a ferrocene based dendrimer A (Fig. 19.7) was prepared by Togni and coworkers by convergent synthesis (Eq. 19.24) which had a tetrameric cyclophosphazene as the core and Josiphos units on the periphery thus acting as a dendrimer supported catalyst precursor.[32, 33]

Addition of 16 equivalents of $[Rh(COD)_2]BF_4$ to dendrimer A led to the formation of the corresponding monodisperse species having 16 equivalent and noninteracting Rh complexes at the periphery of the dendrimer.



Scheme 19.13 Convergent synthesis of a dendrimer having 54 ferrocene units at the periphery

Hydrogenation of dimethyl itaconate under 1 atom H_2, in methanol at room temperature in the presence of the Josiphos based dendrimer (A) and $[Rh(COD)_2]BF_4$ showed enantioselectivity with 98% *ee* of the S product (Eq. 19.25).

Organometallic dendrimers based on other metals and ligands, are also known. Two dimensional polyhexagonal graphite-like polymers were prepared by using 1,3,5-triethynylbenzene as the core along with $Pt(PEt_3)_2$ (Fig. 19.8). These dendrimers are quite similar to rigid rod polyynes.

The use of ferrocene based dendrimers for modification of electrode surfaces has been explored. It is found that platinum, glass and carbon disk electrodes can be modified by electrodeposited films of ferrocene based dendrimers. These modified electrodes are extremely durable and reproducible with no loss of electroactivity or material with their use in

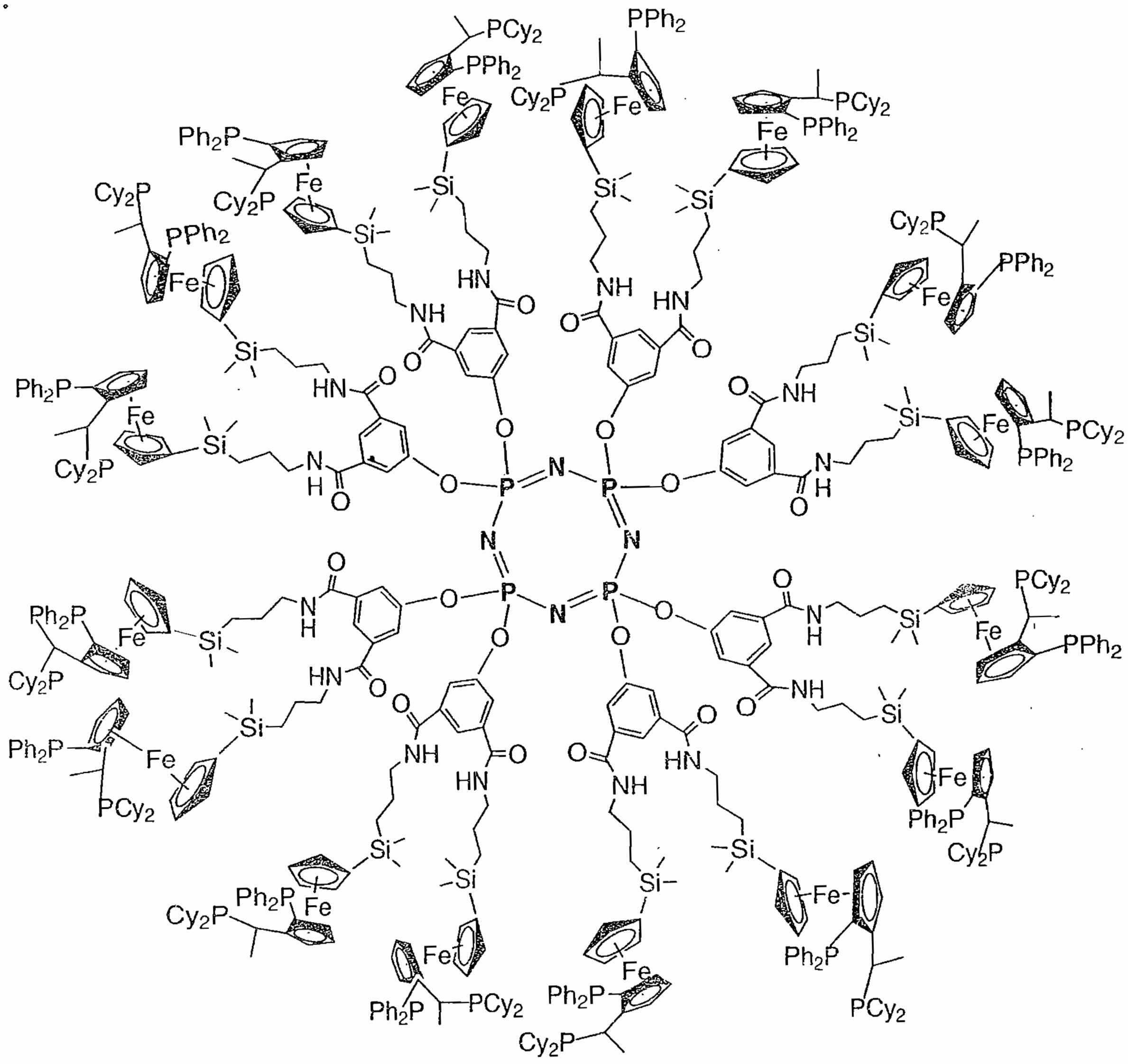
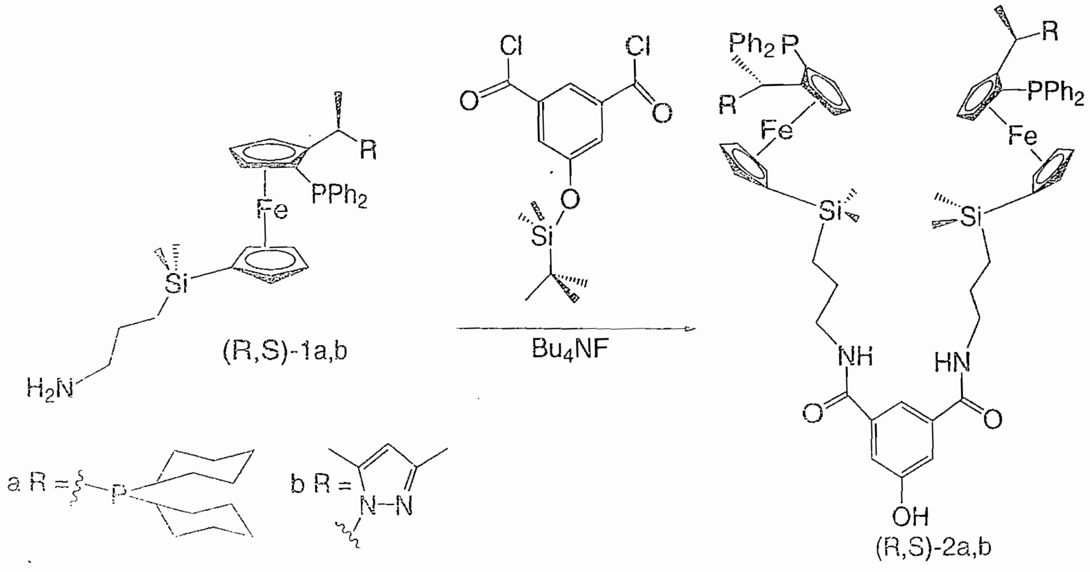
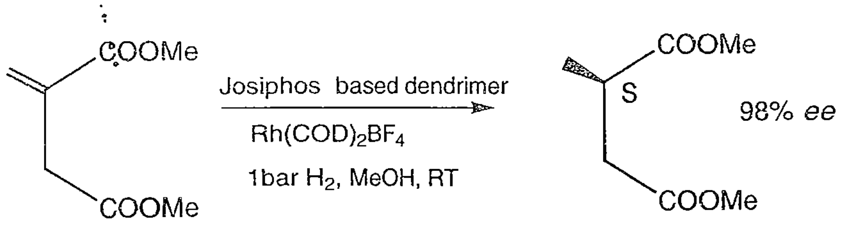


Fig. 19.7 Cyclophosphazene based dendrimer A with Josiphos units at the periphery



(19.24)



(19.25)

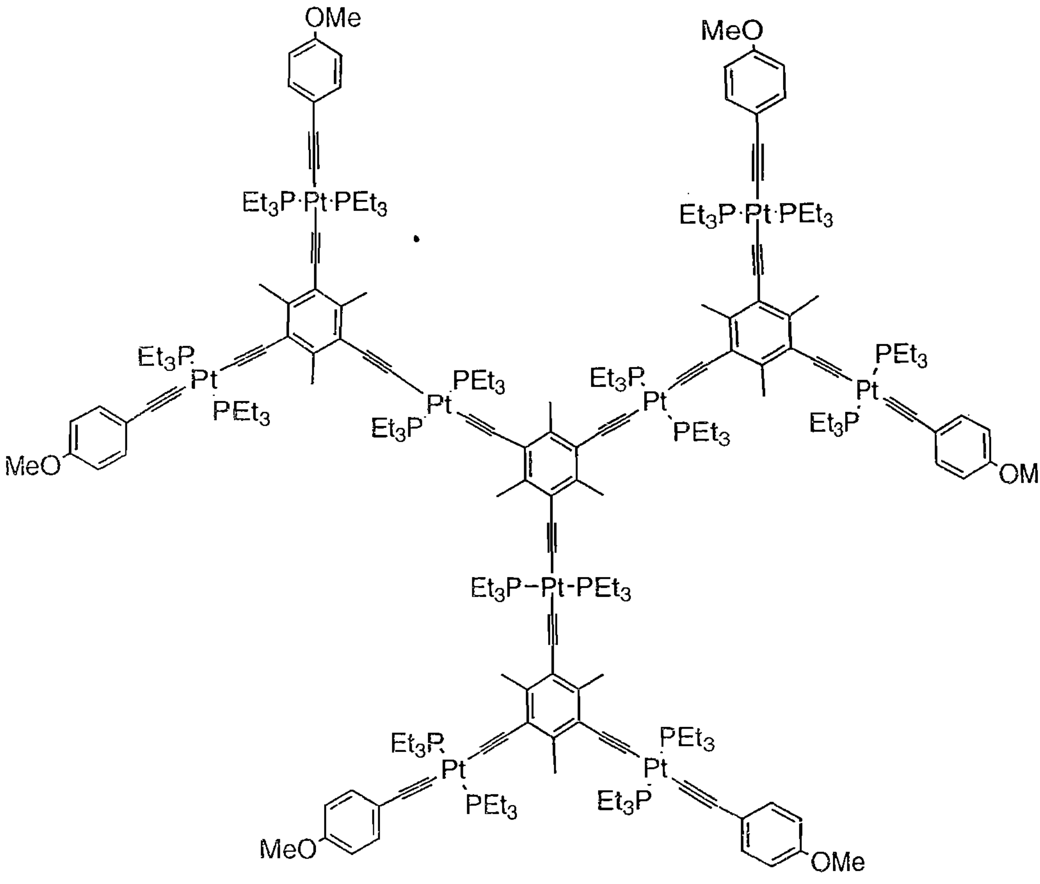
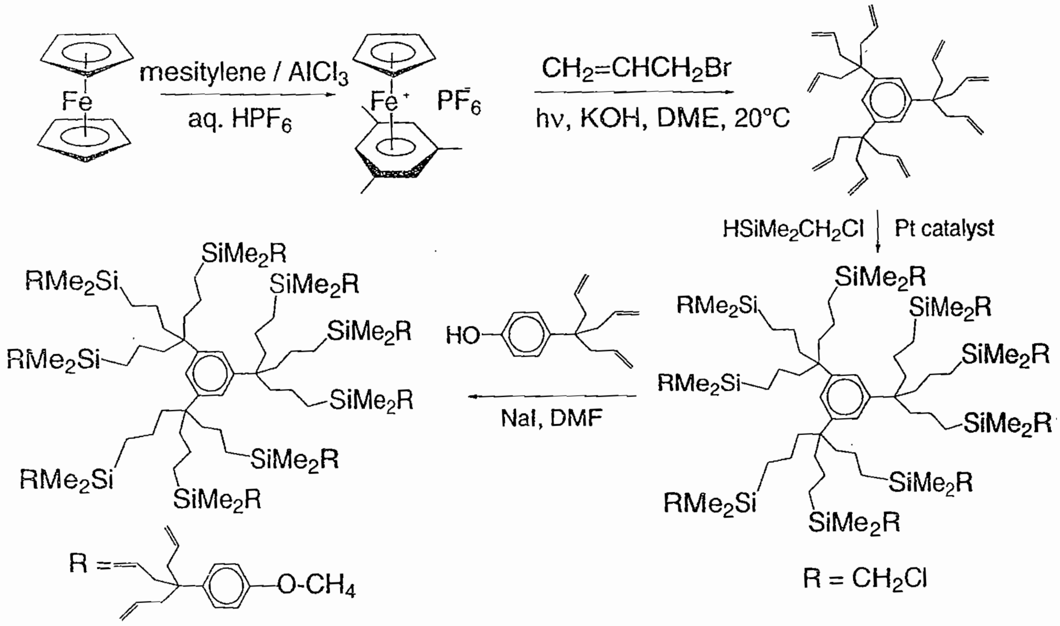


Fig. 19.8 Platinum polyyne based dendrimer

different electrolytic solutions and on exposure to air. As an interface between homogeneous and heterogeneous catalysis, dendrimer based catalysts can react in homogeneous solution and may be recycled by nanofiltration or precipitation from the reaction medium. These well defined macromolecules thus offer a solution for catalyst recovery, which is a common problem in homogeneous catalysis.

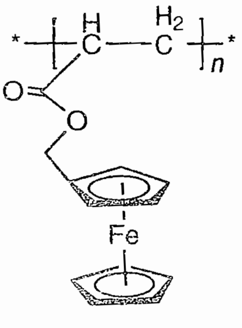
Ferrocene has also been utilised as a platform on which synthesis of organic dendrimers with an aryl core can be assembled. Scheme 19.14 shows how multiple allyl groups can be substituted on a mesitylene unit while bound in the η^6-mode to a CpFe moiety.[34] $AlCl_3$ is utilised initially to displace a Cp ring of ferrocene by a mesityl or substituted aryl group. A strong base is used later to displace the aryl ring from the sandwich compound once the basic dendrimer architecture has been achieved.[35]



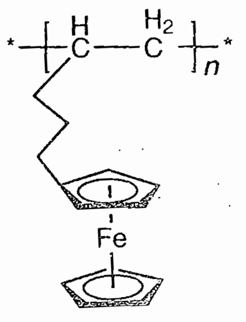
Scheme 19.14 Ferrocene as a platform for divergent synthesis of organic dendrimers

Problems and Exercises

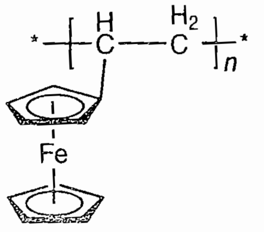
19.1. The given ferrocene pendant polymers have been prepared by free radical polymerisation of their alkenyl precursors. Indicate which among them will have the best combination of high molecular weight and high stability. Justify your answer.



(a)

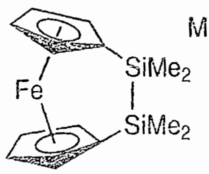


(b)



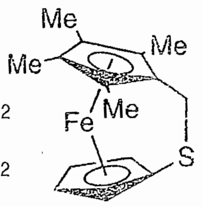
(c)

19.2. Among the following three ferrocenophanes, only one undergoes ring opening polymerisation. Show how that compound is prepared starting from FeCl$_2$.



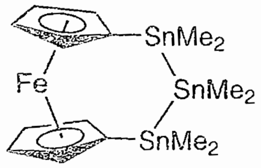
tilt angle (°) 5.0

(a)



18.5

(b)

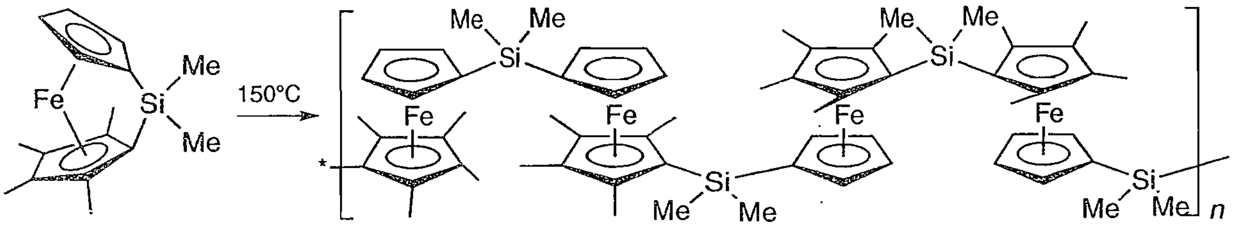


0.7

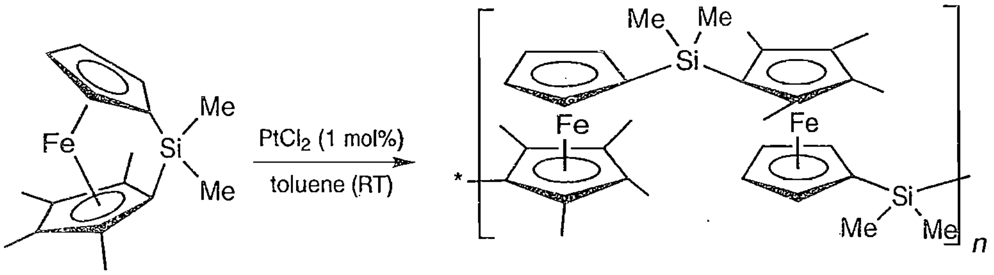
(c)

19.3. Free radical addition polymerisation of the monomer, vinyl ferrocene, in the presence of iodine affords a low molecular weight organometallic polymer. What modifications will you make in the monomer such that a high molecular weight polymer is formed?

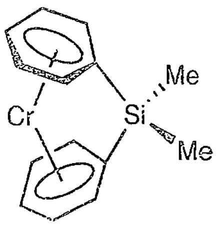
19.4. (a) Thermal ROP of the reactant, unsymmetrical [1]ferrocenophane, proceeds via a nonselective cleavage of the Si–Cp^H and Si–Cp^{Me} bonds as shown. The resulting polymeric product is completely soluble in THF. Would you expect the product to be amorphous or crystalline? Justify your answer (hint: crystallinity of a polymer is associated with regioregularity in the polymer chain). (*J. Am. Chem. Soc.*, 1998, Vol. 120, 8348)

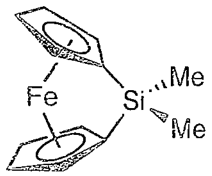


(b) However, transition metal catalysed ROP of the same reactant affords a different polymer. Comment on its solubility and crystalline/amorphous behaviour.



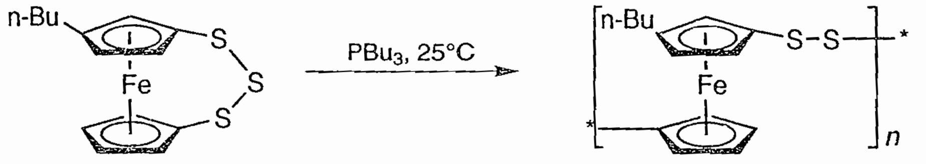
19.5. Silicon bridged bis(benzene) chromium complex, by itself, does not undergo thermal ROP reaction, but its equimolar mixture with dimethylsila[1]ferrocenophane forms a copolymer. Write the structure of the copolymer. (*Organometallics*, 1995, Vol. 14, 5496)



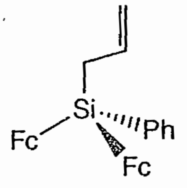


19.6. Conventional polycondensation routes are generally unable to produce high molecular weight metallopolymers. Why?

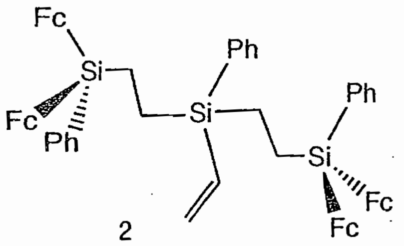
19.7. What is the role of $^{n}Bu_3P$ in the following reaction and what happens to it after the reaction is over?



19.8. (a) The reaction of the tetra-directional hydrosilane, $Si[(CH_2)_3Si(Me)_2H]_4$ with 1 and 2 affords dendrimers with 8 and 16 ferrocenyl moieties respectively. Draw the structures of these molecules and indicate the reaction conditions.

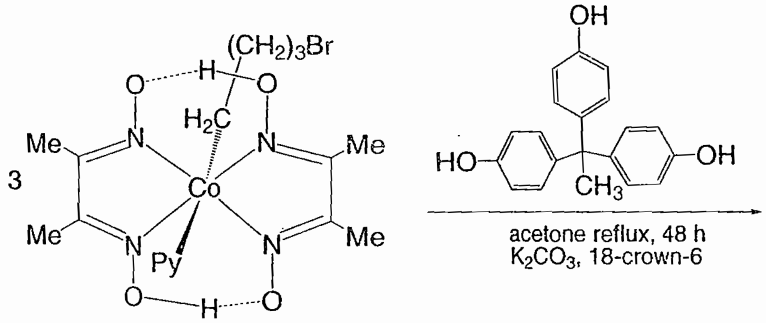


1



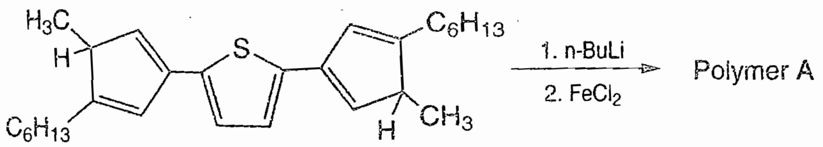
2

19.9. Write the structure of the zero generation dendrimer in the following reaction. (*Inorg. Chim. Acta*, 2004, Vol. 357, 2748)

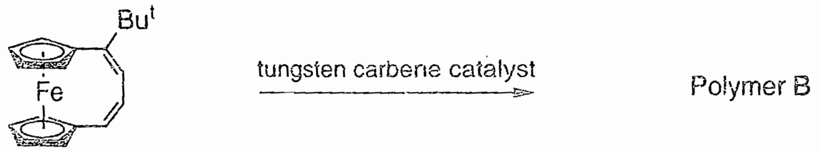


19.10. Predict the structure of the polymer formed in the following polymerisation reactions involving organometallic precursors. Name the type of polymerisation occurring in each case.

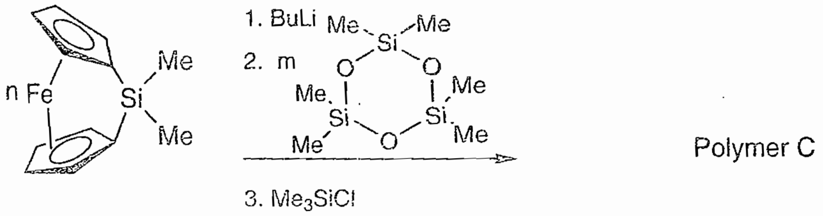
(a)



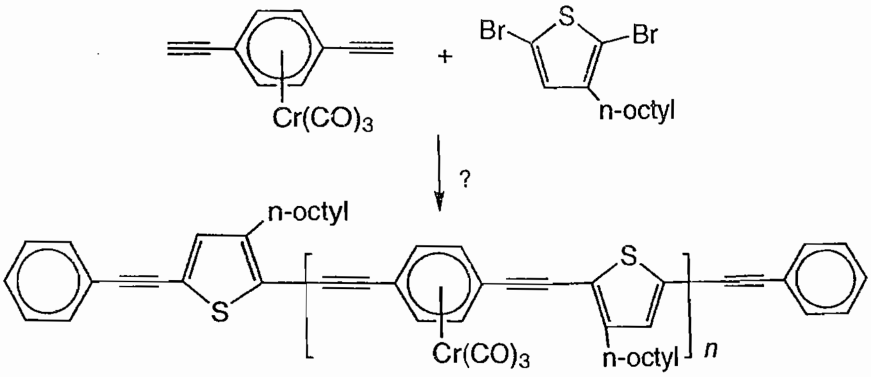
(b)



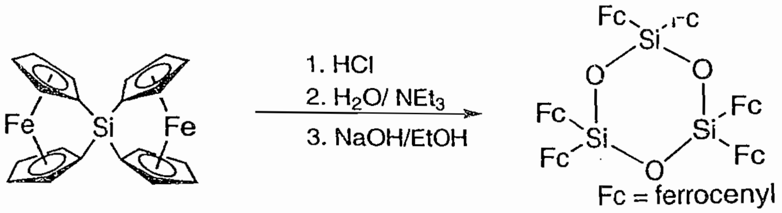
(c)



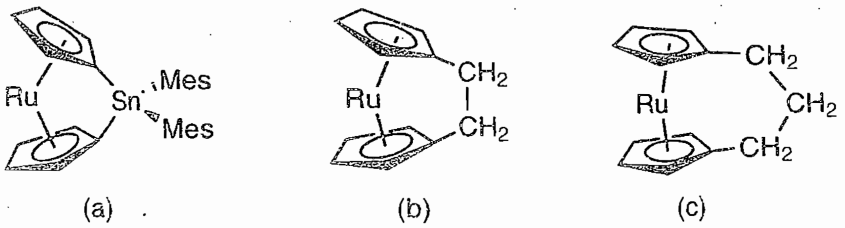
19.11. Provide the reagents/catalysts required for the given polymerisation reaction along with any additional reactant if necessary.



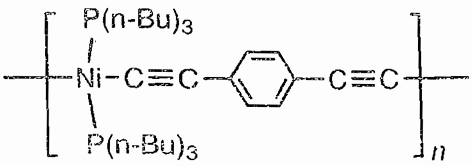
19.12. The spirocyclic sila-bisferrocenophane shown below gives a hexaferrocene substituted cyclosiloxane under the given reaction conditions. The reaction goes through three isolable intermediates (A, B and C) at each of the steps provided. Draw the structures of these intermediates.



19.13. Similar to ferrocenophanes, [1], [2] and [3]ruthenocenophanes have been prepared and the propensity of their ring opening polymerisation explored. Predict whether the tilt angles of the given ruthenocenophanes will be higher or lower than the analogous ferrocenophanes and indicate which among them are likely to undergo thermal strain induced ring opening polymerisation. (*Angew. Chem. Int. Ed.*, 2007, Vol. 46, 5060)



19.14. Given $NiCl_2[(P(n\text{-}Bu)_3]_2$ and 1,4-dialkynylbenzene, suggest a synthetic method to prepare the following polymer.



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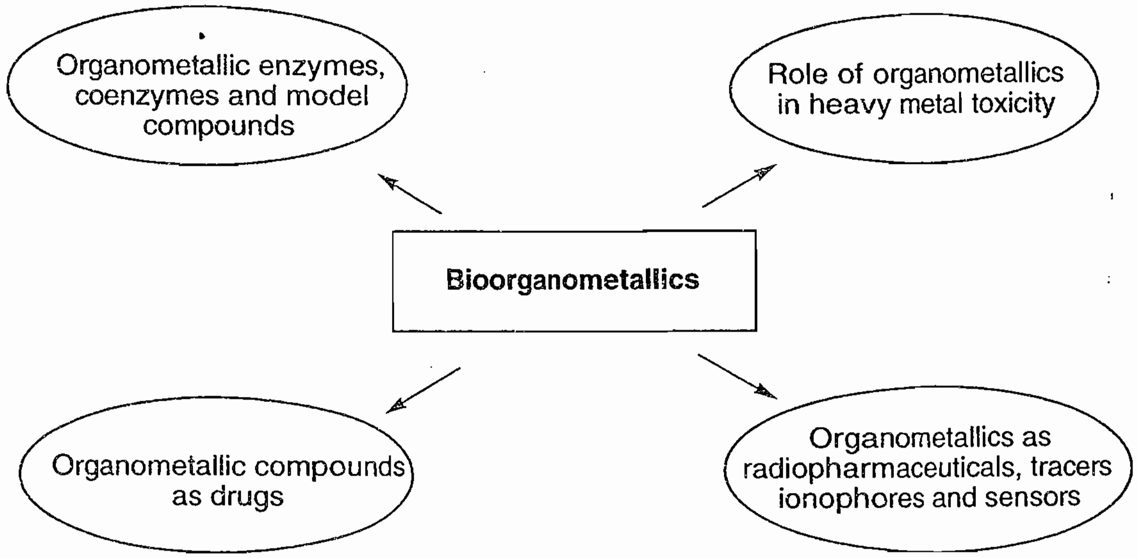
BIOORGANOMETALLIC CHEMISTRY

CHAPTER 20

20.1 INTRODUCTION

Organometallic chemistry and biology were once viewed as mutually incompatible fields of science, because most organometallic compounds were thought to be inherently sensitive to water and oxygen—the substances that are essential for biology. However, continued efforts of researchers have led to the realisation that much of these two fields can be made compatible with each other. In fact, merging these two disciplines has resulted in a new area called bioorganometallic chemistry. Although cyanocobalamin and related compounds which come under this category have been in existence for quite some time, most of the progress in this area has taken place in the second half of twentieth century. The term bioorganometallic chemistry was coined in the mid 1980s by Ge'rard Jaouen, Richard H Fish and others and was applied to the study of organometallic compounds which had biological and medicinal applications.[1] The term covers metal complexes formed using classical ligands (CO, alkyls, π bonded species) or biomolecules (sugars, peptides, amino acids, nucleic acids, enzymes, antibodies, vitamins) possessing direct M–C linkages. The one thing that all such compounds have in common is that they have the ability to play a significant role in some biological processes. The field has developed significantly over the years and is now a well-recognised sub-discipline of organometallic chemistry. One of the factors responsible for its growth has been the understanding of the M–C bond following the discovery of ferrocene and similar sandwich complexes, metal carbonyls, metal carbenes and carbynes. The structural diversity, novel reactivity and properties of the M–C bond in these compounds have helped in the rapid development of transition metal organometallic chemistry in general and bioorganometallic chemistry in particular.

Water is present in all biosystems and a major requirement for almost all bioorganometallic compounds is their stability in water. Therefore, this area has a significant overlap with aqueous organometallic catalysis as well. Here, organometallic compounds are used as homogeneous catalysts in aqueous media; this has been gaining attention in recent years. The topics dealt under the bioorganometallic banner include enzymes and coenzymes (with a major emphasis on cobalamin and related molecules), biomethylation of heavy metals and related toxicity studies (for example, mercury poisoning), synthesis and testing of drugs having an organometallic component (for example, the antimalarial ferrocene-derived drug Ferroquine) and radiopharmaceuticals (for example, Cardiolite, a technetium based myocardial imaging agent). In addition, studies on organometallic tracers of common drugs in nonisotopic immunoassays, synthesis of organometallic ionophores capable of selectively binding to a specific ion and use of organometallic complexes as tracers and sensors are also considered as part of bioorganometallic chemistry (Scheme 20.1). A rapid expansion in research in bioorganometallic chemistry has taken place in the last two decades. Recent developments in some of the most important areas under bioorganometallic chemistry are discussed in this chapter.



Scheme 20.1 Major branches of bioorganometallic chemistry

20.2 ORGANOMETALLIC ENZYMES AND COENZYMES

While vitamin B_{12}, its coenzyme and methylcoblamin were for long considered as the only naturally occurring compounds having metal carbon bonds, new examples of organometallic compounds which play a significant role in biosystems are being explored. The capability of FeS and NiS species to catalyse the synthesis of acetylmethyl sulphide from CO and methyl sulphide, is closely related to pre-biotic synthesis in hydrothermal fluids. Many other metalloenzymes, such as *hydrogenases* and *nitrogenases* are also dealt with under bioorganometallic chemistry. Nevertheless, vitamin B_{12} and related cobalamin cofactors still dominate the scene as mature and well-studied systems.[2]

20.2.1 Vitamin B_{12} Coenzyme: 'Nature's most Beautiful Cofactor'

Cobalamin has been referred to as 'nature's most beautiful cofactor'. Coenzyme B_{12} has long fascinated chemists because of its complex structure and diverse catalytic activity. Interest in this large biomolecule is stimulated by the roles that B_{12} coenzymes play as cofactors in a series of essential enzymatic reactions related to nucleic acid, protein and lipid syntheses. The isolation of vitamin B_{12} coenzyme by Barker in 1958 and the elucidation of its structure by Lenhert and Crowfoot-Hodgkin in 1961 indicated for the first time that organometallic reactions occur in biological systems as well. Also, the complicated structure of vitamin B_{12} (Fig. 20.1) showed that the macrocyclic ligand system modifies the properties of cobalt significantly, enabling it to form a stable Co–C bond. Not many compounds with stable Co–C σ bonds were known at that time.

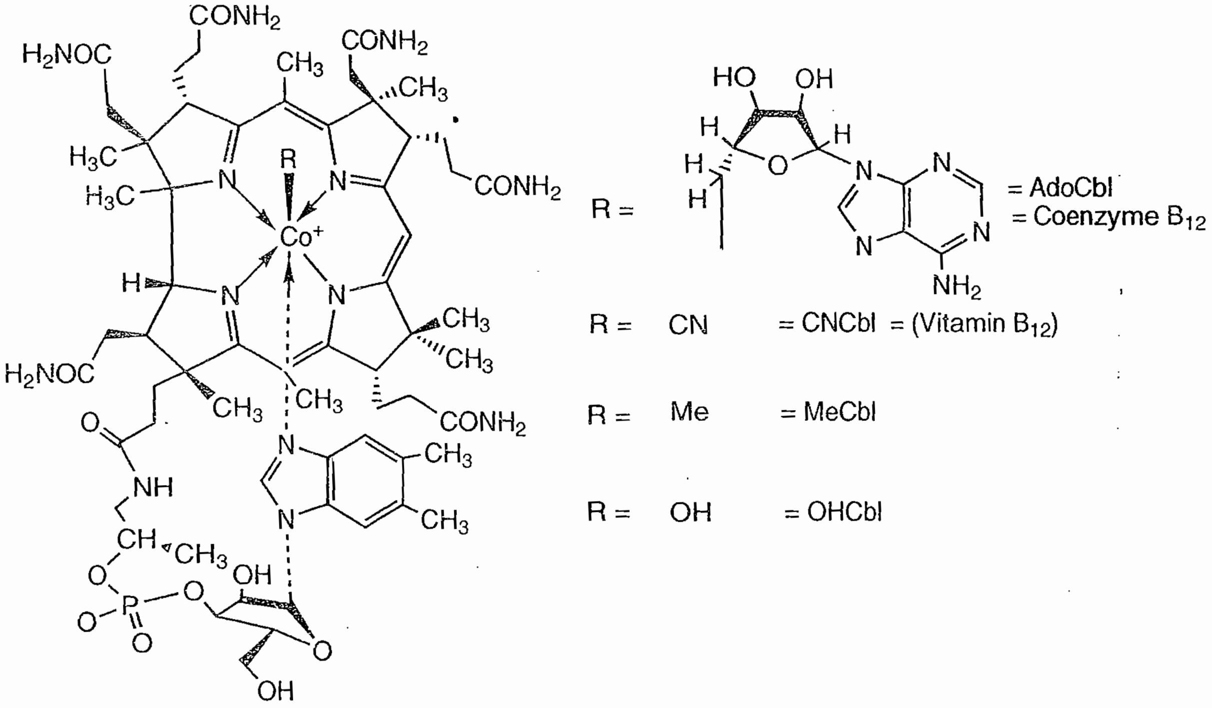


Fig. 20.1 Coenzyme B_{12} and related cobalamins

20.2.2 Nomenclature and Structure

Vitamin B_{12} is the name given to a class of chemically related compounds, all of which have vitamin activity and belong to a family of substances called correnoids. These share the common cobalamin structure. The core of coenzyme B_{12} is a low spin* Co^{III} which in addition to the four equatorial pyrrole nitrogen atoms of the corrin ring is further bonded to the R group and the 5′- carbon atom of the deoxyribose moiety, which is further connected to adenine. The combination of ribose with adenine is called adenosine. The sixth ligand on the other side of the corrin ring is a benzimidazole

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[*] The cobalt is considered as +3; the four corrin nitrogens contribute 8e and a charge of –2, the benzimidazole nitrogen contributes 2e and the cyanide or adenosine in the sixth position contributes 2e and a charge of –1. The moiety without the R ligand is called cobalamin.

base that is linked with the side chain of the pyrrole ring via the ribose and phosphate entities. The terminology for different derivatives of the vitamin B_{12} is linked to the nature of R, such as cyanocobalamin (CNCbl, R = CN), methylcobalamin (MeCbl, R = CH_3) and adenosylcobalamin (B_{12} coenzyme) (AdoCbl, R = 5′-deoxy-5′-adenosyl). So B_{12} is cyanocobalamin – the form used for treating pernicious anemia – and adenosyl cobalamin is called coenzyme B_{12}. It is now known that CNCbl, as originally isolated, was an artifact of the isolation procedure, which converted AdoCbl to CNCbl. Unless strict precautions are taken to avoid exposure to light, AdoCbl and MeCbl are converted to hydroxocobalamin (OHCbl), which reacts with cyanide ions (present in the charcoal columns originally used to isolate vitamin B_{12}) to give CNCbl. So cyanocobalamin itself is not present in biological systems.[3]

From the reactivity point of view, alkyl cobalamins are stable, acid resistant but thermo- and photo-labile organocobalt complexes. One-electron reduction gives the Co(II) species called coenzyme B_{12r} and further reduction gives the Co(I) species, B_{12s}. Such reductions can be achieved in biological systems by the biological reducing agent FAD (flavin adenine dinucleotide). B_{12s} is a powerful nucleophile and like any low valent transition metal complex, reacts with MeI to give methylcobalamin.[4]

20.2.3 Correnoid Dependent Enzymatic Reactions

Coenzyme B_{12} acts in concert with a variety of enzymes and about a dozen enzymatic reactions are known in which some form of B_{12} participates as a catalyst and there is reason to believe that many more remain to be discovered. In all the enzymatic reactions, the correnoids act in association with a protein. A large number of enzymes consist of a protein (called the apoenzyme) and a smaller molecule (a cofactor, enzyme or a prosthetic group) which together form an enzyme. As a general rule, it is the cofactor that contains the active site and determines the general type of reaction that the enzyme can catalyse, while the protein governs the specificity of the reactions and enhances the rate.[†]

Important correnoid-dependent enzymatic reactions are given below.[5–7]

(i) *Reactions which require MeCbl*
   (a) Synthesis of methionine (by N^5-methyl tetrahydrofolate: homocysteine methyltransferase)

$$N^5\text{-Methyltetrahydrofolate} + \text{Homocysteine} \longrightarrow \text{Tetrahydrofolate} + \text{Methionine}$$

Since methionine is an essential building block of so many proteins, the conversion of homocysteine to methionine is important.

[†] Enzymes may not function well or at all unless some other species known as a cofactor is present. An enzyme alone is referred to as the apoenzyme and the combination of enzyme and cofactor is called holoenzyme. Among the species that function as cofactors are organic compounds that interact with the enzyme. If the organic moiety is strongly attached to the enzyme, it is called the prosthetic group, but if it is loosely bound to the enzyme, it is referred to as a coenzyme.

Landmarks in the discovery and chemistry of vitamin B_{12}

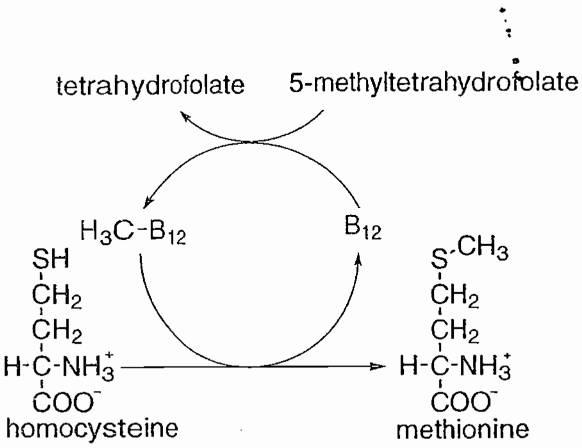
Vitamin B_{12} is the largest of all vitamins and is the only vitamin which contains a metal ion—cobalt. It is apparently the only vitamin which requires a special mechanism for absorption into the body from the gut. There are fewer molecules of vitamin B_{12} in a human being than there are red blood cells. An adult human body contains 4–5 mg of vitamin B_{12} of which 1 mg is in the liver alone. Vitamin B_{12} deficiency leads to a variety of diseases that can now be cured easily by the administration of adequate amounts of vitamin B_{12}. It catalyses a number of unusual reactions, some of which do not have an analogy in organic chemistry. The past five decades have recorded very significant progress in vitamin B_{12} chemistry and biochemistry.

The study began in 1821 with a mysterious disease now known as pernicious anemia, caused by B_{12} deficiency. It took almost one hundred years to gain knowledge into the signs of the disease and method of diagnosis. The disease was primarily recognised by the decrease in the number of red blood cells, many of which also lacked their normal disc-like appearance. Further symptoms of the disease included a lemon yellow complexion, redness and soreness of the tongue, absence of hydrochloric acid in the stomach and in the later stages, neural degeneration associated with gradual paralysis of limbs. There was, however, no treatment and the disease remained incurable. Following a lead from W Whipple in California (1925), physicians W P Murphy and G R Minot in Boston (1926) (Nobel Prize 1934) reported a remarkable improvement in patients fed on a diet of raw liver. This started the search for the 'liver therapy factor'.

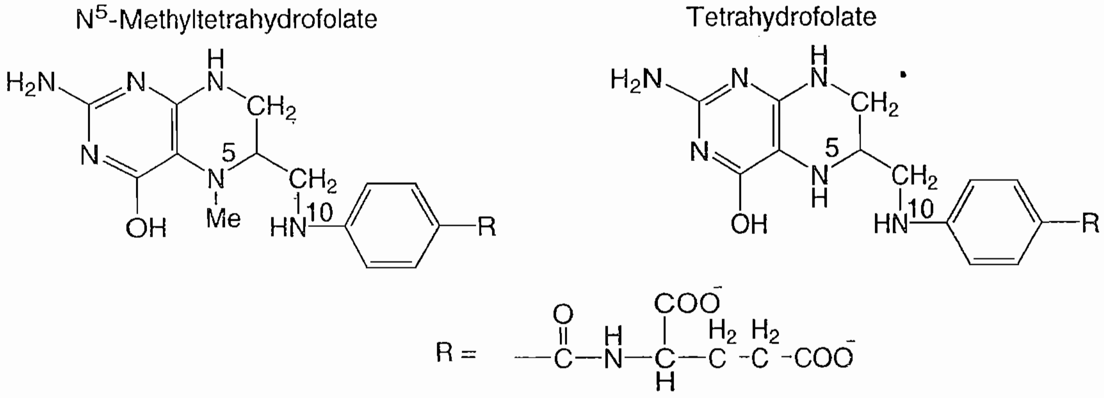
The first phase of research was to isolate the compound (liver therapy factor) that was present in liver in a concentration of only 1 ppm. Scientists from Glaxo and Merck isolated this red crystalline material and they named it vitamin B_{12}. It was highly active against pernicious anemia.

The second phase of research was to elucidate the structure of B_{12} by chemical and physical methods and to evolve methods for its large-scale production. Many microorganisms, capable of synthesising B_{12}, were discovered. Dorothy Hodgkin of Oxford was awarded the Nobel prize in 1964 for elucidating the structure of this molecule. The work was an exciting episode in the history of X-ray crystallography because B_{12} was the largest structure studied successfully up to that time. By then it has become evident that B_{12} is one of a family of closely related compounds called 'correnoids' in nature (correnoids is a generic name for compounds containing a corrin ring). The most important single discovery was by H A Barker and his associates in California (1958) who isolated the so called 'coenzyme form of correnoid' which is generally referred to as vitamin B_{12} (coenzyme). It is also known as adenosyl cobalamin (AdoCbl). This form of correnoid is present in animal tissue. The compound which was isolated earlier and named B_{12} actually resulted from the isolation procedure which converted B_{12} (coenzyme) to the cyano derivative (B_{12}).

The third phase of research activity was aimed at the synthesis, properties and reactions of cobalamins and determining their precise role in enzymatic reactions. The total synthesis of this molecule with the correct number of substituents and stereochemistry was achieved in 1976. It required 65–70 steps and took 11 years and the dedicated contribution of 100 chemists in a collaborative effort directed by R B Woodward, the noble laureate (Harvard) and A Eichenmoser (Zurich).[8,9]

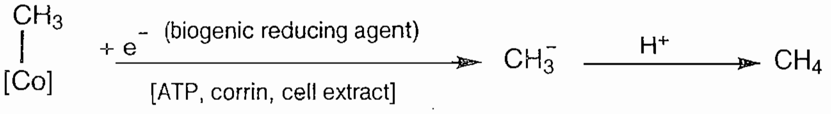


(20.1)


N^5-Methyltetrahydrofolate

Tetrahydrofolate

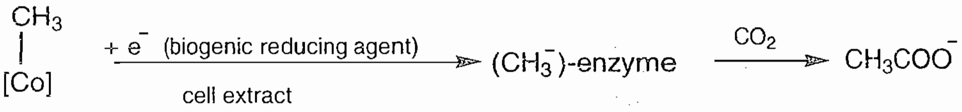
(b) Synthesis of methane



$$\underset{[Co]}{\overset{CH_3}{|}} \xrightarrow[\text{[ATP, corrin, cell extract]}]{+e^- \text{ (biogenic reducing agent)}} CH_3^- \xrightarrow{H^+} CH_4$$

(20.2)

(c) Synthesis of acetate

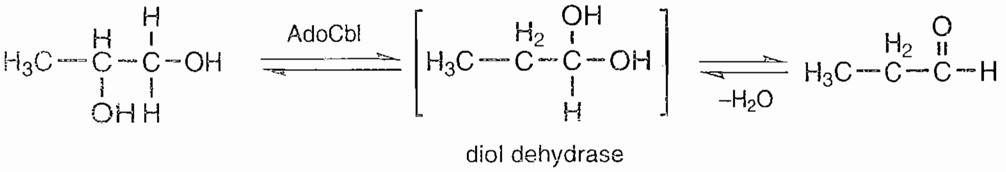


$$\underset{[Co]}{\overset{CH_3}{|}} \xrightarrow[\text{cell extract}]{+e^- \text{ (biogenic reducing agent)}} (CH_3^-)\text{-enzyme} \xrightarrow{CO_2} CH_3COO^-$$

(20.3)

(ii) *Reactions which require AdoCbl*

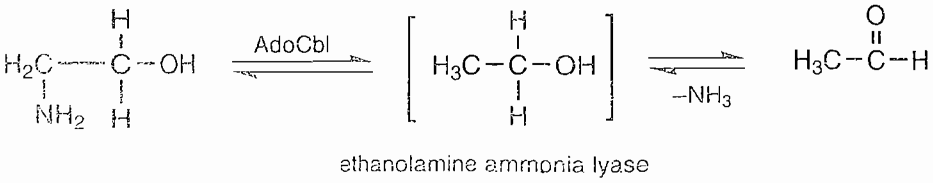
(d) Diol dehydrase



$$H_3C-\underset{OH}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-OH \xrightleftharpoons{AdoCbl} \left[H_3C-\overset{H_2}{C}-\underset{H}{\overset{OH}{C}}-OH\right] \xrightleftharpoons[-H_2O]{} H_3C-\overset{H_2}{C}-\overset{\overset{O}{\|}}{C}-H$$

(20.4)

(e) Ethanolamine ammonia lyase

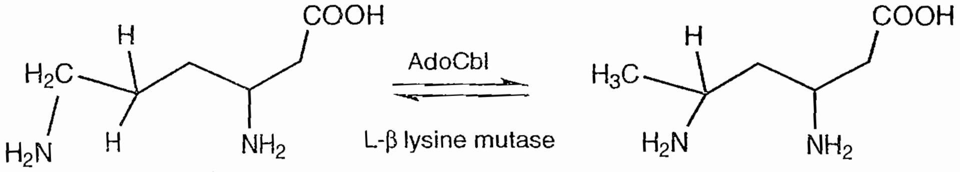


$$H_2\underset{NH_2}{\underset{|}{C}}-\underset{H}{\overset{H}{C}}-OH \xrightleftharpoons{AdoCbl} \left[H_3C-\underset{H}{\overset{H}{C}}-OH\right] \xrightleftharpoons[-NH_3]{} H_3C-\overset{\overset{O}{\|}}{C}-H$$

(20.5)

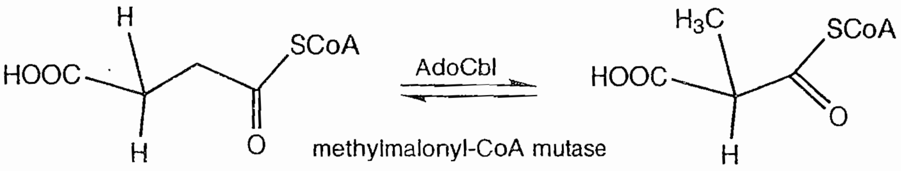
Several mutases in which hydrogen and another group on an adjacent carbon exchange places are shown below.

(f) Aminomutase utilising (S)-3,6-diaminohexonoate, (R)-2,6-diaminohexonoate, (R)-2,5-diaminopentanoate or α and β-leucine.



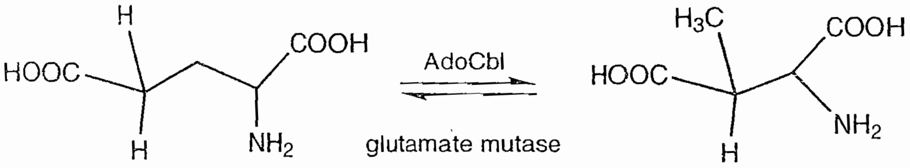
(20.6)

(g) Methylmalonyl-CoA mutase



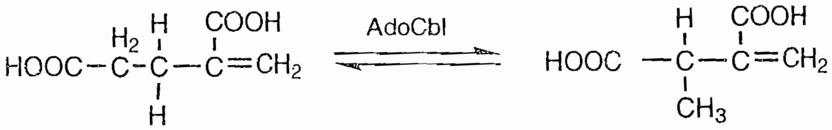
(20.7)

(h) Glutamate mutase



(20.8)

(i) α-Methyleneglutarate mutase

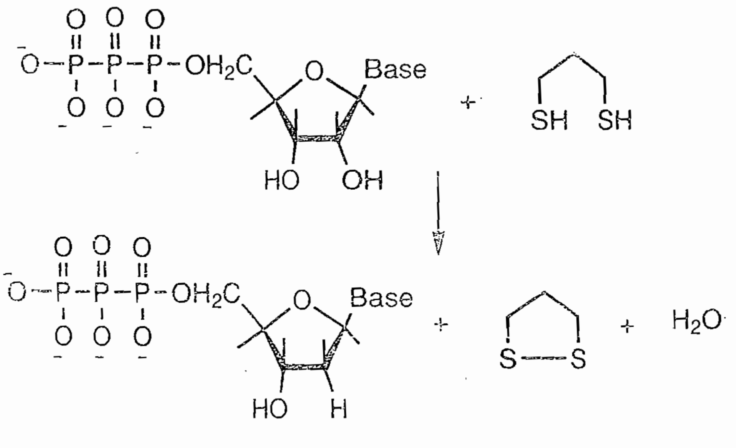


$$\mathrm{HOOC{-}\overset{H_2}{C}{-}\underset{H}{\overset{H}{C}}{-}\overset{COOH}{C}{=}CH_2} \xrightleftharpoons{\text{AdoCbl}} \mathrm{HOOC{-}\underset{CH_3}{\overset{H}{C}}{-}\overset{COOH}{C}{=}CH_2}$$

(20.9)

(j) Ribonucleotide reductase

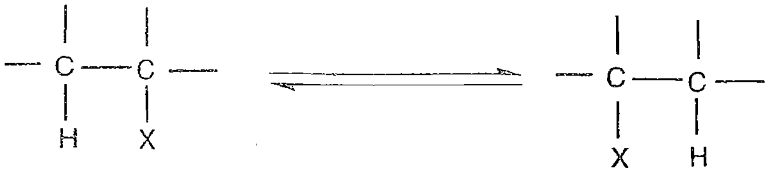
Here ribose is reduced to deoxyribose.



(20.10)

ribonucleotide reductase

One can see from the above description, the broad classification of the known reactions into two groups depends upon whether MeCbl or AdoCbl is involved. All B_{12} dependent enzymes involve the making and breaking of the Co–C bond. AdoCbl is the cofactor in isomerase and mutase enzymes, which catalyses the intramolecular 1,2-shift of a hydrogen atom and an electronegative X group.



(20.11)

MeCbl-based enzymes (methyltransferase) on the other hand, catalyse the transfer of a methyl group from the N or O atom to cob(I)alamin (to form MeCbl) for onward transmission to a sulphur atom, as in methionine synthase. The mechanisms are fundamentally different for these two B_{12} coenzymes. Enzymes that bind MeCbl require heterolytic cleavage of the Co–C bond, leaving both electrons on cobalt, to form Co^I and CH_3^+ whereas, homolytic cleavage of the Co–C bond in AdoCbl forms cob(II)alamin and the 5′-deoxyadenosyl radical and acts as a radical generator. Table 20.1 compares the Co–C and Co–N bond distances as well as Co–C bond dissociation energies (BDE) of MeCbl and AdoCbl.[5]

Table 20.1 Comparison of bond distances and bond dissociation energies of MeCbl and AdoCbl

	Co–C (Å)	$Co–N_{ax}$ (Å)	Co–C BDE (kcal/mol)	$E_{1/2}$ (V)
MeCbl	1.979(4)	2.162(4)	(37 ± 3)	–1.60
AdoCbl	2.030(3)	2.237(3)	(30 ± 2)	–1.35

Despite 50 years of active research on AdoCbl, the mechanism of enzymatic activation of AdoCbl is not yet known for any AdoCbl-dependent enzyme and remains one of the outstanding problems in bioinorganic chemistry. The X-ray structure of a cobalamin binding fragment of some of the enzymes together with EPR studies, has revealed that proteins bind cobalamin in atleast two distinct modes—*base-off* and *base-on* (Fig. 20.2). In the base-off mode, a histidine side chain from the protein replaces the coordinated base [5,6-dimethylbenzimidazole (Bza)]. The bond between cobalt and histidine is significantly longer (2.5 Å) compared to free cobalamin (1.95–2.2 Å). This stretched bond explains how the enzyme weakens the metal-carbon bond of the cofactor and stabilises the reduced state, in order to favour the formation of the adenosyl radical.

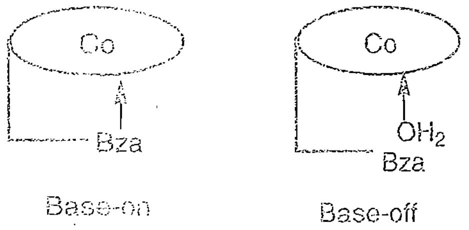
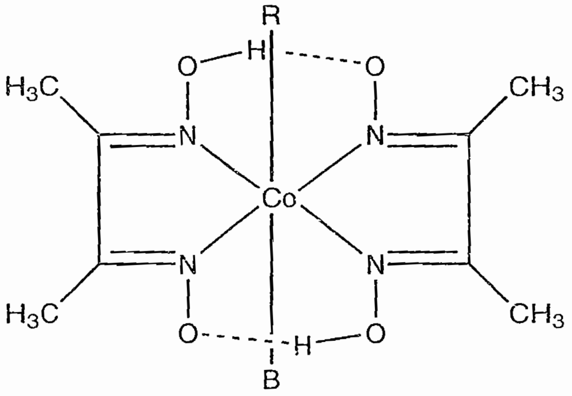


Fig. 20.2 Schematic depicting base-on and base-off binding modes on cobalamin

20.2.4 Vitamin B_{12} Model Compounds

After the work of Hodgkin, in the ensuing years, numerous papers have appeared on organocobalt compounds and some of these compounds have been proposed as models of vitamin B_{12} (Fig. 20.3). In 1964, Schrauzer and Kohnle reported that the reaction of coenzyme B_{12} could be simulated with much simpler model complexes of dimethylglyoxime, pyridine and an R group on cobalt and named these compounds 'cobaloximes' to stress their similarity to cobalamins. They also provided the theoretical justification for using of organocobaloximes as vitamin B_{12} models. MO calculations revealed that eigen values and essential eigen vectors of axial bond molecular orbitals in cobaloximes and cobalamins were strikingly similar.



$RCo(dmgH)_2B$

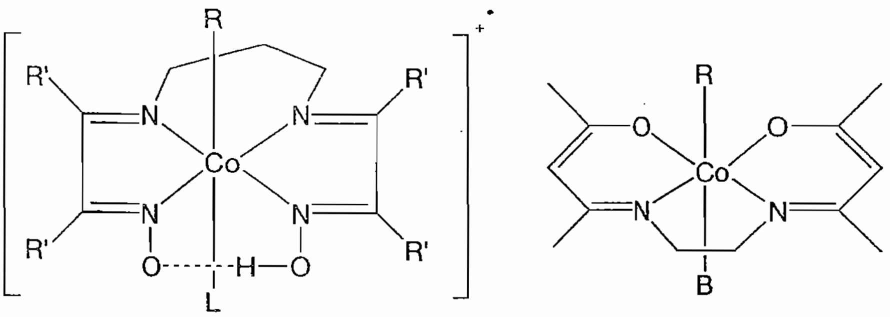
R = alkyl, allenyl, propargyl, benzyl etc.
B = pyridine, PPh_3, H_2O etc.

Fig. 20.3 Structure of cobaloximes

In addition, numerous other vitamin B_{12} analogues have been recognised, encompassing a variety of ligands, notably the Schiff-base type, such as BAE and SALEN. In 1969, Costa and coworkers reported complexes of the type $[RCo(DO)(DOH)pn)B]^+$ [pn = $(CH_2)_3$] where the tetradentate ligand is a monoanion, as in corrinoids. Other B_{12} models include cobalt porphyrins and complexes of tetraaza macrocyclic ligands such as 1,4,8,11-tetraaza cyclotetradecane. Since 1990, many more B_{12} model complexes have appeared and most of these are derived either from cobaloxime or Costa type complexes (Fig. 20.4). The main reason for the synthesis of these complexes was to study the steric and electronic influence of the axial and the equatorial ligands on the Co–C bond stability in these complexes.[10]

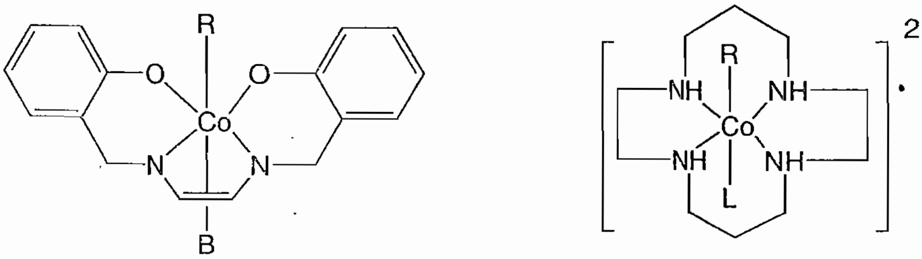
Cobaloxime: A better model

Of all the reported model compounds, cobaloximes simulate the reaction of vitamin B_{12} more closely, both qualitatively and quantitatively. Two dimethylglyoxime ligands model the corrin, a pyridine (or any neutral base, B) models the axial base and the sixth position can be an alkyl group or a water molecule. The crystallographic data on cobalamins suggests that the structural effects of changes in R groups are similar to those found in cobaloximes and often can be related to their chemical behaviour. The alkyl compound, for example,



$[RCo((DO)(DOH)pn)B]^+$
(Costa type)

RCo(BAE)B



RCo(SALEN)B

$[Co([14]aneN_4)(B)R]^{2+}$

Fig. 20.4 Vitamin B_{12} analogues other than cobaloximes

ethyl or adenosyl, is very stable and does not undergo β-hydrogen elimination easily. This is because the rigid equatorial dioxime ligands prevent the formation of a vacant site *cis* to the alkyl group in this 18e system. Cobaloximes can be reduced to Co(I) and Co(II) just like the species B_{12r} and B_{12s}. The Co(I) form is a super-nucleophile and reacts very fast with MeI to form the $MeCo(dmgH)_2Py$ complex. This is quite similar to vitamin B_{12} chemistry. Both, homolytic and heterolytic cleavage of the Co–C bond in cobaloximes have been achieved just like in vitamin B_{12}. The studies on cobaloximes have furnished some insight into the factors that affect homolysis of the Co–C bond and have allowed indepth analysis of the variation in the geometry of the R-Co-B fragment (in terms of electronic and steric properties of R and B). Organocobaloximes have therefore been extensively used to mimic the B_{12} coenzyme and results have continued to complement those on the more complex cobalamin and B_{12}-based proteins. Most of the recent work on cobaloximes has focused on the spectral and structural properties of cobaloximes.

Widespread use of cobaloximes as models for cobalt corrins is also because these can be easily synthesised by one-step alkylation of Co^I, generated in situ from readily available and inexpensive starting materials such as dimethylglyoxime and pyridine. Most other chelate systems demand the synthesis of the ligand followed by the insertion of the metal ion. Further, other cobalt containing products should be isolated before introduction of the organic ligand. Although ligands with diverse properties have been readily incorporated into the alkylcobaloxime class of B_{12} models, a comparable range of ligands cannot be introduced so readily into other models or into cobalamin.

In addition, the cobaloximes are ideal systems for structural determination by ^{1}H-NMR spectroscopy. All these advantages have led to the development of cobaloxime chemistry as an independent research field.

20.3 ROLE OF ORGANOMETALLICS IN HEAVY METAL TOXICITY

Heavy metals and metalloids such as mercury, arsenic, tin and lead are highly toxic to living systems and many of them have an organometallic connection with regard to their toxicity. Alkyls, especially methyl derivatives of these metals such as dimethylmercury, trimethylarsine and methylmercury cation are cumulative poisons and they are often found to attack enzymes having a thiol group in a living system. The word mercaptan itself means 'capturing mercury'.

20.3.1 Heavy Metal Toxicity: Mercury Related Cases[11]

The toxicity of mercury has been known even from the times of Romans as criminals sentenced to work in cinnabar (ore of mercury) mines had a short life expectancy and it was almost considered a death sentence. Modern day incidents of mercury poisoning begin

$MeHg^+$ poisoning: Fish from Minamata Bay, Japan

Late in 1953, a strange and severe neurological disorder was observed among inhabitants in the vicinity of the Minamata Bay, a fishing hamlet situated in the southwestern Kyushu province in Japan. The victims were diagnosed as having degeneration of their nervous systems and the disease soon reached epidemic proportions. Typical symptoms were numbness in their limbs and lips, lack of coordination in hand movements, wobbling gait and slurred speech. Some people had serious brain damage, while others lapsed into unconsciousness, suffered from involuntary movements, paralysis and eventually died after suffering for months. The cats living in the bay also behaved oddly, moving around erratically, having convulsions and salivating and some even ran to the sea and drowned. Even sea birds were flying erratically and strangely, even dropping dead from the sky. Dead fish were also found floating in the sea and these unexplainable occurrences were bringing panic to Minamata.

A local doctor linked the fish diet of this coastal village to the disease, and soon investigators were promulgating that the sea was being polluted by poisons released by a chemical factory located in the vicinity belonging to the Chisso Corporation. In July 1959, researchers from the Kumamoto University concluded that organic mercury was the cause of the 'Minamata disease'. Methylmercury compounds were identified as the real culprits. Originally, it was believed that the methyl derivatives of mercury were produced by the factory. This was debunked in 1979, when Jensen and Jernelöv discovered natural methylation of mercury by methylcobalamin present in bioorganisms from the sea sediments. Background sediment mercury concentration in the seas is normally in the order of 10–200 μg/kg. Concentrations found in the Minimata Bay were around 2000 mg/kg (0.2%). Many sulphate-reducing bacteria methylate mercury and the biochemical reason appears to be to protect themselves from mercury poisoning. Metal cations such as the toxic mercuric ion (Hg^{2+}), move only slowly through bacterial membranes. But, the methylated forms pass through the membrane much more readily than the inorganic form. The process appears, then, to be a way for bacteria to excrete mercury and protect itself.

The aftermath of the Minamata disaster continued for a long time and law suits were being taken up even in the 1990s. The most disturbing aspect of the disaster was the effect it had on women of that locality as they either did not conceive or when they did, had miscarriages or still born babies. Those babies who survived often had serious deformities or brain damage.

with the Minamata bay (Japan) incident in 1953, where people who ate fish caught from the polluted sea were found to be affected with mercury poisoning. This was followed by cases of poisoning of people in Iraq and Pakistan (1956–61) who used pink coloured wheat seeds, which had been treated with mercury containing pesticides. In 1997, the death of Professor Karen Wetterhahn of Darthmouth college, USA, who while handling Me_2Hg, accidentally spilled a drop of the compound on her gloved hands, stands out as a horrifying incident of mercury poisoning. Very recently, many parents of children having autism spectrum disorders (a disability which affects social interaction and learning development of a child) have blamed the onset of the disease on the use of an ethylmercury preservative called thiomersal in childrens' vaccines. More than 5,000 US parents having autistic children have filed claims in US federal vaccine courts implicating thiomersal. The use of thiomersal containing vaccines has been discontinued in the UK since 2004.

Bioalkylation

Methylmercury (CH_3Hg^+) is a form of mercury that is most easily bioaccumulated in organisms. Mercury biomethylation is the transformation of divalent inorganic mercury Hg(II) to CH_3Hg^+, and is primarily carried out by sulphate-reducing bacteria that live in anoxic (low dissolved oxygen) environments such as lake bottom sediments. Several forms of mercury occur in the environment. Elemental mercury (Hg^0) is a shiny, silver-white, odourless liquid, commonly used in thermometers. Contamination of elemental mercury was found at abandoned gold mine sites where it was used to extract gold from gold-bearing ores. Divalent mercury Hg(II), can combine with sulphur, oxygen and chlorine to form mercury salts. Mercuric chloride ($HgCl_2$) which has been used as a preservative for water quality samples for nutrient analysis, can cause gastrointestinal and kidney problems. Mercuric sulphide (HgS) is the mineral cinnabar, which is mined as a source for mercury.[12]

Methylmercury cation ($MeHg^+$) is a neurotoxin that can adversely affect the development of the brain and nervous system, especially in children. The symptoms include vision, speech and hearing impairment, memory loss, lack of coordination of movements, disturbance in sensations, mood swings and skin rashes. High doses may lead to seizures, severe neurological impairments and can be fatal. Bioalkylation is a process in which direct linkage of an alkyl group to metals or metalloids to form the metal–alkyl bond occurs in living organisms. The methyl group is the most common alkyl group that can be transferred and the process is referred to as biomethylation.

Initially, the large amount of mercury found in fish in the Minamata bay was thought to be due to inorganic mercury, released as industrial waste to the bay. Later it was shown that mercury was present almost entirely as methyl mercury ($MeHg^+$). The question is, how does inorganic mercury get converted to methyl mercury and get accumulated in the fish? Bacteria convert inorganic mercury into methyl mercury through biomethylation. Fish absorb this methyl mercury through their gills as they feed on aquatic organisms. The toxin gets biomagnified as it moves up the food chain, and a little methylmercury can magnify a great deal in an ecosystem. Since larger fish eat little fish and as larger fish live longer, the problem exacerbates. Cooking does not remove appreciable amounts of the toxin. The FDA has recommended a level of 1 ppm as the threshold level for safe human consumption.

Me_2Hg poisoning : A drop of Me_2Hg spilled on a gloved hand

Karen Wetterhahn was a professor of chemistry at Dartmouth College, Hanover, USA. She specialised in toxic metal exposure and the effects of heavy metals upon living systems. In August 1996, she was preparing a standard solution of $[Hg(CH_3)_2]$ (b.p. 92°C; density 2.96 g/cm^3) as a standard reference material for ^{199}Hg NMR measurements. Wetterhahn was aware of the high toxicity of dimethylmercury and took very reasonable precautions, wore safety glasses and latex gloves, did manipulations in a fume cupboard and only worked with very small quantities. A colleague of hers cut the top of the glass vial of the purchased compound and opened it for her after cooling it in ice-water to reduce the volatility of the $Hg(CH_3)_2$. Prof. Wetterhahn pipetted a small sample into an NMR tube and transferred the rest into a storage container, sealed and labelled the tubes and cleaned up, and disposed off the latex gloves.

By January 1997, she began to notice definite symptoms that worried her—tingly fingers and toes and slurred speech. She was also having an unsteady gait and visual disturbances and her field of vision started to shrink. Mercury poisoning was diagnosed very soon. Tests revealed that she had a blood mercury level of 4000 micrograms per litre, 80 times that of the toxic threshold. Wetterhahn later recalled spilling a drop of dimethylmercury, on her gloved hand while handling it. Test showed subsequently that this would have penetrated the glove and entered her skin within 15 seconds. Two weeks later she slipped into a coma from which she never recovered; she died in June 1997.

Dimethylmercury is one of the most potent neurotoxins known. It readily crosses the blood–brain barrier, probably due to the formation of a methylmercury–cysteine complex. It causes ataxia (lack of coordination), sensory disturbances and changes in the mental state. It inhibits several stages of neurotransmission in the brain. It is a cumulative poison and by the time its effects are noticed, it is too late to do anything about it.

The biomethylation of Hg^{2+} ions to $MeHg^+$ and/or to a limited extent to dimethylmercury, is achieved by microorganisms which use methylcobalamin. The latter are able to transfer the methyl group to Hg^{2+} as a carbanion to form $MeHg^+$.[13]

The formation of highly toxic methyl mercury compounds ($MeHg^+$ and Me_2Hg) under environmental conditions has been shown to result from the methylation of mercury (II) by methylcorrenoids. While the re-methylation of the correnoid (and hence the whole catalytic cycle) is enzyme dependent, it is not clear whether the actual step involving the transfer of [illegible] from $[Co–CH_3]$ to mercury (II) is an enzymatic process since this reaction has been demonstrated to occur readily under nonenzymatic conditions also. In 1964, Halpern [illegible] first demonstrated the methylation of mercury (II) by methyl cobalt compounds [illegible] found that $[CH_3Co(CN)_5]^{3-}$ on reaction with $HgCl_2$ in aqueous solution was found [illegible] CH_3HgCl. Such reactions and their analogues – for example, the [illegible] methylation of Tl(III) and As(III) – have subsequently received considerable attention [illegible] following the demonstration by Wood in 1968 that methylcobalamin was [illegible] effecting the synthesis of both monomethyl and dimethylmercury(II) in enzymatic [illegible] nonenzymatic systems. The most interesting difference between these two processes [illegible] to be the formation of methylmercury(II) salts in the latter and of dimethylmercury [illegible] the former. This process is now widely believed to be responsible for the [illegible] of highly toxic methylmercury compounds under environmental conditions.

$$[CH_3Co^{III}(CN)_5]^{3-} + Hg_{(aq)}^{2+} + H_2O \longrightarrow CH_3Hg^{+}_{(aq)} + [(H_2O)Co^{III}(CN)_5]^{2-} \quad (20.12)$$

$$[RCo^{III}(dmgH)_2H_2O] + Hg_{(aq)}^{2+} + H_2O \longrightarrow [RHg_{(aq)}]^{+} + [Co^{III}(dmgH)_2(H_2O)_2]^{+} \quad (20.13)$$

20.3.2 Arsenic Poisoning

Inorganic arsenic is considered as one of the most potent human carcinogens and humans are exposed to it from soil, water, air and food. Arsenic, therefore, is ubiquitous in our environment, however, under normal ecological conditions, the level of arsenic bioavailability is not a threat to human health. Soil may contain arsenic levels between 0.1 and 40 ppm if the underlying bedrock is not disturbed or redistributed by natural processes. Since a large number of artificially prepared arsenic compounds were used in agriculture as effective agents against pests, parasites or weeds, they have gradually accumulated in the soil. Arsenic occurs naturally in several forms such as native arsenic, arsenic acid (H_3AsO_4) and its salts called arsenates (MH_2AsO_4, M_2HAsO_4), arsenous acid, its salts, and its anhydride, As_2O_3, AsH_3, an extremely poisonous gas, and various minerals in which arsenic has a oxidation states varying from -3 to $+5$. Arsenic acid (As^{5+}) is the least toxic of the inorganic forms. Arsenous acid (As^{3+}) is more toxic in vivo than arsenic acid and in addition, it is more inhibitory in vitro. A large number of diverse chemical and biological reactions, that is, oxidation, reduction, adsorption, precipitation, methylation and volatilisation are involved in the cycling of this toxic element and these reactions control the availability of arsenic in nature. Hence, arsenic concentrations effectively exposed to humans are governed more by arsenic speciation rather than by the total amount of arsenic.[14–16]

In living systems arsenic poisoning results in the inhibition of certain metabolic enzymes. In the citric acid cycle, arsenic inhibits the enzyme pyruvate dehydrogenase. As a result of this, substrates before the dehydrogenase-steps (such as pyruvate and lactate) accumulate, and this causes neurological disturbances. By competing with phosphate, arsenic compounds are believed to disrupt oxidative phosphorylation thus inhibiting energy linked NAD+ reduction, mitochondrial respiration and consequently ATP synthesis. Production of hydrogen peroxide is also increased which leads to oxidative stress. The result of these metabolic interferences will be multi-system organ failure leading to death.[17]

Organoarsenic chemistry, though of minor importance nowadays, has played an important part in the ancient history of chemistry. Cacodyl, $(CH_3)_2As\text{-}As(CH_3)_2$, and cacodyl oxide $[(CH_3As)]_2O$, classified as the first synthetic organometallic compounds and referred to as components of Cadet's fuming liquid, were reported as early as 1760. By 1909, Salvarsan also known as arsphenamine, was well known as the first modern chemical therapeutic agent and was used for the treatment of syphilis. This compound was thought of as a cyclic organo–arsenic hexamer $[(ArAs)_6]$ (Ar = 3-amino, 4-hydroxy benzene) for a long time. Mass spectral studies carried out in 2005 indicated it to be a mixture of the cyclic trimer and a pentamer with the same basic unit (Fig. 20.5).[18]

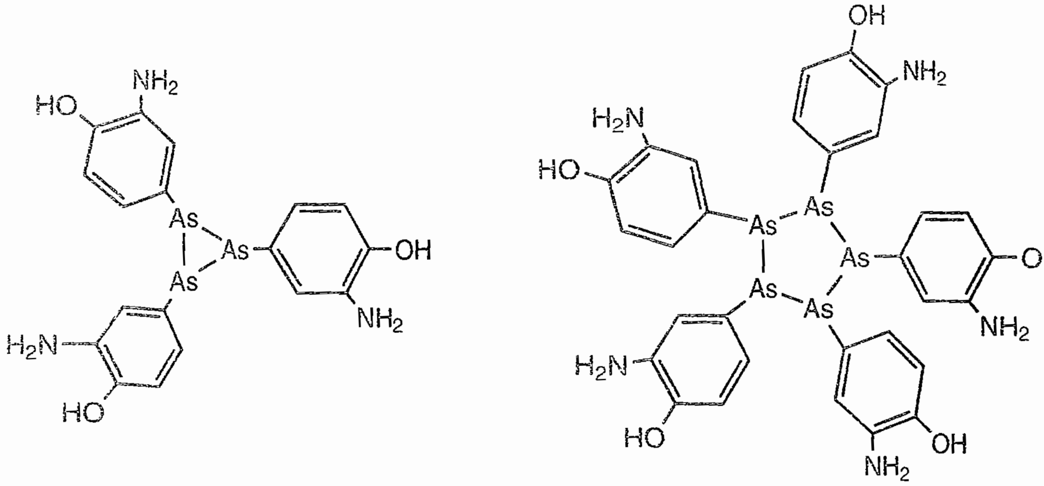


Fig. 20.5 Trimeric and pentameric forms of Salvarsan

Me$_3$As poisoning : Deadly wallpapers decorated with a green pigment

In 1778, Carl Wilhelm Scheele discovered a bright green dye basically composed of copper arsenate. Around 1814, the Wilhelm Sattler dye and white lead company in Schweinfurt, Germany, began making a mixed copper acetate–arsenate salt for lending a beautiful green colour to paint, cloth and paper and named it Schweinfurter green. Unlike most pigments in use then, this green colour did not turn grey or dull on exposure to sulphides in the air. Wallpaper was just becoming popular in Europe at that time. For sticking the wallpaper to walls, a starch-based paste was used. Northern Europe has a cool, damp climate even in summer. This climate is ideal for the growth of mould and mildew, and that became the basis for a widespread and unusual health problem.

As the green wallpaper became popular, other companies in Germany and France also started making green copper–arsenic dyes for wall papers such as Paris Green, Bremer Green and Kaiser Green. People began to notice that in bedrooms with green wallpaper, all the bedbugs died which was seen as a major benefit and led to increased sales of the paper. However, two other phenomena soon came to light. First, a garlic odour was often present in rooms decorated with such wallpaper, and secondly people who slept in rooms with this green wallpaper got very sick. When the poisoning became acute, there was diarrhea, vomiting, blood in the urine, hair loss and stomach pain. The final result of this poisoning was death in many instances. Although some governments of Europe of that time banned the use of poisonous chemicals in wallpapers, no one could find out the exact chemical compound causing this problem.

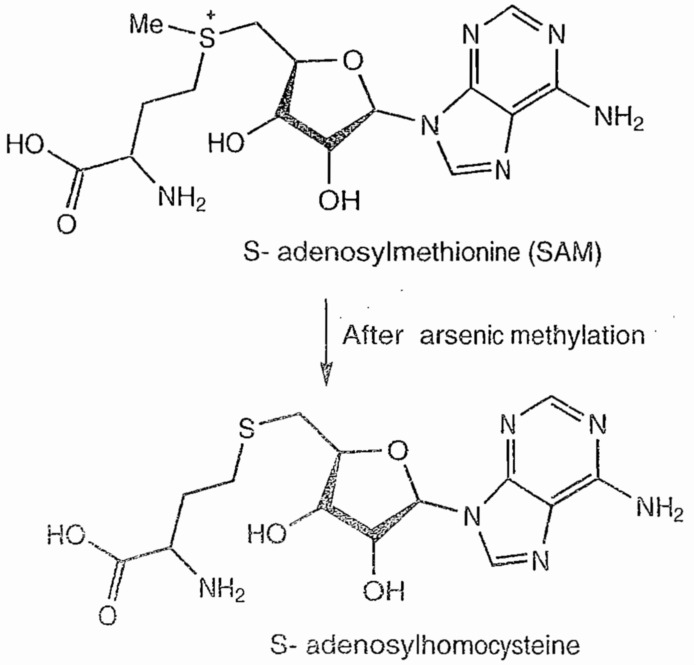
In 1897, an Italian chemist, B Gosio, established that the starch in the paste and sizing was being consumed by a common mould known as *Scopulariopsis brevicaula*. The mould was taking up arsenic from the dye and was excreting it as a gas. The gas had a strong garlic odour and was very toxic. Gosio knew the gas was an organoarsenic compound but was unable to identify it exactly. The poisonous vapours emanating from the green wallpaper became known as 'Gosio gas'. In 1945, Frederick Challenger identified the gas as trimethylarsine. We now know that the fungus converts arsenate to trimethylarsine oxide through a complex series of biochemical reactions and as a last step, the oxide is reduced to trimethylarsine, Me$_3$As and the gas is excreted.

Organoarsenic in nature

Poisoning events due to a gas produced by certain microbes was assumed to be associated with the arsenic present in certain paints used for making wallpapers. In 1897, the Italian physician Bartolomeo Gosio published his results on the poisonous 'Gosio gas' that was subsequently shown to be trimethylarsine.

The general principle of arsenic detoxification

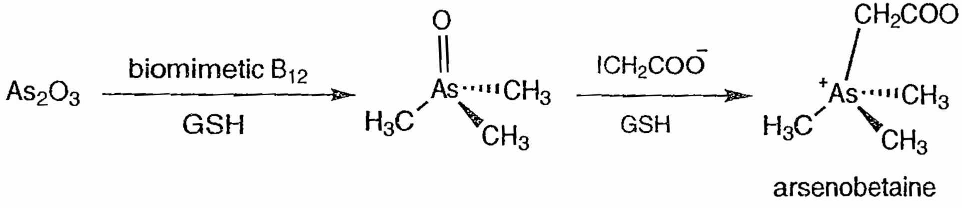
Biomethylation of arsenic is considered as the primary detoxification mechanism, since the highly reactive inorganic species of arsenic is potentially more toxic to the living world, including humans. A large number of diverse microorganisms - yeast, fungi, algae, plants and animals – were found to transform inorganic arsenic compounds into the methyl derivatives of organoarsenic compounds, such as arsenosugars, arsenobetaine, arsenocholine and arsenolipids by a process termed as arsenic detoxification. Though these are widespread in aquatic organisms, it is unlikely that consumption of those organisms constitutes a hazard from arsenic poisoning. In higher organisms, inorganic arsenic is methylated to monomethylarsonic acid (MMA) and finally to dimethylarsinic acid (DMA) by the methyl donor, S-adenosylmethionine (SAM), and the reaction is catalysed by methyltransferases in the presence of glutathione. These methyl derivatives are a thousand-fold less potent as mutagenic agents than the inorganic arsenic species. The trivalent arsenic compounds are preferred substrates for methylation reactions and hence the reduction of arsenic from the pentavalent to trivalent state may be a critical step to control the rate of metabolism of arsenic.[19]



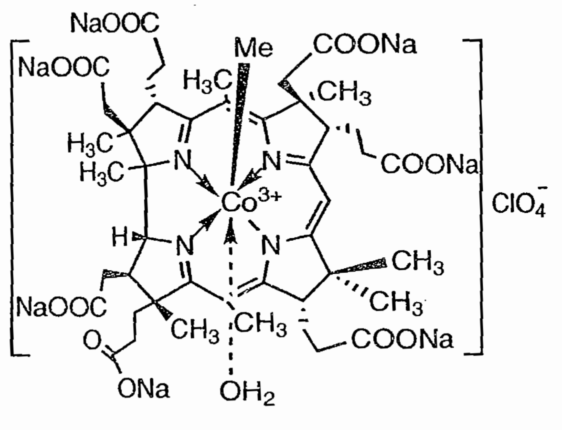
(20.14)

Biomimetic studies involving the methylation of the inorganic arsenic compound, As_2O_3 to arsenobetaine ($Me_3As^+CH_2COO^-$, commonly found in shellfish and prawns) were carried out in the laboratory recently. This biochemical methylation involves a methyl transferase and reductase. A biomimetic vitamin B_{12} [sodium (methyl) (aquo)cobyrinate perchlorinate] which mimics methylcobalamin and is prepared from vitamin B_{12} served as a model for methyl transferase. The reduced form of glutathione (GSH) served as a reductase model.

The system afforded a highly efficient conversion of arsenic trioxide to trimethyl arsine oxide through a series of oxidative methylation and reduction steps. This was converted to arseno betaine by the reaction with haloacetic acid in the presence of GSH (Eq. 20.15).



(20.15)



biomimetic B_{12}

20.4 ORGANOMETALLIC COMPOUNDS AS DRUGS

One of the most promising applications of bioorganometallic chemistry is in the area of drug development. The goal is to develop organometallic drugs which can increase the effectiveness of a known organic drug molecule by incorporating an organometallic moiety into it. The ferrocene incorporated versions of tamoxifen (for breast cancer) and chloroquine (antimalarial) are the well-known examples under this category which have shown great promise. In addition, entirely new organometallic molecules with medicinal properties have also been discovered (for example, η^6-aryl-ruthenium compounds as anticancer drugs).[20]

20.4.1 η^6-Aryl-ruthenium Compounds as General Anticancer Drugs

The discovery of the anticancer activity of platinum complexes especially *cisplatin*, *carboplatin* (Figs 20.6a and 20.6b) and related platinum amine complexes was an important landmark in the use of metal complexes in cancer chemotherapy. The first organometallic complex, seriously investigated for anticancer activity, was Cp_2TiCl_2 (Fig. 20.6c). It was hoped that the *cis* $TiCl_2$ motif would react with DNA in a similar manner as *cisplatin* and lead to cross linking of the affected DNA. Cp_2TiCl_2 was found to bind weakly to DNA bases and more strongly to the phosphate units present in the DNA. Also, as Cp_2TiCl_2 is susceptible to hydrolysis forming hydroxyl and oxo bridged species, formulation of drugs based on this compound was practically difficult. The response to this compound in clinical trials was also not very encouraging and such studies were therefore abandoned.

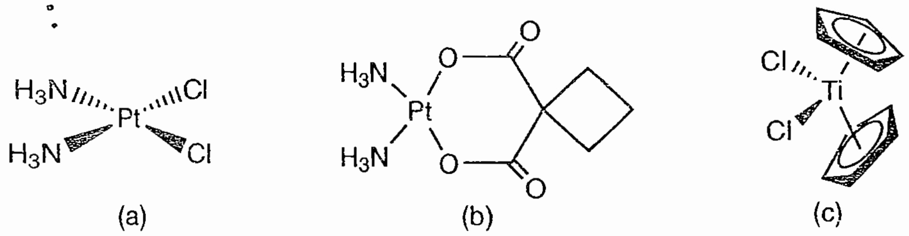


Fig. 20.6 Early Pt and Ti based molecules tested for anticancer activity

Studies on cationic chelated diamine η^6-arene-ruthenium(II) complexes were, however, quite encouraging for anticancer activity on human ovarian cancer. The activity increased with the size of the coordinated arene and the cytotoxicity of the biphenyl complex was found to be similar to that of *cisplatin*. An additional important finding was that $[(\eta^6\text{-arene})\text{Ru(en)Cl}]^+$ complexes (Fig. 20.7) were equally active towards the wild type and *cisplatin*-resistant cancer cells as well. These complexes appear to have a wider spectrum of cytotoxicity towards a variety of cancer cells. $[(\eta^6\text{-biphenyl})\text{Ru(en)Cl}]\text{PF}_6$ and $[(\eta^6\text{-dihydroanthracene})\text{Ru(en)Cl}]\text{PF}_6$ were found to be active against some forms of human ovarian, colon, pancreatic and lung cancer cells. The IC_{50} values (the dose which inhibits growth of 50% of the affected cells) for human ovarian cancer cells varied in the range of 1–13 μM which are comparable to that of *cisplatin* and *carboplatin*.[21]

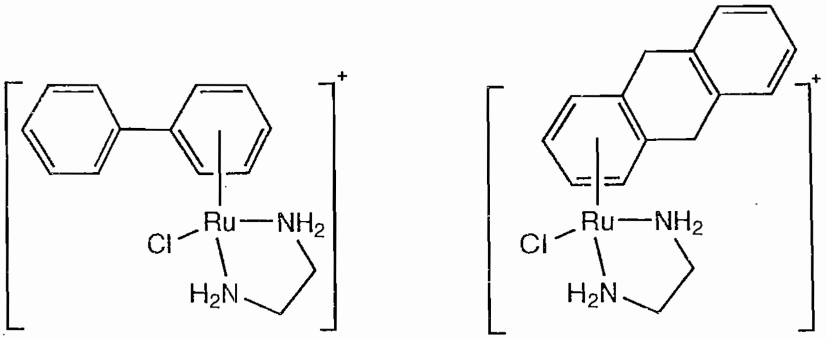


Fig. 20.7 η^6–arene–ruthenium(II) based anticancer compounds

20.4.2 Ferroquine as Antimalarial Drug

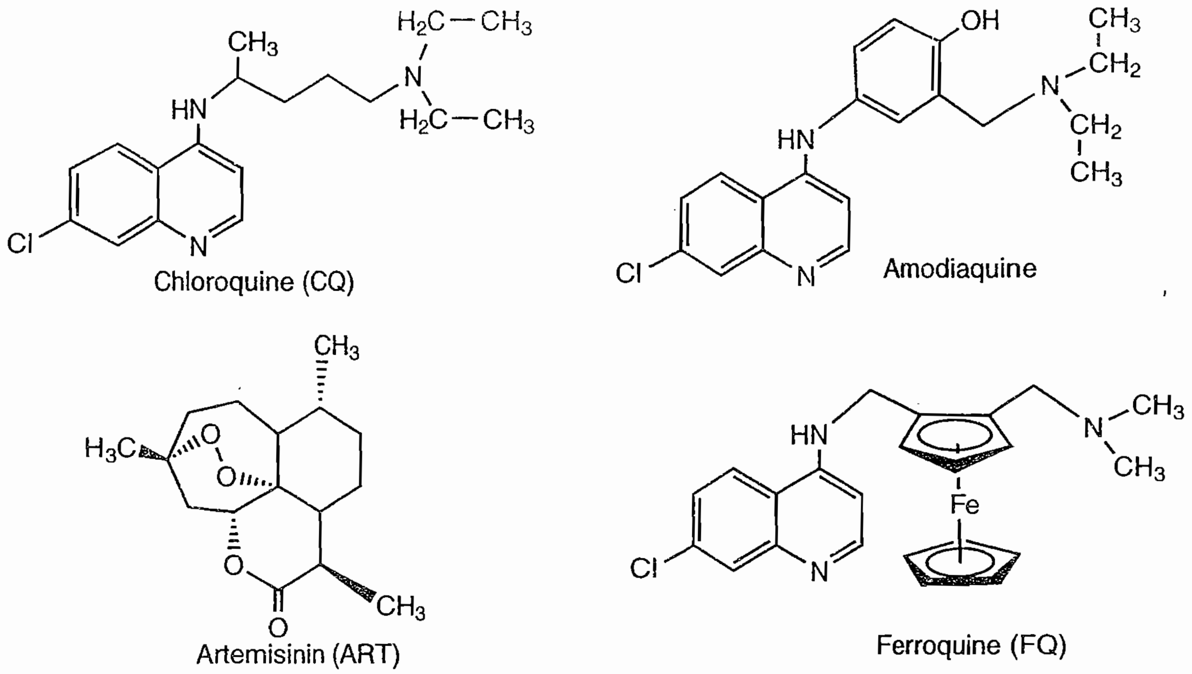
Malaria is a tropical disease and causes almost three million deaths every year, mainly in Africa and South East Asia. Even though the casualty in children below the age of 5 years is very high, the disease affects all age groups. It is caused by single cell protozoan parasites of the *Plasmodium* species, of which *Plasmodium falciparum* is the most dangerous and accounts for 90% of all deaths from malaria. Quinine, prepared from cinchona bark, was the first antimalarial drug developed and the synthetic antimalarials like chloroquine, primaquine, proguanil, pyrimethamine and mefloquine were developed later. Chloroquine (CQ), introduced for chemotherapy of malaria in 1943, is the most widely used drug. It has remained the most effective and safe therapeutic option for almost 15 years, however CQ-resistant parasites emerged in the 1960s. Several approaches to rescue the therapeutic effect of CQ were undertaken. Artemisinin (ART) derivatives represent a promising curative alternative for the future but their thermal instability and high cost of therapy limits their use. The structural variations in CQ have shown that amodiaquine (trade name Camoquin, Flavoquine), a 4-aminoquinoline compound related to CQ, is more effective than CQ in curing CQ-resistant *Plasmodium falciparum* malaria. This motivated the scientists to develop new and modified CQ derivatives. Many countries in Africa have tried to treat *P. falciparum* malaria by resorting to the use of a combination of drugs because of the increase in drug resistance; for example, amodiaquine alone, amodiaquine along with sulphadoxine–pyrimethamine, amodiaquine along with artesunate or artemether–lumefantrine. The studies show that there are only few options of treatment when there is already a high level of resistance to these drugs.[22–24]

Inspired by the work of G Jaouen in cancer chemotherapy, an attempt has been made to use a bioorganometallic strategy to generate an antimalarial class of compounds having ferrocene. Today, more than 100 ferrocene analogues of known antimalarial drugs have been synthesised and screened. Ferrocene, in particular, was selected because of its low toxicity, lipophilicity, relative thermal and chemical stability and redox behaviour. The study on a number of ferrocene containing CQ analogues showed that the derivatives having ferrocene as an integeral part of the side chain [known as ferroquine (FQ)] showed superior efficacy as compared to derivatives in which ferrocene was either bonded through the quinoline nitrogen or was a terminal component of the side chain. Ferrocene alone neither shows antimalarial activity nor does it affect CQ-resistant malaria when coadministered as a separate molecule. But FQ is extremely active against both CQ-susceptible and CQ-resistant *P. falciparum*. Nevertheless, the cause of activity of FQ on CQ-resistant strains remains totally unexplained. It may in all probability involve enhanced retention of the drug in the food vacuole, the compartment where CQ analogues exert their action. Ferroquine is one of the best antimalarial compounds tested so far and is being developed by Sanofi-Aventis; it entered the second phase of clinical trials in Sept 2007 (Fig. 20.8). FQ satisfies the 'Lipinski's rule of 5' which orally active drugs must follow to be efficient. Recent work has further shown that the ferrocenyl moiety has to be an integral part of the side chain of CQ.

Other analogues of ferroquine, derived from the 1,1′-ferrocene unit in which a reactive secondary amino group was introduced between the quinoline and ferrocene moieties were also developed with the hope to serve as compounds with further chemical diversity. The length of the methylene spacer between the two nitrogens in the CQ analogues has also been varied. It was shown that it influences the efficacy in CQ-resistant strains of *P. falciparum*, and in the CQ-sensitive strain, the longer the methylene spacer, the lower the efficacy.

Since the chemistry of ferrocene is similar to that of ruthenocene, the biological activity of ruthenocene analogues has also been examined. Though their synthesis is more difficult than the ferrocene analogues, all the ruthenocene complexes tested exhibit a good efficacy in both CQ-sensitive and CQ-resistant strains.

Coordination complexes of CQ were also synthesised and evaluated for efficacy against both CQ-sensitive and CQ-resistant strains of *P. falciparum* with the hope to get better results. These show improved efficacy in both types of strains as compared to CQ and the efficacy is found to be somewhat dependent on both the metal and the ligand. Similarly, the coordination complexes of FQ and the heterobimetallic complexes have been tested. The continuing biological success of FQ means that this avenue of research will remain open for a long time.



Chloroquine (CQ)

Amodiaquine

Artemisinin (ART)

Ferroquine (FQ)

Fig. 20.8 Well known antimalarial drugs

20.4.3 Ferrocifen as Breast Cancer Drug

The personal and social consequences of breast cancer are well documented. It occupies a prominent position among hormone-related diseases with one in nine women affected and a high mortality rate (35%). To date, other than surgery and radiotherapy, the therapeutic treatment consists mainly of using (i) antiestrogenic selective estrogen receptor modulators (SERMs) of which tamoxifen is the primary drug used to treat the disease, (ii) aromatase inhibitors, the key enzyme of the biosynthesis of estradiol (a hormone involved in reproductive functioning) in women, and (iii) chemical cocktails of classic chemotherapy. There are associated problems with respect to each one of these. Tamoxifen is generally tolerated well but has troublesome side effects and other drawbacks. Long term therapy can lead to resistance to the drug. It increases the risks of uterine cancer and blood clotting in the lungs and it is not effective against hormone-independent tumours, which accounts for about one-third of all breast cancer cases.

Significant developments on the estrogen receptor and its mode of activity have taken place in the recent past. Important findings are (i) both forms of the estrogen receptor – α form (ER α) and β form (ER β) – are implicated in the causation of breast cancer but to different degrees (the α form has been known for a long time), (ii) the structure of ligand binding domain (LBD) of these two receptors attached to various bioligands has recently been elucidated, and (iii) two activation pathways – involving the estrogen response element (ERE) and activator protein 1 (AP 1) – modulating the hormonal effect at the DNA level have been identified.

These advances have added a new level of complexity to the understanding of regulatory phenomena in the body. The goal has been to search for molecules whose antiestrogenic properties (ability to block the estrogen receptor) are preserved or even improved, and also those showing higher cytotoxicity than tamoxifen or its hydroxy derivative (Fig. 20.9). In addition, since the standard SERM tamoxifen is only effective on approximately 60% of tumours (ER+ type), a new molecule or a considerable improvement on tamoxifen itself is required which will be effective for both ER (+) and ER (-) tumours.

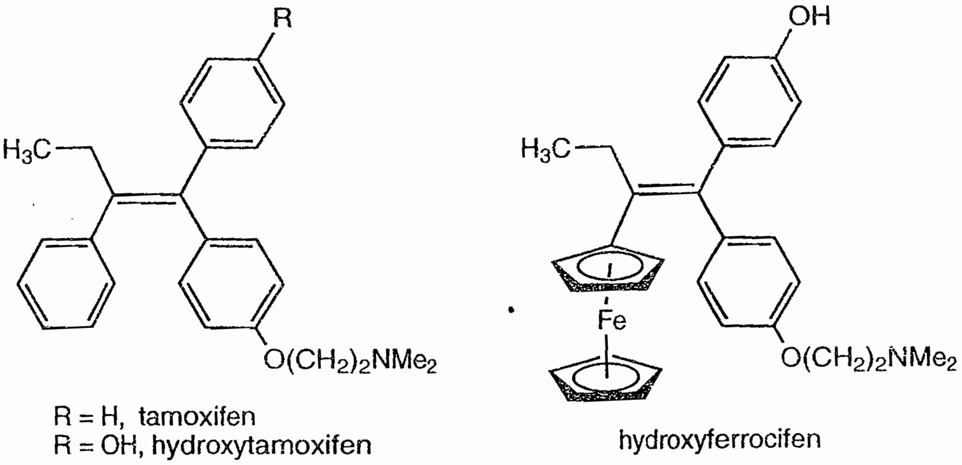


Fig. 20.9 Tamoxifen and related drugs

Cisplatin has a well established status as an antitumour agent despite a narrow therapeutic range (testicular, urogenital, head, neck and colon cancers). The idea of using a hormonal vector to deliver *cisplatin* at the level of estrogen receptor though extensively studied, has proved to be ineffective. For example, a tamoxifen derivative with Pt has failed as an antitumour agent for breast cancer (Fig. 20.10). But, a similar study using a Cp_2TiCl_2–tamoxifen hybrid showed anticancer activity. However, in contrast to expectations, this molecule turned out to behave like an estrogen, sharply promoting the growth of breast cancer cells. So, all attempts to incorporate titanium-based drugs were also discarded.

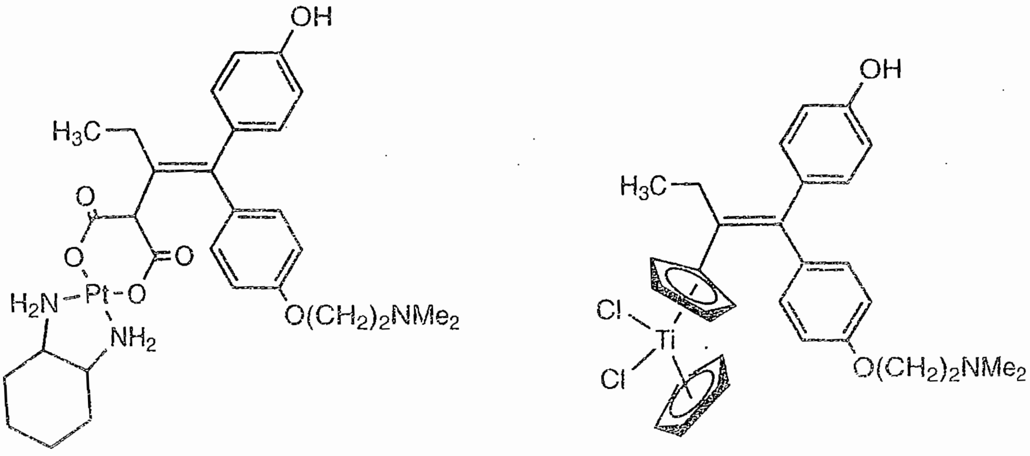
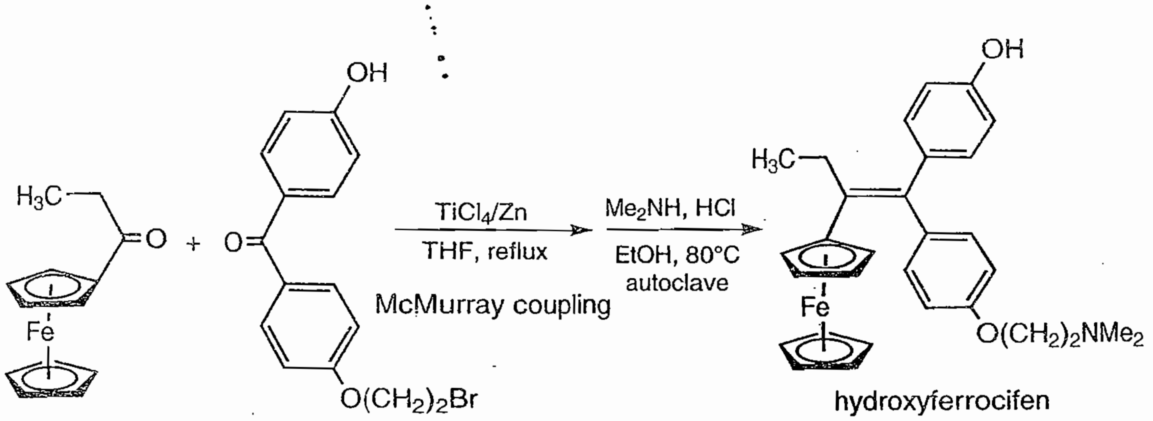


Fig. 20.10 Carboplatin and titanocene incorporated tamoxifen

However, the results obtained with ferrocene-hybrids of tamoxifen and hydroxy tamoxifens were very encouraging. Jaouen and coworkers have reported several novel organometallic derivatives of tamoxifen where the phenyl group has been replaced by a ferrocenyl group. The synthesis of these derivatives (called ferrocifens) is described in Eq. 20.16.[25-27]



(20.16)

The replacement of the phenyl group in hydroxytamoxifen by a ferrocenyl moiety brought about novel pharmacological properties for the compound, hydroxyferrocifen. For example, the latter displays an in vitro antiproliferative effect on both hormone dependent (MCF-7) and independent (MDA-MB231) breast cancer cell lines whereas hydroxytamoxifen is active only against hormone dependent cell lines. Also, the length of the carbon chain significantly perturbs its effect. Hydroxyferrocifen is indeed the first molecule shown to be active against both hormone-dependent and hormone-independent breast cancer cells.

In addition, it was observed that hydroxyferrocifen strongly inhibits the proliferation of kidney and ovarian cancer cells and also have some lesser anti-proliferative activity against prostrate and endometrial cancer cells. Tests carried out on live rats with hydroxyferrocifen also exhibited less acute kidney toxicity than tamoxifen.

20.5 ORGANOMETALLICS AS RADIOPHARMACEUTICALS, TRACERS, IONOPHORES AND SENSORS

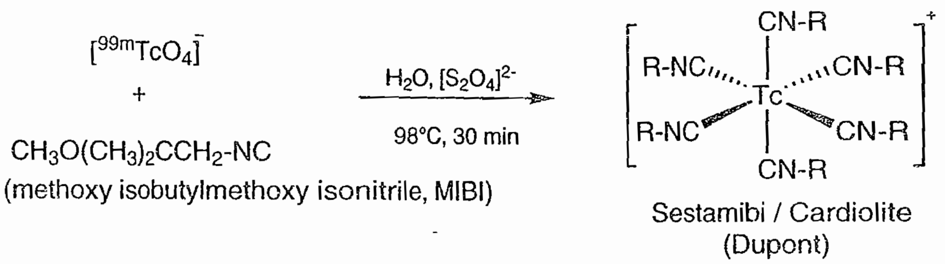
20.5.1 Radiopharamaceuticals

Radiopharmaceuticals are used in the field of nuclear medicine as tracers in the diagnosis and treatment of many diseases. For example, ^{123}I is used in thyroid imaging. Technetium is an artificial element prepared by a nuclear reaction. Its metastable form, ^{99m}Tc is a radionucleide useful in the medical diagnostic technique SPECET (single photon emission computed tomography) as a myocardial imaging agent. The half life of this nuclide is only 6 hours and it decays by γ-emission. ^{99m}Tc is particularly attractive for medical applications as the radiation from this isotope is a γ-ray with the same wavelength as X-rays (used for common medical diagnostic applications), giving it adequate penetration while causing minimal tissue damage for a γ-photon. The short half life of this metastable nuclide, followed by the relatively long half life of the daughter isotope, ^{99}Tc, allows it to be eliminated from the body before it undergoes further nuclear decay. This leads to a relatively low dose of administered radiation in biologically dose-equivalent amounts for a typical ^{99m}Tc based nuclear scan. The metastable radionuclide has to be generated by neutron capture of molybdenum as shown.[28-30]

$$^{98}\text{Mo} \xrightarrow{\text{neutron capture}} {}^{99}\text{Mo} \xrightarrow[90\text{ h}]{\beta\ \text{decay}} {}^{99m}\text{Tc} \xrightarrow[6\text{ h}]{\gamma\ \text{emission}} {}^{99}\text{Tc} \qquad (20.17)$$

Cardiolite, also called sestamibi (by Dupont), marketed in 1990, consists of the chemical $[^{99m}Tc(CN{-}R)_6]^+$ where $R = CH_2{-}C(CH_3)_2OCH_3$, [hexakis(2-methoxy-isobutylisonitrile) technetium-99m] that migrates and binds to undamaged heart muscle. This highly stable compound resulted from the original contribution of Alan Davison and coworkers of MIT, in 1983. They prepared a series of hexakis-isonitrile complexes of technetium by a simple one-step synthetic route using boiling water as the medium. Compared to other isonitrile technetium complexes, the methoxy isobutylisonitrile complex is more rapidly cleared from the lung and has lower accumulation in the liver.

The ^{99m}Tc radioisotope allows a gamma camera to take images of the heart. The complex, which is the first FDA approved cardiac imaging agent, noninvasively evaluates the heart's pumping ability (function) and gauges the amount of blood flow to the heart muscle itself (perfusion) and thus can quickly assess whether a patient has already had a heart attack or is at risk for one in the future. Cardiolite allows imaging of the heart for up to four hours after injection. This is a much longer period than was possible with ^{201}Tl, a widely used cardiac imaging isotope before the entry of Cardiolite in the market. The low energy of ^{201}Tl also results in significant scatter and attenuation impairing image quality and contrast. The synthetic procedure for the technetium complex is shown in Eq. 20.18.



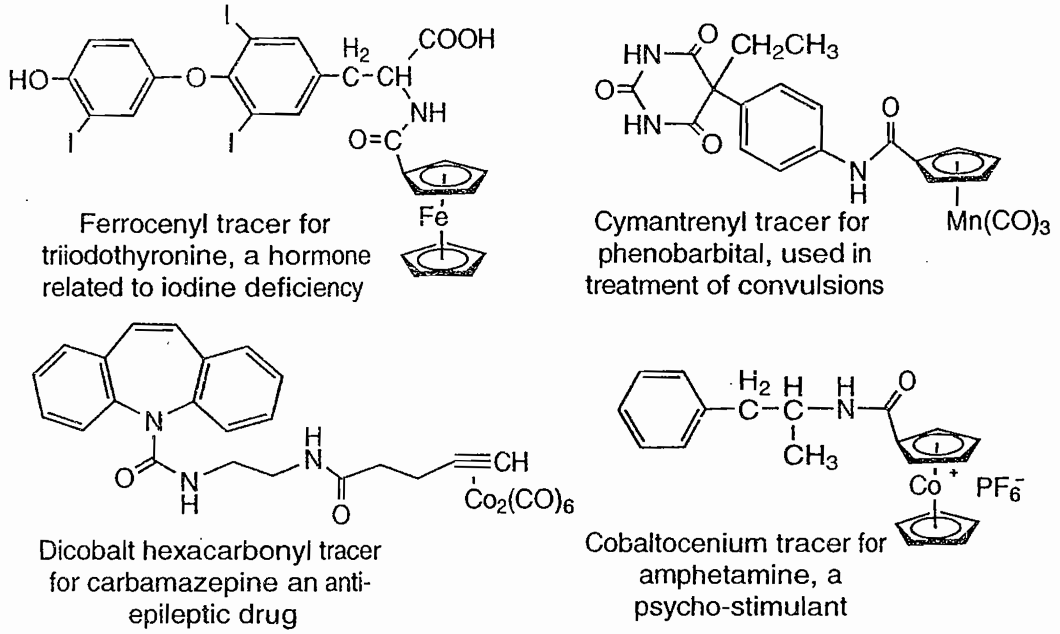
(20.18)

20.5.2 Organometallic Tracers

An organometallic tracer is a common drug molecule or a biomolecule to which a stable organometallic moiety has been tagged whose presence can be easily monitored and amount estimated even in very low concentrations by common analytical techniques. Organometallic tracers are now being used in immunoassay, which is an indirect determination of the concentration of an analyte in the microgram scale in mediums such as blood, plasma and urine. Generally, nonisotopic immunoassays are carried out using three well known analytical techniques—atomic absorption spectroscopy, infrared spectroscopy and electroanalytical methods. A few examples of organometallic tracers of some of the well known drugs/biomolecules are given in Fig. 20.11.[31, 32]

20.5.3 Organometallics as Ionophores

Self-assembly of many organometallic compounds can lead to organometalla-macrocycles that can selectively sequester specific metal ions in their cavity. Many ruthenium, rhodium and iridium chloro-bridged halfsandwich compounds of the type $[(\pi\text{-ligand})\,MCl_2]_2$, when reacted with ligands such as oxopyridonates result in trimeric organometalla-macrocycles


Ferrocenyl tracer for triiodothyronine, a hormone related to iodine deficiency

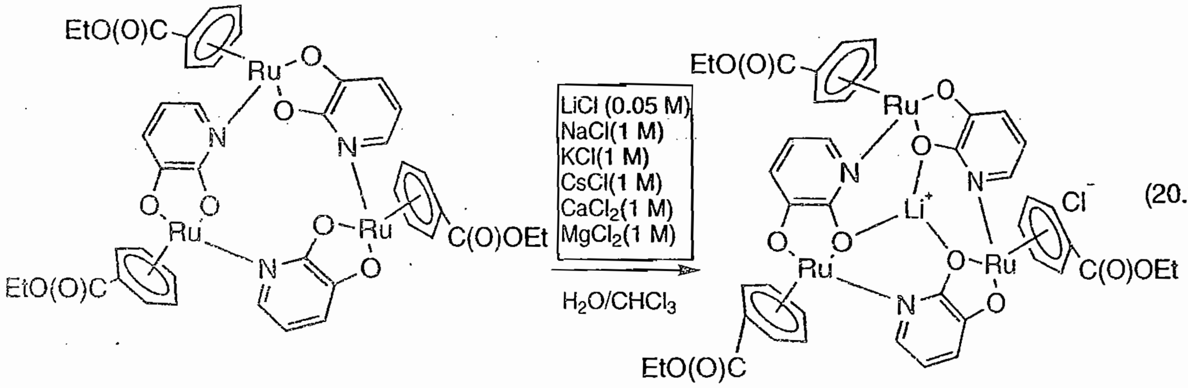
Cymantrenyl tracer for phenobarbital, used in treatment of convulsions

Dicobalt hexacarbonyl tracer for carbamazepine an anti-epileptic drug

Cobaltocenium tracer for amphetamine, a psycho-stimulant

Figure 20.11 Examples of organometallic tracers

of the general formula $[(\pi\text{-ligand})M(L)]_3$ having a cavity of specific size at its centre. By suitably designing the molecule, one can realise ionophores which have specificity for a particular alkali metal ion. Equation 20.19 shows an organometalla-macrocycle which is highly specific to Li^+ ion as compared to alkali and alkaline earth metals present in high concentration in an aqueous medium. Lithium carbonate is a frequently used drug in the treatment of manic depression. Sensors based on such organometalla-macrocycles can have potential applications such as monitoring the amount of lithium ions in the presence of sodium ions in biological fluids such as blood.[33, 34]



(20.19)

20.5.4 Organometallic Compounds as Sensors

One of the finest medical applications of ferrocene derivatives is in blood glucose level monitors. The apparatus consisting of a disposable strip and an amperometer is commercially available as a hand held device. This device has practically replaced the old diabetes test kit that uses Fehlings/Benedicts solution.

The enzyme, glucose oxidase normally catalyses the reaction of glucose with oxygen with the formation of hydrogen peroxide. The earlier method of glucose detection involved electrochemical measurement of hydrogen peroxide, its amount being proportional to the amount of glucose concentration. This method, however gave erroneous results as the concentration of oxygen on the enzyme layer of the test strip varied. Ferrocene based mediators were brought in to reduce oxygen dependence of this reaction and in short, this mediator substitutes for oxygen in the reaction. Ferrocene and a few of its well known derivatives were tested for activity. Based on factors such as the low solubility of the reduced form of the ferrocene derivative in aqueous solution, the stability of the oxidised form of the metallocene at physiological pH and the low formal potential to reduce interference, 1,1′-dimethyl-3-(2-amino,1-hydroxyethyl) ferrocene was chosen as the most suitable mediator. The mediator lowers the required working electrode potential from 0.6 V to 0.2 V versus Ag/AgCl. Gluconolactone is formed along with the 1,1′-dimethyl-3-(2-amino,1-hydroxyethyl) ferrocene when glucose gets oxidised.[35–36]

The test strip (Fig. 20.12) consists of two carbon working electrodes and a reference Ag/AgCl electrode. As little as 4 microlitres of blood, when applied on the circular opening, is evenly spread over the three electrodes by a hydrophilic mesh. The measurement, which takes less than a minute begins when the blood reaches the reference electrode. The first working electrode is coated with glucose oxidase enzyme along with ferricinium cation as mediator. The ferrocenium mediator gets reduced to 1,1′-dimethyl-3-(2-amino,1-hydroxyethyl) ferrocene (Eq. 20.20). The second working electrode is coated only with 1,1′-dimethyl-3-(2-amino,1-hydroxyethyl) ferricinium cation mediator. The actual potential measured is the difference between these two working electrodes and it helps to eliminate errors due to interfering species in blood such as ascorbic acid and uric acid.

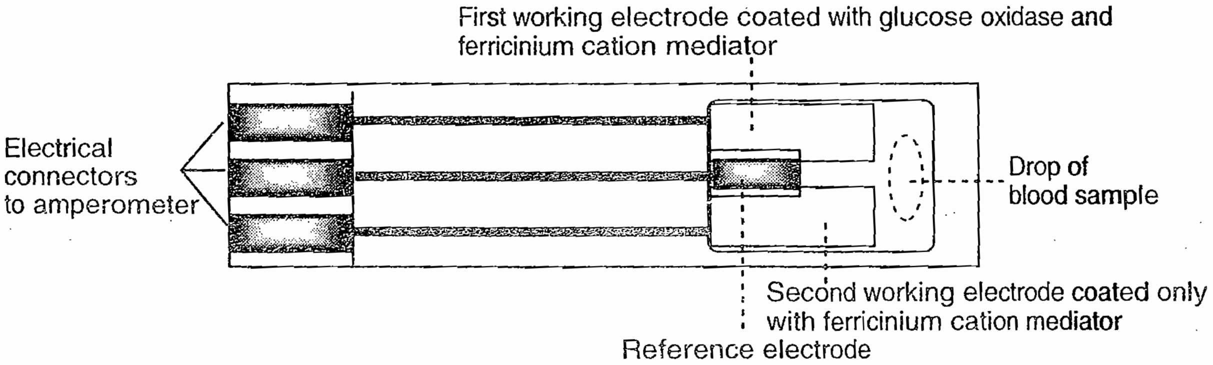
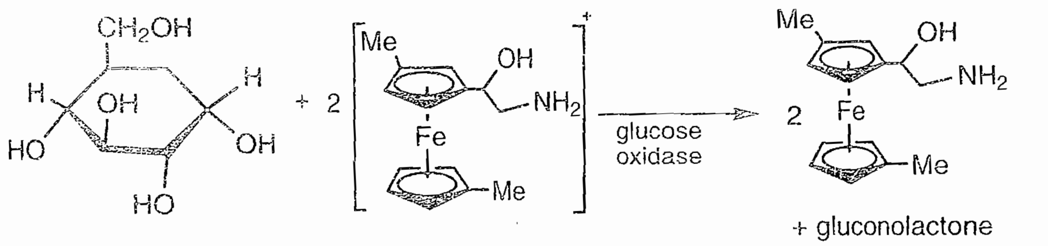
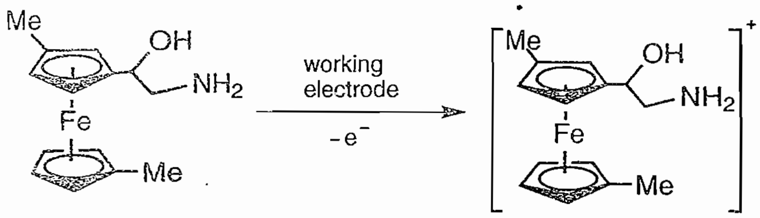


Fig. 20.12 Schematic of the test strip used in blood glucose level monitoring by amperometry



(20.20)

The mediator consumed in the reaction with glucose is regenerated at the working electrode (Eq. 20.21). The current at the working electrode will thus be proportional to the concentration of mediator, which in turn will be proportional to the concentration of glucose in the blood sample.



(20.21)

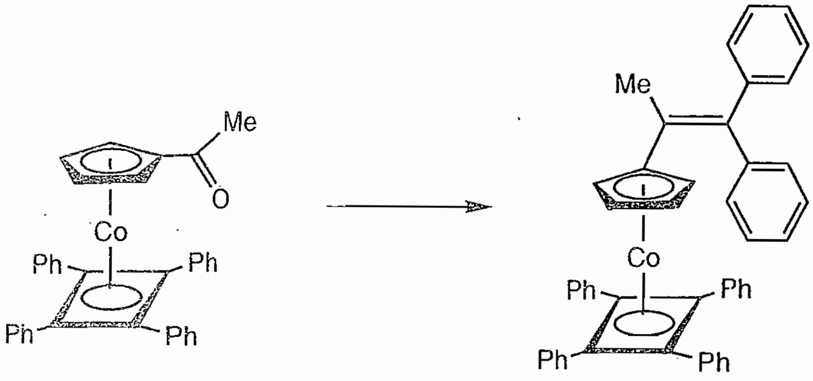
Problems and Exercises

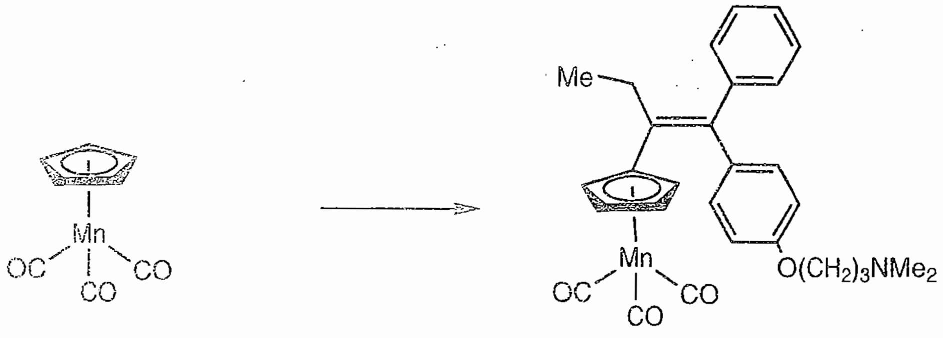
20.1. How does corrin differ from porphyrin?

20.2. Can cobalamins act as antidotes for cyanide poisoning? If so, which one will be the best candidate?

20.3. Ferroquine is made of two components, the quinoline part and the ferrocenyl amine part. Give a set of equations by which you can synthesise the ferrocenyl amine part starting from N,N-dimethylaminomethyl ferrocene. Once you have synthesised this, show how you will make ferroquine.

20.4. Suggest steps to make the following analogues of ferrocifen having cobalt and manganese sandwich / half sandwich moieties starting from the given precursors.

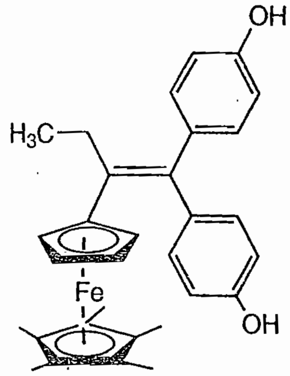




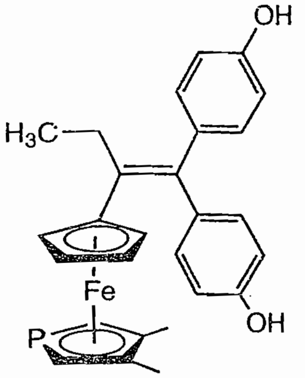
20.5. Compounds possessing a ferrocenyl moiety linked to a *p*-phenyl group by a conjugated system show considerable potency against breast cancer cells. It has been suggested that these compounds can be activated by in situ oxidation to form a cytotoxic quinine methide species (QM). If QM formation is an important mechanism of cyclotoxicity, how will the study of sulphur congeners help in clarifying this suggestion?

20.6. The relative binding affinity (RBA) for compounds A and B has been measured for the α and β forms of estrogen receptor (ER). The RBA values found for ER$_\alpha$ are 0.5 and 1.5

respectively and are lower than the values for the corresponding ferrocenyl derivative C. However, the values for ER$_\beta$ are much higher (8.5% and 10% respectively) and are approximately identical to the value in C (10%). What meaning do these values convey? (*Tetrahedron Lett.*, 2003, 2749)



(a)



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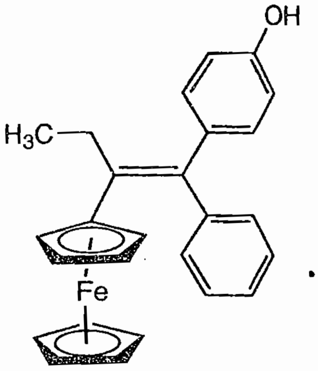

(c)

20.7. Identify the two activation pathways that modulate the hormonal effect at the DNA level in breast cancer.

20.8. Examine the figure of B$_{12}$ coenzyme. The peripheral carbon atoms of the corrin ring are substituted by amide moieties. Write how many amide groups are present and categorise them.

20.9. The formation of highly toxic methyl mercury cation $(CH_3Hg)^+$ as one of the products in the reaction of Hg(II) salt with methylpentacyanocobaltate (III) points to the involvement of methyl cobalamin in the biomethylation of Hg^{2+} to form of $(CH_3Hg)^+$ and $(CH_3)_2Hg$. Can you outline the process?

20.10. Define the terms B$_{12r}$, B$_{12s}$, cofactor, prosthetic group, apoenzyme and holoenzyme.

Supplementary reading

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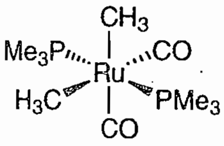
APPENDIX

1

SOLUTIONS TO PROBLEMS AND EXERCISES

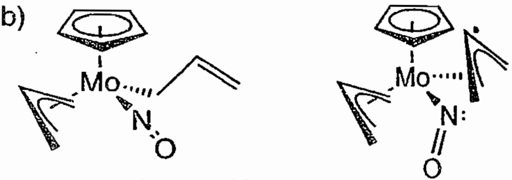
CHAPTER 2

2.1. (a)



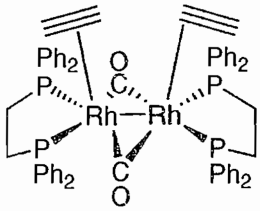
8 + 2 + 2 + 2 + 2 + 1 + 1 = 18

(b)



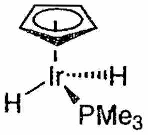
6 + 5 + 3 + 1 + 3 = 18   6 + 5 + 3 + 3 + 1 = 18

(c)



9 + 4 + 2 + 2 + 1 = 18

(d)



9 + 5 + 2 + 1 + 1 = 18

2.2. (a) $Na_2Fe(CO)_n$ $n = 4$

(b) $MnBr(CO)_n$ $n = 5$

(c) $W(\eta^6\text{-}C_6H_6)(CO)_n$ $n = 3$

(d) $Rh(\eta^5\text{-}C_5H_5)(CO)_n$ $n = 2$

(e) $Cr(\eta^3\text{-}C_5H_5)(CO)_n(CH_3)$ $n = 4$

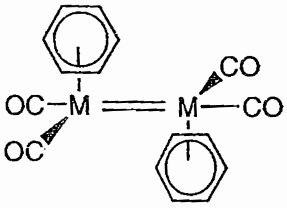
(f) $IrBr_2(CO)_n(PPh_3)_2(CH_3)$ $n = 1$

2.3.

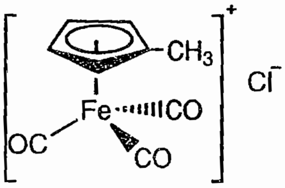
Complex	Ox. State	*d* e count	TVE	M–M bonds
$[CpCo(CO)_2]$ (μ-CO)	+1	8	34	1
(*cyclo* C_4H_4) $PdCl_2$	+2	8	16	0
$(\eta^3\text{-allyl})_2Ni$	+2	8	16	0
$CpMo(CO)_3^-$	0	6	18	0
$Ru(PPh_3)_2Cl(NO)$ linear	0	8	16	0
$Cp(\eta^6\text{-}C_6H_6)Mn$	+1	6	18	0
$Cp_2ZrH(CH_2CH_2CH_3)$	+4	0	16	0
$CpMn(CO)_3$	+1	6	18	0
Cp_2ZrCl_2	+4	0	16	0

2.4. In the given compound M + 3 + (2 × 5) = 18, Hence M must be d^5 which is vanadium.

2.5. M can be Cr, Mo or W.



2.6.



2.7. (a) TVE = 32; 2 M–M bonds (b) TVE = 34; one M–M bond.

2.8. (a) It has 1 M–M bond, which means that TVE is 17 × 2 = 34e. Therefore $x = 3$.

(b) It has one Ni–Co bond; TVE = 34e. Therefore $z = -3$.

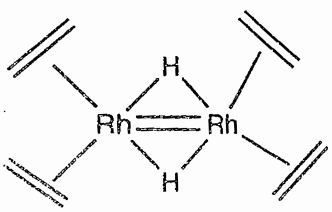
(c) It has Mn=Mn double bond; so TVE required is 32e. Hence $x = 2$.

(d) It has 3 Ni–Ni bonds. TVE required is 48. Hence $z = +1$.

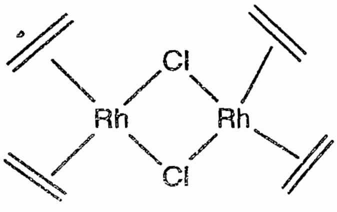
(e) It has 1 M–M bond; TVE required is 34e. Hence M = d^6, that is, Cr.

2.9. (a) NO is linear nitrosyl (b) NO is bent nitrosyl, and (a) will have a shorter M–N bond as three electrons are donated to Ru.

2.10. Both (a) and (b) have Rh in the +1 oxidation state and have 16e square planar geometry. [TVE (a) = 28; 2 Rh–Rh bonds and (b) = 32; 1 Rh–Rh bond].

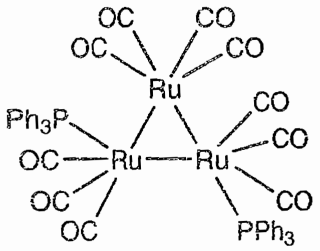


(a)



(b)

2.11. TVE (3Ru + 10CO + 2PPh$_3$) = 48. The complex is short by 6 electrons in terms of the 18e rule and hence will have 3 M–M bonds. The electron per metal is 16 and thus each metal has two M–M bonds. B will be the actual structure of the molecule.



B

2.12. (a) = Ni, (b) = Co, (c) = Mn.

2.13. $Cr(CO)_6$ ($n = 6$, $m = 0$), $Cr(NO)_4$ ($n = 0$, $m = 4$), $Cr(CO)_3(NO)_2$ ($n = 3$, $m = 2$).

2.14. (a) The compound has one Os–Os bond and so the total valence electrons should be 34; the unit in parentheses should have 17e. Since Cp, Os contribute 13e, there must be 2CO to make it 17. Hence $x = 2$.

(b) Since Co and 3CO contribute a total of 15e, x should be -3 in order to follow the 18e rule.

(c) Ni, 3CO and NO contribute a total of 19e and hence $x = +1$ to achieve 18e.

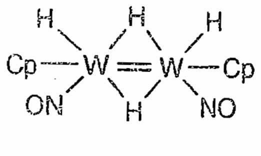
(d) Cp, Fe and 3CO contribute 19e. Hence x should be +1.

(e) C_6H_6, Mn, 2CO and H contribute [6 + 7 + 4 + 1 = 18e], hence $x = 0$.

(f) Cp, 2CO, Fe and (PhC≡CH) contribute [5 + 4 + 8 + 4 = 19e], hence $x = +1$.

2.15.

Compound		TEC	Total M–M bonds	Bonds per M
(a)	$(\mu\text{-H})_2[\eta^5\text{-Cp(NO)WH}]_2$	32	(18 × 2) – 32 = 4/2 = 2	2
(b)	$(\mu\text{-Br})_2\,[\text{Mn(CO)}_4]_2$	36	(18 × 2) – 36 = 0	0
(c)	$\mu\text{-CO-}\mu\text{-CH}_2\text{-}[\eta^5\text{-CpRh}]_2$	32	(18 × 2) – 32 = 4/2 = 2	2
(d)	$[\mu\text{-X-}\mu\text{-CH}_2(\text{Os}_3(\text{CO})_{10}]^-$	50	(18 × 3) – 50 = 4/2 = 2	-
(e)	$(\text{CO})_4\text{V}(\mu\text{-PR}_2)_2\text{V(CO)}_4$	32	(18 × 2) – 32 = 4/2 = 2	2
(f)	$[\eta^5\text{-CpMn(CO)}_3]_2$	36	(18 × 2) – 36 = 0	0
(g)	$[\eta^5\text{-CpCr(CO)}_3]_2$	34	(18 × 2) – 34 = 2/2 = 1	1
(h)	$[\eta^5\text{-CpFe(CO)}_2]_2$	34	(18 × 2) – 34 = 2/2 = 1	1
(i)	$[\eta^5\text{-CpMo(CO)}_2]_2^{2-}$	32	(18 × 2) – 32 = 4/2 = 2	2
(j)	$\text{Ir}_4(\text{CO})_{12}$	60	(18 × 4) – 60 = 12/2 = 6	60/4 = 15; 3
(k)	$(\mu\text{-CO})\text{-}[\eta^5\text{-CpRe(CO)}_2]_2$	34	(18 × 2) – 34 = 2/2 = 1	1
(l)	$(\mu\text{-CO})\text{-}[\eta^4\text{-}(\text{C}_4\text{H}_4)\text{Fe(CO)}]_2$	30	(18 × 2) – 30 = 6/2 = 3	3
(m)	$(\mu^3\text{-CO})\text{-}[\text{Fe}_4(\text{CO})_{12}]^{2-}$	60	(18 × 4)- – 60 = 12/2 = 6	60/4 = 15; 3



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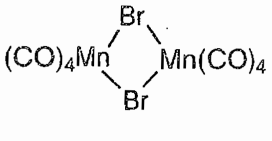

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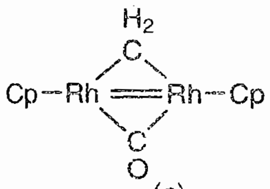

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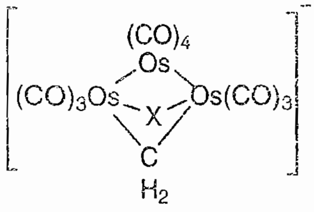

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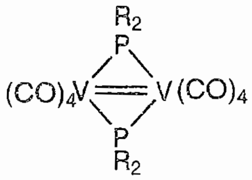

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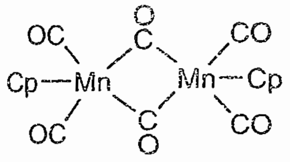

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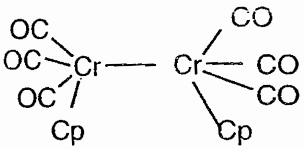
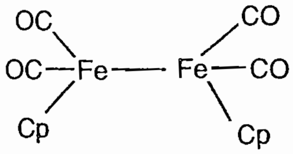
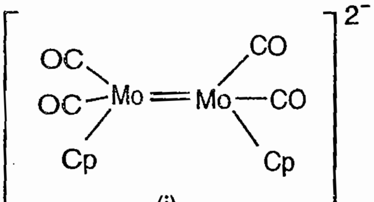


CO can be bridged

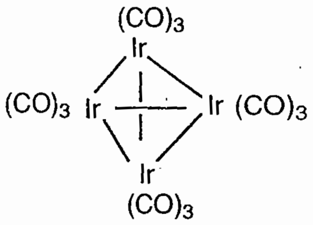
(g)



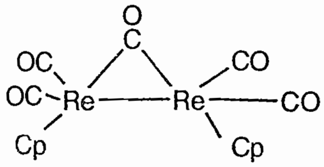
(h)



(i)



(j)



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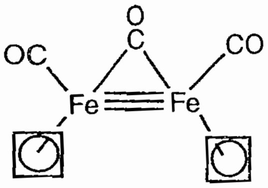
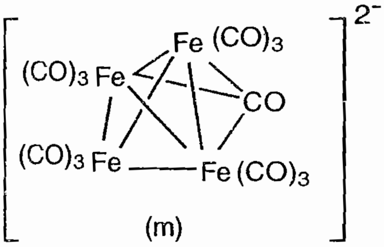
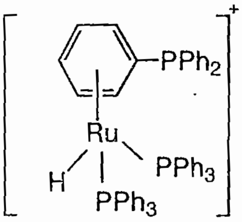


(l)

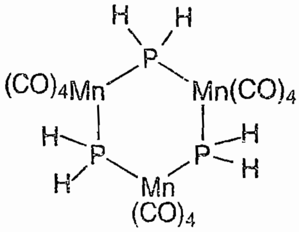


(m)

2.16.



2.17. TVE $Mn_3(\mu PH_2)_3(CO)_{12} = (6\times 3) + (4\times 3) + (2\times 12) = 54$; hence there is no M–M bond.



2.18.

	X	Y	Z
Formal charge	–1	–2	0
Ox. state *e* count	6	6	4

CHAPTER 3

3.1. The back bonding is more in $V(CO)_6^-$ than $V(CO)_6$ because of the additional negative charge on V. Hence the decrease in bond order of CO and increase in the bond order of V–C occurs in the former case.

3.2. ν_{CO} will change as follows.

(a) Since Et_3N is a non π acid ligand, the back donation from M to the COs will increase and hence ν_{CO} will decrease.

(b) Less back bonding because of positive charge and hence ν_{CO} increases.

(c) Back bonding increases because of negative charge, and hence ν_{CO} decreases.

3.3. $Cr(NO)_4 = Cr(CO)_6$; $Mn(CO)(NO)_3 = Mn(CO)_4NO$; $Co(NO)_3 \Rightarrow Co(NO)(CO)_3$; $Fe(CO)_2(NO)_2 = Fe(CO)_5$.

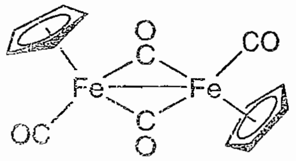
3.4. $V(CO)_6$ is a 17e species and therefore to stabilise itself, it reacts readily with Na and attains a 18e structure.

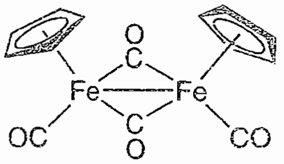
3.5. CO is a better σ donor than N_2 as the HOMO of CO is slightly antibonding in nature whereas it is bonding in N_2. Also N_2 is a poor π acceptor.

3.6. When CO gets coordinated to BH_3, its ν_{CO} goes up slightly as the HOMO of CO is slightly antibonding and pure σ donation by it makes the CO bond stronger as BH_3 is just a Lewis acid. ν_{CO} goes down when it coordinates to $Ni(CO)_3$ because of increased back bonding in the complex.

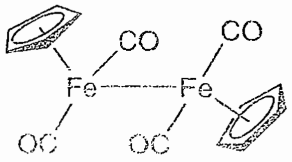
3.7. When a Lewis acid coordinates to the oxygen of CO which is already bound to a metal, more electron density is pulled out from the group. This will increase back bonding and hence the ν_{CO} will be lower in the complex molecule.

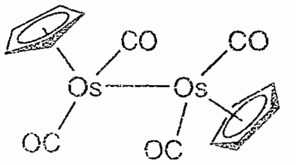
3.8. The room temperature bands of $[\eta^5\text{-CpFe(CO)}_2]_2$ indicate the presence of terminal and bridging carbonyl groups. High temperature bands of $[\eta^5\text{-CpFe(CO)}_2]_2$ indicate only terminal carbonyls. The spectra of $[\eta^5\text{-CpOs(CO)}_2]_2$ indicate that the isomer having bridging carbonyls is absent for the compound. The possible structures at room temperature based on spectral data are the following.





Possible structure at high temperature for iron compound and for the osmium compound based on spectral data are the following.





3.9. $[\eta^5\text{-CpFe(CO)}_2]_2 \rightarrow$ Products

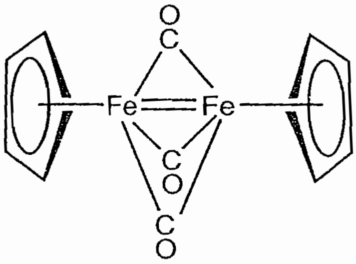
The molecule may lose one or more CO groups (colourless gas). However, the compound will have an oxygen content of 14.7% only on losing one CO. Therefore, the loss of one CO is considered.

$[\eta^5\text{-CpFe(CO)}_2]_2 \rightarrow (5+8+4)2 = 17e$ per metal, 1 M–M bond

Since one CO is lost (2es are lost), therefore one additional bond will form in the molecule.

$\eta^5\text{-Cp}_2\text{Fe}_2\text{(CO)}_4 \rightarrow \eta^5\text{-Cp}_2\text{Fe}_2\text{(CO)}_3 + \text{CO}$

10 + 16 + 6 = 32 = 16 electrons per metal; 2 M–M bonds



Alternative solution

14.7% oxygen is due to the carbonyl oxygen. Let the number of carbonyls in the product be X.

$$\frac{16X}{112 + 130 + 28X} = \frac{14.7\%}{100}$$

2Cp = 130
2Fe = 112
XCO = 28X

$$X = 2.99$$

Therefore the number of carbonyls present in the product is 3. The rest of the calculation is the same as above.

3.10. $[\text{Ti(CO)}_6]^{2-} > [\text{V(CO)}_6]^- > \text{Cr(CO)}_6 > [\text{Mn(CO)}_6]^+ > [\text{Ir(CO)}_6]^{3+}$

3.11. A disubstituted hexacarbonyl may exist in the *cis* and or *trans* configuration. In the *cis* form, four CO ligands are in a low symmetry (C_{2v}) environment and therefore four IR bands should be observed. The *trans* isomer has a square planar array of four CO ligands (D_{4h}) for which only one band in the CO stretching region is expected. The *trans* CO arrangement is indicated by the data, since it is reasonable to assume that the weak bands reflect a small departure from the D_{4h} symmetry imposed by the PPh_3 ligands.

3.12. The most general way to synthesise the ligand substituted metal carbonyl is to treat the parent metal carbonyl with the ligand of choice.

$\text{Fe}(s) + 5\,\text{CO}(g) \rightarrow \text{Fe(CO)}_5(l)$ high temperature and pressure required

$\text{Fe(CO)}_5 + \text{Norbornadiene} \rightarrow \text{Fe(CO)}_3\text{(NBD)}$

$\text{Fe(CO)}_3\text{NBD} + \text{PPh}_3 \rightarrow \text{Fe(CO)}_3(\text{PPh}_3)_2(s) + \text{NBD}$

3.13. In general, lower the symmetry of a $M(CO)_n$ fragment, greater the number of CO stretching bands in the IR spectrum. In the given complexes with $M(CO)_3$ fragments, the complex with C_s symmetry will have the greatest number of bands. The number of bands for other symmetries is one and two for D_{3h} and C_{3v} respectively.

3.14. In view of the number of bands (see table in text), $W(CO)_4(NCC_3H_7)_2$ is the *cis* isomer and $W(CO)_3(NCC_3H_7)_3$ is the *fac* isomer. Since butyronitrile is a poor π acceptor ligand than CO, the back bonding from the metal to the remaining CO increases and hence ν_{CO} decreases.

3.15. CSe is apparently a better net electron withdrawing (σ donor + π acceptor) group than CO. Therefore, the back bonding to the other two CO groups is decreased.

The bonding and electron donation to the metal is similar in NO and NS. Both, in the formal sense, are three-electron donors. The data suggests that NS is more effective in removing electron density from Cr than the NO ligand. With the result, the back donation to the two CO groups is less in the NS complex.

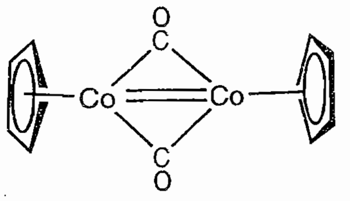
3.16. The formal oxidation state of Zr is +4 in A and +2 in B. More back bonding to CO will occur in B and hence it will have lower CO stretching frequency.

3.17. The mechanism of ligand substitution is different in both cases. $V(CO)_6$ is a 17e system and it will prefer ligand substitution by associative mechanism. However, $[V(CO)_6]^-$ is an 18e coordinatively saturated complex and it will undergo ligand exchange by a dissociative mechanism. Since CO is more tightly bound in $[V(CO)_6]^-$ [higher back donation], $[V(CO)_6]^-$ will be less reactive than $V(CO)_6$.

3.18. A. $Mn_2(CO)_{10}$ B. $NaMn(CO)_5$ C. $MeC(O)Mn(CO)_5$ D. $CpMn(CO)_3$.

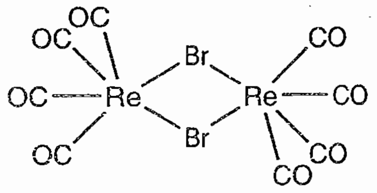
3.19. (a) Shortest CO bond: $Ni(CO)_4$ (least back bonding), (b) lowest CO stretching: $[V(CO)_6]^-$ (highest back bonding).

3.20. Infrared absorption of B indicates only bridging carbonyls. To attain 18 electrons, dimerisation will take place with the formation of a Co–Co double bond.



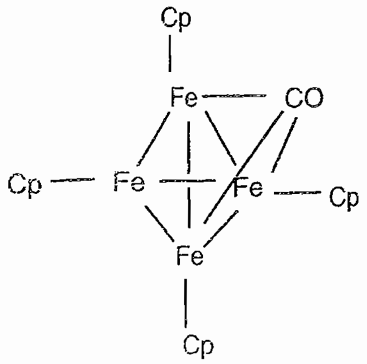
3.21. A: $Co_2(CO)_8$, B: $Co(CO)_3NO$ (NO linear), C: $Co(NO)_3$ (NO linear).

3.22. The colourless gas has to be CO as bromine vapours are coloured. Equimolar amount means one CO is released per $Re(CO)_5Br$; 2040–1965 cm^{-1} is the terminal carbonyl region. Based on this and the absence of metal–metal bonds, the structure is one with bridging bromines.



3.23. $[\eta^5CpFe(CO)]_4$

TVE = 60; electrons per metal = 15. This means each metal makes 3M–M bonds. The total number of M–M bonds in the molecule = (18 × 4) – 60 = 12e = 6 M–M bonds. ν_{CO} at 1640 cm^{-1} indicates μ^3 CO. The proposed structure is as follows (only one μ^3 CO is shown).



3.24. (a) $Mo(CO)_5PPh_3$ will have lower ν_{CO} since PPh_3 is a poorer π acceptor ligand than CO.

(b) $Fe(CO)_4Br_2$ [$Fe^{2+} = d^6$]; $Fe(CO)_5$ [$Fe^0 = d^8$]. Since the electron density on Fe higher, back donation to CO will be more. Hence $Fe(CO)_5$ will have lower ν_{CO} val

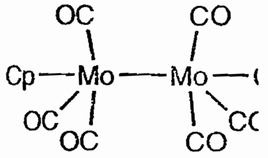
3.25. (a) The two CO bands of the PMe_3 complex are 100 cm^{-1} or more lower in frequer than the corresponding bands of the PF_3 complex. This is primarily because PMe a σ donor ligand while PF_3 is primarily a very poor σ donor and a good π accept ligand (PF_3 is a ligand that resembles CO most electronically).

(b) The five methyl groups on Cp* make it more electron rich than Cp and therefc the Mn on $MnCp^*(CO)_3$ is relatively more electron rich. This is reflected in its ba bonding to CO.

3.26. ν_{CO} of A at 1960 cm^{-1} means that all carbonyls are similar and terminal.

[η^5-$CpMo(CO)_3]_2$: TVE = 17 × 2 = 34; 1 M–M bond.

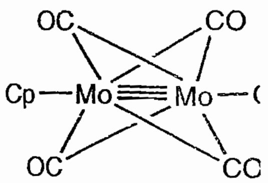
The proposed structure of A is



For B, since two CO molecules are lost, it means 4 electrons are lost; ν_{CO} of A at 1850 cm^{-1} means all the COs are bridged.

[η^5-$CpMo(CO)_2]_2$: TVE = 15 × 2 = 30; 3 M–M bonds.

The proposed structure of B is



CHAPTER 4

4.1. PF_3, $P(OEt)_3$, PPh_3, PMe_3, PCy_3, SIMes.

4.2. The substrate is a coordinatively saturated 18e Ni^0 complex. The reaction will follow dissociative pathway and hence the rate of reaction will depend upon the Ni–CO bor strength. This bond is stronger when L = PMe_3 since it is a good sigma donor but ve poor pi acceptor ligand. Therefore, the dissociation of CO is slower when L = PM Hence the rate of reaction will be slower with L = PMe_3.

4.3. Since PMe_3 is sterically less bulky, the *fac* isomer will result from the reaction.

4.4. (a) The PF_3 complex will have stronger C–O bonds as there will be less back bonding.

(b) The PMe_3 compound will have a stronger M–C bond due to higher back bonding.

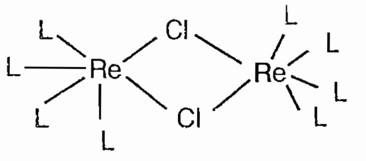
4.5. (a) $TiO_2(PEt_3)_2(CO)_2$ (complex is d^0; no back bonding).

(b) $Rh(CO)_2(P(OPh)_3]_2^+$ (cation; poor σ donor phosphine).

(c) (η^3-allyl)$Co(P(OMe)_3(CO)_2$ (allyl is a poor σ donor and is also relatively a le strong donor compared to the dimethyl allyl analogue, also phosphites are po donors).

(d) $Os(CF_3)_2(CO)_2$ $[P(OMe)_3]_2$ (CF_3 and phosphites are poor donors).

4.6. $Rh(CO)Cl(P(C_6F_5)_3)_2$ > $Rh(CO)Cl(PPh_3)_2$ > $Rh(CO)Cl(PEt_3)_2$. The best donor will lea to the shortest M–C bond.



L = PMe_2Ph

4.7. N_2 is the colourless gas that is liberated. The product must be a dimer with two bridging chloride ligands and no M–M bond. The plausible structure is as follows.

4.8. 2013, 2015, 2022, 2037, 2046, 2092 cm^{-1}.

PEt_3, PMe_3, PPh_3, $P(OMe)_3$, $P(OPh)_3$, PF_3.

4.9. (a) Hydrocyanation of butadiene $P(OPh)_3$.

(b) Hydrogenation of propylene dppe.

(c) Kumada–Hayashi coupling dppf.

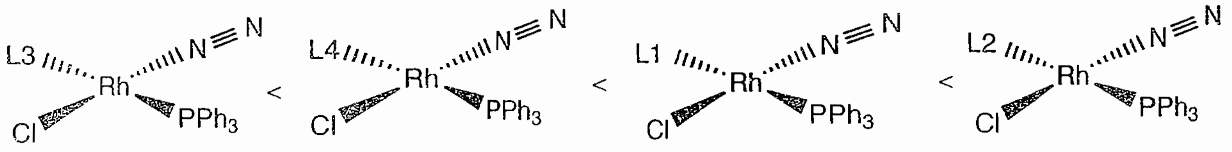
(d) Suzuki coupling of aryl chlorides $P(^tBu)_3$.

(e) Hydroformylation of propene BISBI.

4.10. $(Bu^t)_3P$ and Et_3P and $(4\text{-}MeOC_6H_4)_3P$. These are more basic than PPh_3.

4.11. The χ values of the NHCs will fall below 0 up to –50, since the χ value of $(t\text{-}Bu)_3P$ is taken as 0 for calcualting χ and the NHCs are more basic than $(t\text{-}Bu)_3P$.

4.12. Here the nature of L will decide the extent of back bonding to N_2. As the phosphine becomes more electron deficient, it will decrease the elctron density on the Rh center. This will decrease backbonding to the π^* orbitals of N_2 and hence will cause little change to the N–N bond distance.



L1 = Ph_3P L2 = Me_3P L3 = F_3P L4 = $(MeO)_3P$

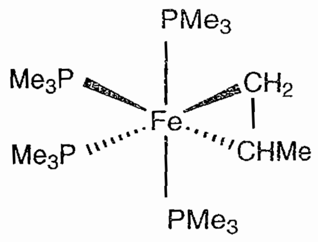
4.13. The substrate is an 18e system and must undergo ligand substitution by a dissociative mechanism. The rate limiting step in this mechanism is the ligand dissociation. Because of the steric interactions, the ligands with the large cone angles are bound weakly to the metal. The cone angle varies as $Ph_3P > Ph_2PMe > PhPMe_2$. Therefore, the ligand dissociation and ligand substitution will be most facile when L = Ph_3P and least facile in $PhPMe_2$.

CHAPTER 5

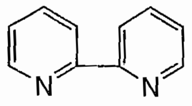
5.1. B < A < C < D. In this series, B has the shortest C–C bond length; the back donation from Fe to ethylene is least because of (a) higher positive charge on the complex and (b) the presence of two good π acceptor CO groups; D has the longest C–C bond length indicating the highest back donation to ethylene. This is due of the presence of two good σ donor Et_3P groups.

5.2. Norbornene (c) will bind the strongest. A maximum ring strain is released in this bicyclic compound as the alkene carbon goes from sp^2 to sp^3

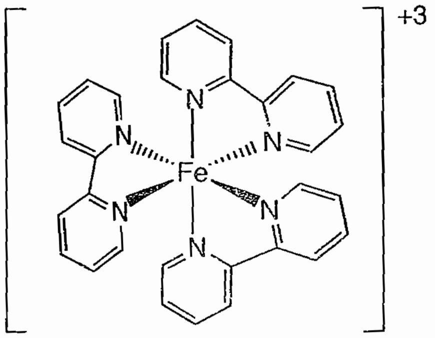
5.3. Propene forms a η^2-complex with octahedral arrangement and the four PMe_3 units will appear at four different chemical shifts due to the unsymmetry on the alkene. On heating, the alkene starts rotating around the M–alkene axis and the four phosphines now appear to the alkene as two sets, axial and equatorial. Hence only two peaks will be observed.



5.4. This is an example of a cycloaddition reaction in which the cyano group of 2- cyanopyridine and two acetylene units cyclise to afford bipyridine (A). Three molecules of bipyridine will form a red coloured octahedral complex (B) with iron (III).



A



B

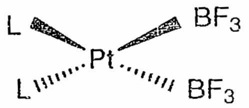
5.5. (a) 1,3,5-triphenyl benzene and 1,4,5-triphenyl benzene.

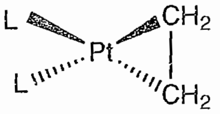
(b) 2-vinylpyridine.

(c) 2-thiomethylpyridine.

5.6. The tungsten complex will bind most strongly since the third row transition metals bind the strongest and also due to the presence of two highly donoting biphosphines. Ti^{+4} has no electron density for back donation since it is a d^0 system.

5.7. The unusual product formed is *cis*-$(PPh_3)_2Pt(BF_3)_2$. Pt acts as a Lewis base in this unusual product. Since Pt is in the zero oxidation state, ethylene must be η^2 in the complex $(PPh_3)_2Pt(C_2H_4)$.





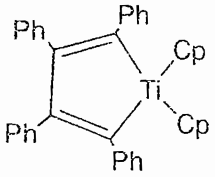
L = PPh_3

5.8. *Trans*-cyclooctene has more strain when compared to the *cis* isomer and hence will bind strongly to metal to release this strain.

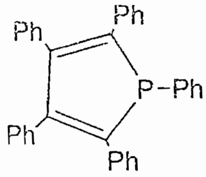
5.9. (a) $(CH_2=CH_2)Ni(PPh_3)_2$, since it has a more electron rich metal.

5.10. A: $Cp_2Ti(PMe_3)_2$

B:



C:



CHAPTER 6

6.1. (a) The carbene unit without the N containing heterocycle.

(b) The bond to the NHC will be longer, since it is a Fischer type of carbene.

(c) The NHC carbenes are Fischer type due the presence of the nitrogen atoms. The other carbene units (the reactive carbenes) can also be considered as Fischer type due to the presence of phenyl groups. However it may be noted that Grubbs does not consider these carbenes as either Fischer type or Schrock type.

6.2. The fact that the carbonyl stretching frequency is lower in the carbyne complex indicates that the electron density is more on the metal and the back donation to CO is higher. This means that the carbynes are better donors than the carbenes.

6.3. $Cr(CO)_6$ on treatment with EtLi followed by reaction with MeI will result in the formation of $(CO)_5Cr{=}C(OMe)(Et)$. $Cr(CNMe)_6$ on treatment with aniline directly yields the carbene, $(MeNC)_5Cr{=}C(NHMe)(NHPh)$.

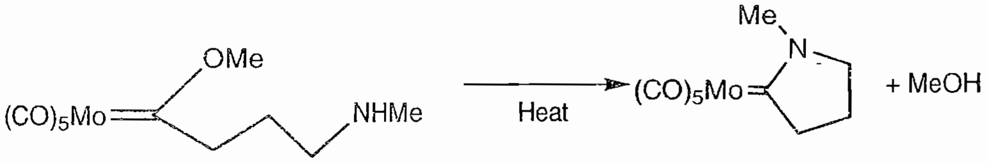
6.4. The electrons on the phenyl group can be delocalised on the system similar to the lone pair from a heteroatom. One can explain this better by drawing resonance structures.

6.5. A and B are Fischer type, C and D are Schrock type and E is in between the two.

6.6. (a) S, (b) S, (c) F, (d) none, (e) F, (f) none—borderline, (g) F, (h) S.

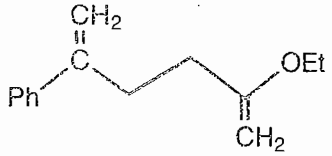
6.7. At low temperature, there is hindered rotation around the C–O bond leading to a mixture of *cis* and *trans* structures. Hence there are two peaks at low temperature for the methyl groups.

6.8.

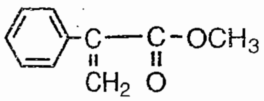


6.9

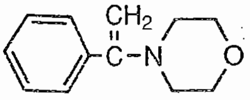
(a)



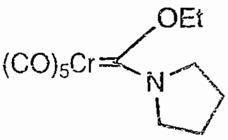
(b)



(c)



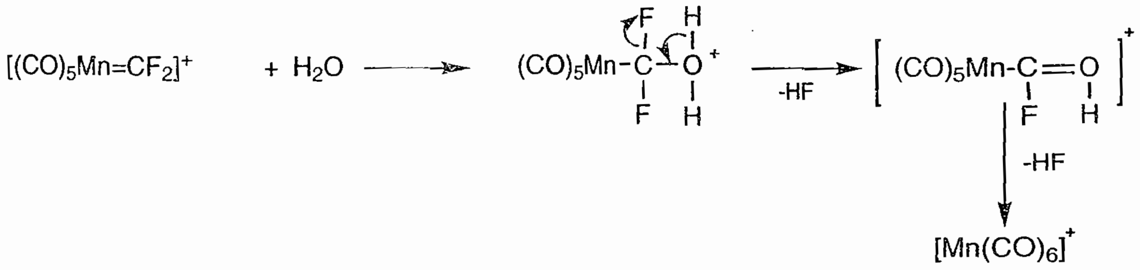
6.10.



6.11. $(CO)_5Mo{=}C(OMe)Ph + LiSO_3CF_3$

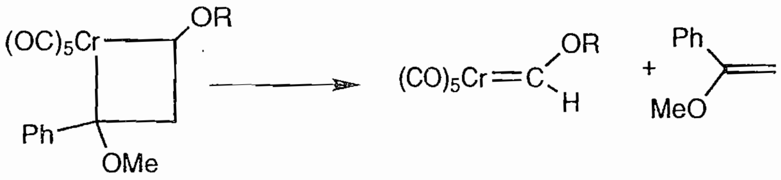
6.12. The carbene carbon is electron deficient in both the cases. However, in I there is only one heteroatom containing electron donating group while in II there are two heteroatom based electron donating groups on the carbene carbon. The effect of the phenyl group seems to be less when compared to the heteroatoms.

6.13.



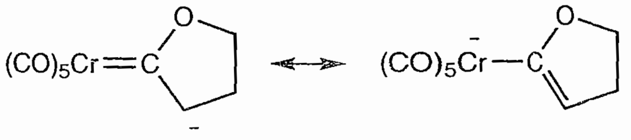
Here, the CF_2 carbene is electronically similar to a Fischer carbene. Because of the presence of fluorines, the carbon of CF_2 undergoes nucleophilic attack by water. The intermediate eliminates two HF molecules to give the molybdenum carbonyl complex.

6.14.

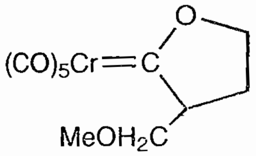


6.15

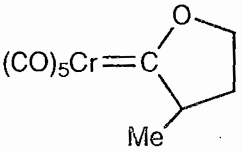
A



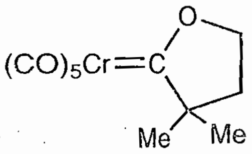
B



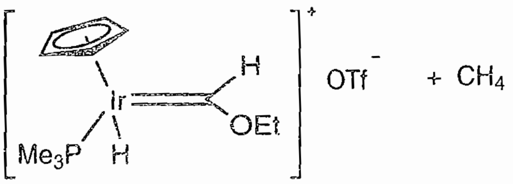
C



D



6.16.



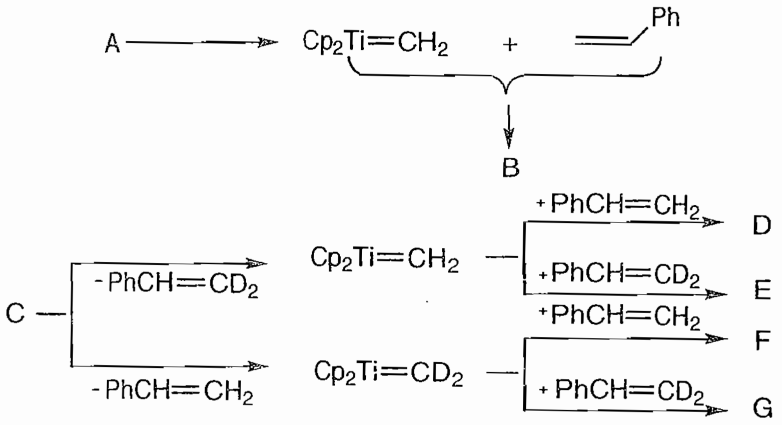
6.17. In the bonding of metal carbenes, the π bond between the metal and the carbene carbon results due to the back bonding interaction between a filled metal *d* orbital of the appropriate symmetry and an empty *p* orbital of the carbene. Any factor that increases the electron density at the metal centre will strengthen the M–C π bond and will result in higher activation energy for the rotation around this bond. The factors to include are (a) *d* electron count of the metal, (b) the donor properties of the ligands and (c) which row the metal is located.

(I) The only difference between the two complexes is the metal. Since the electron density on the metal atom increases down the group, a higher back donation in tungsten will make the metal carbene bond stronger and increase the ΔG value.

(II) Here, the only difference is in the ligand. Since PEt_3 is a stronger donor than PPh_3, the M–carbene bond is stronger in the former.

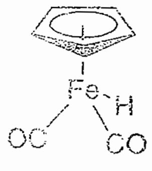
(III) Fe^{+2} and Re^{+1} are both d^6 systems. Here, two factors need to be considered—the electronic effects of the ligand and the location of the metal ($3d$ vs $5d$). Iron has strong electron donating ligands and Re has one electron donating and one electron withdrawing ligand. If the electronic properties of the ligands were the only operating factors, then we would expect the Fe complex to have a higher ΔG than the Re complex. However, the result is just the opposite. This means that the ligand effects are not the major contributing factor. The increased electron density on a third row metal as compared to a first row metal explains the observed data.

6.18.

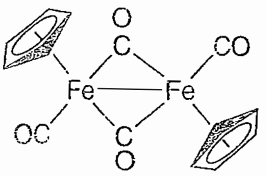


CHAPTER 7

7.1.



A



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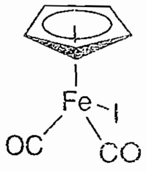

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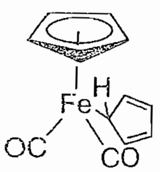

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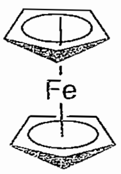
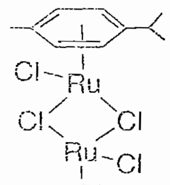


E

7.2.



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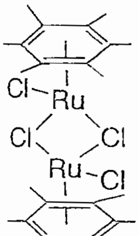

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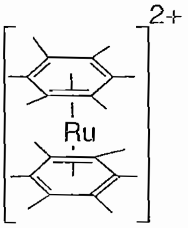

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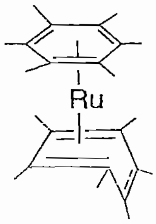
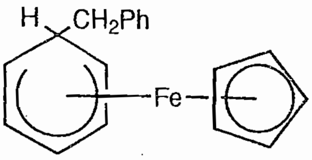


D

7.3.

(a)



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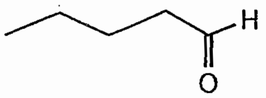

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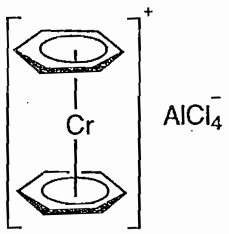
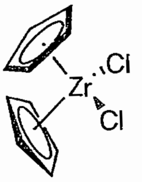
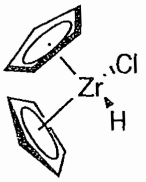


7.5. Those which do not have β hydrogens will be stable: (a) $BeMe_2$, (d) $Be(CH_2Bu^t)_2$.

7.6.



A



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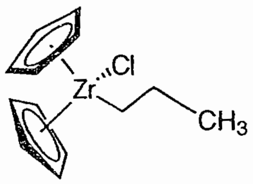
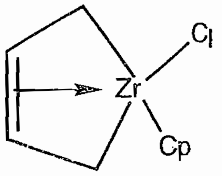


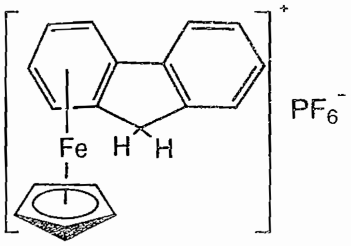
C

7.7. In the case of the Fe complex, a combination of π back donation from Fe and σ donation from the diene to the metal weakens and lengthens the C=C bond. In the Zr complex, a reversal is seen, where the single bond across the back of butadiene shortens. Surprising!!



What is happening here is that Zr is in a low oxidation state (+2 but it really wants t be +4) and is therefore electron rich. So rich that it transfers two electrons to butadien via the π back donation and generates a metallacyclopentene resonance structure.

7.8.



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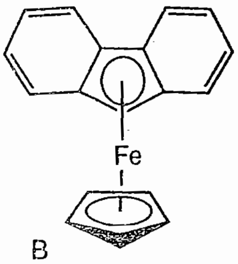
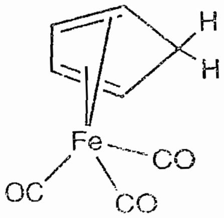


B

7.9.



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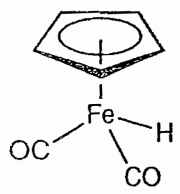
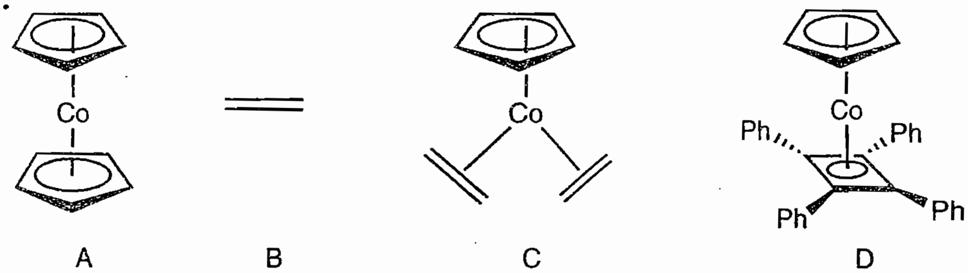
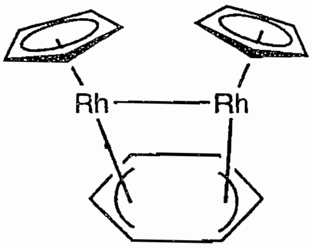


B

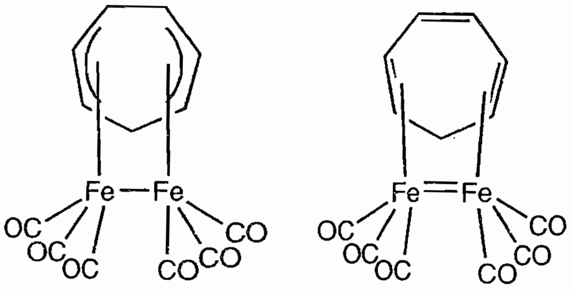
7.10.



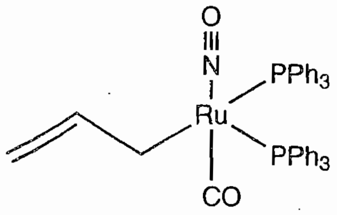
7.11.



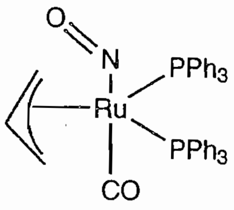
7.12.



7.13.



Ru	8
η^1 allyl	1
linear NO	3
2 PPh_3	4
CO	2
	18

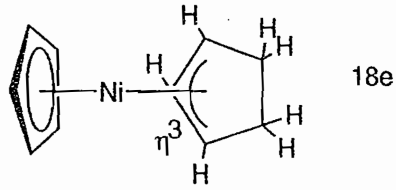


Ru	8
η^3 allyl	3
Bent NO	1
2 PPh_3	4
CO	2
	18

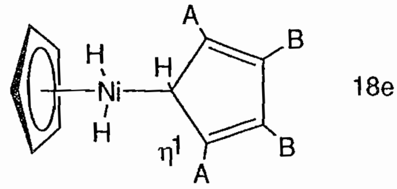
7.14. The longer ring Cr–C bond length in II suggests that the back bonding from Cr to the benzene ring is reduced because of the presence of three good π acceptor CO groups in II. However, in I the back donation from Cr to the arene ring is more. Because of this enhanced electron density in the benzene ring, electrophilic substitution should be more facile in I.

7.15. Ferrocene has 18 valence electrons and the protonation at the Fe centre does not change the total valence electrons in the product. $NiCp_2$ has 20e and if the same mechanism occurs, then the hypothetical $[NiCp_2H]^+$ would still be a 20e species. However, if the protonation occurs directly at the Cp ring, the product $[NiCp(\eta^4\text{-}C_5H_6)]^+$ attains the 18e configuration. The reaction is more facile in the Ni complex because of the driving force to attain the 18e product.

7.16 The given structure obeys the 18 electron rule and the ^1H NMR is satisfied as per the given information.

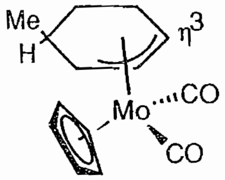


The following structure is also a possibility as at room temperature AA and BB will become equivalent. However since the +4 oxidation state in Ni is not that stable, it will not be an acceptable structure.

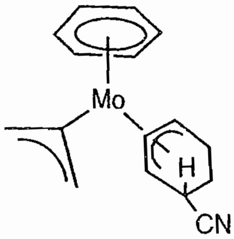


7.17

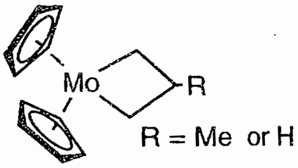
(a)



(b)



(c)



CHAPTER 8

8.1. (a) Migratory insertion (b) Oxidative addition

(c) Oxidative addition (d) Addition (simple)

8.2. To answer these questions, the important factors to consider are the position of the metal in the periodic table, formal oxidation of the metal, the nature of ligands present on the metal, that is, the electron density on the metal ion. In (a) it is Ir^{+1} vs Co^{+1} (b) PPh_3 vs CO (c) Ir^{+1} vs Rh^{+1} and in (d) Pt^0 vs Ir^{+1}.

(a) $[Ir(dppe)_2]^+$ (b) $Rh(PPh_3)_2Cl$

(c) $IrCl(CO)(PPh_3)_2$ (d) $(PMe_3)_2Pt(CO)_2$

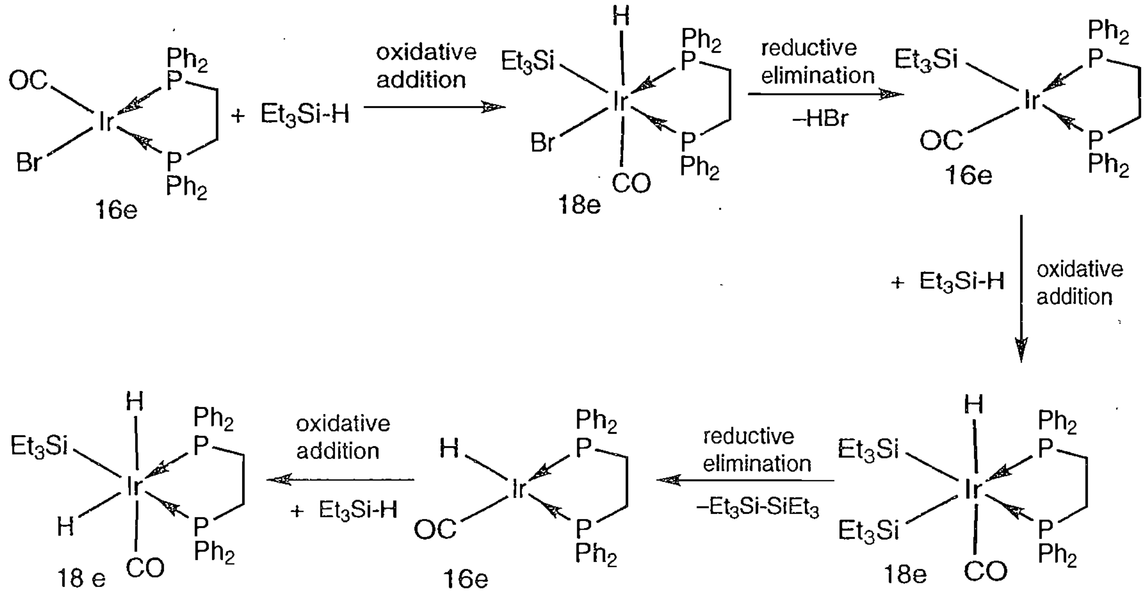
8.3. (a) (c) η^5-$Cp_2Ti(Me)Cl$

The metal Ti is in the highest oxidation state (+4) and has no *d* electrons present.

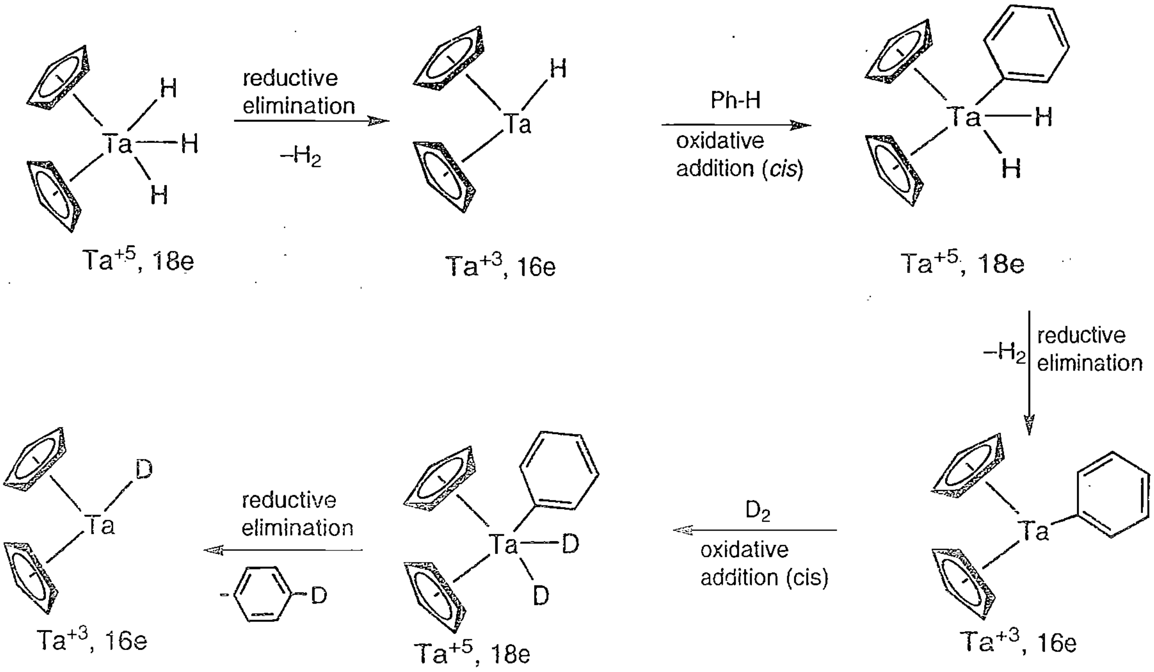
(b) Both are d^8 metal systems. Oxidative addition with MeI will occur by the S_N2 mechanism. Ir^{+1} is more nucleophilic in Ir(dmpe)Cl(CO) because of the presence of the dmpe ligand which is more electron donating than dppe. Hence it will react faster with MeI.

8.4. (a) Reductive elimination and migratory insertion.
(b) Oxidative addition.
(c) Migratory insertion.
(d) Oxidative addition and β-hydrogen transfer.
(e) Oxidative addition.
(f) Oxidative addition and β-hydrogen transfer.

8.5.

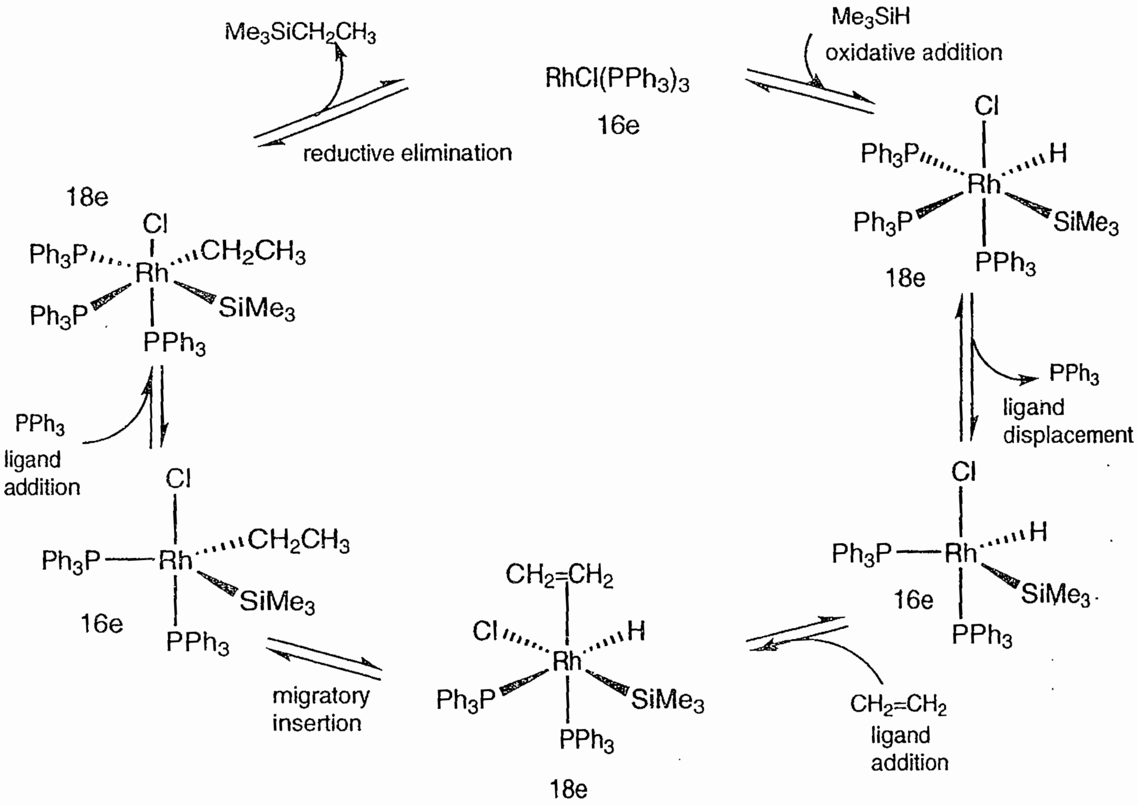


8.6.



The reaction is continued on C_6H_5–D and finally gives C_6D_6.

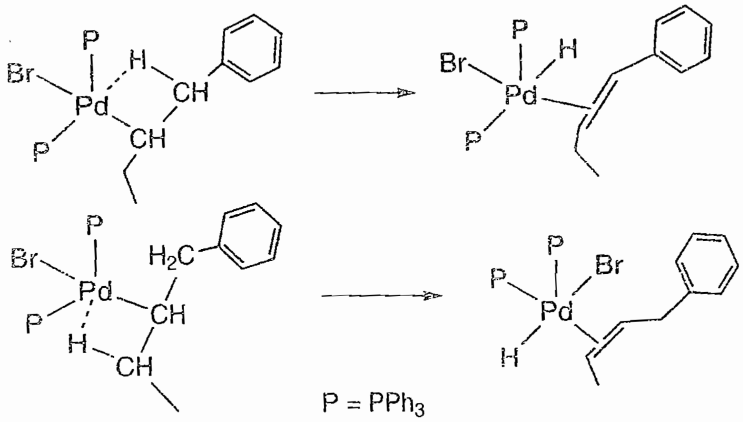
8.7.



8.8. (a) Loss of PPh_3, (b) addition of CO, (c) migratory insertion of CO, (d) addition of excess CO along with reductive elimination of acetone.

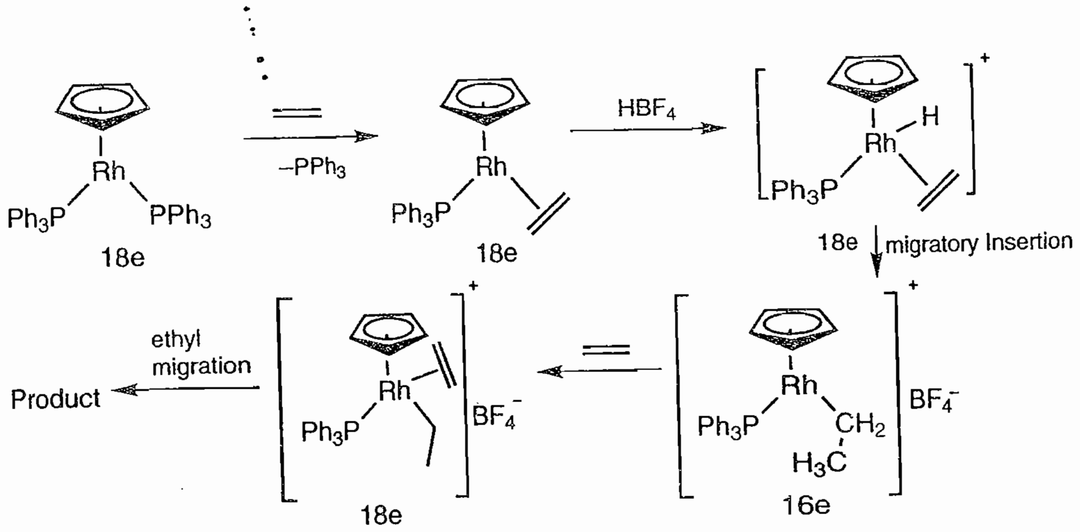
8.9. The reductive elimination cannot occur in (d). This can be due to two possible reasons—the compound is formally Nb III and the Nb (I)–Nb(III) redox couple is not easily accessible, and more importantly, there is no group to eliminate. η^5-Cp_2 or η^5-CpH cannot be eliminated since Cp rarely undergoes reductive elimination in transition metals. Even if this had happened, the resulting product would be a highly electron deficient nine electron system. All others give the organic compounds after reductive elimination (a) gives butane, (b) gives $CH_3C(O)I$ and (c) gives CH_4.

8.10.

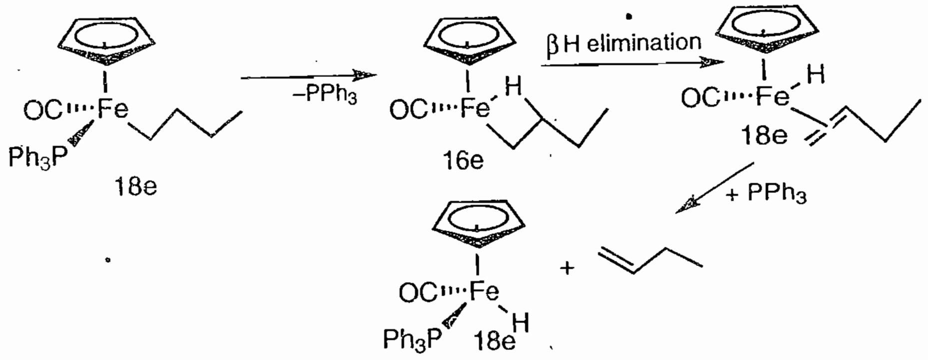


8.11.

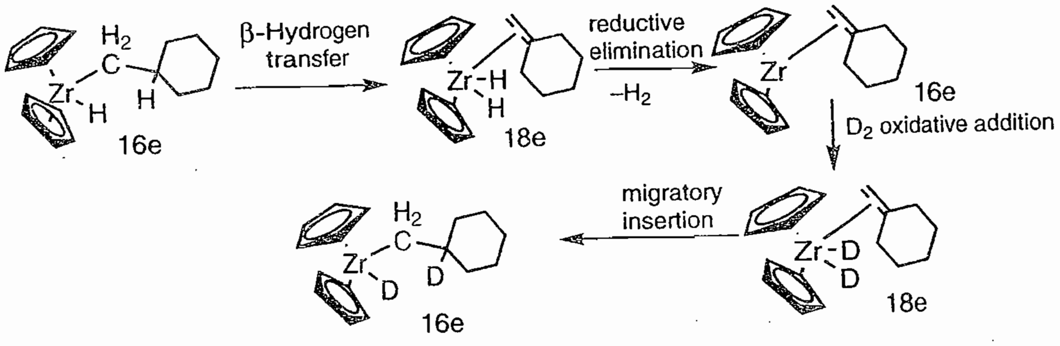
(a)



(b)



(c)



8.12. (a) $Ir(PPh_3)_2(CO)(Cl) + CF_3I \longrightarrow Ir(PPh_3)_2(CO)(Cl)(CF_3)(I)$

Ir^{+1}, 16e $\qquad$ Ir^{+3}, 18e *trans*

(b) $\eta^5\text{-}CpRh(CO)_2 + CF_3CF_2I \longrightarrow \eta^5\text{-}CpRh(CO)(CF_3CF_2)(I) + CO$

Rh^{+1}, 18e $\qquad$ Rh^{+3}, 18e *trans*

(c) $\eta^5\text{-}Cp_2W(CH_3)(H) \xrightarrow{h\nu} \eta^5\text{-}Cp_2W + CH_4 \xrightarrow[D]{\text{benzene}} \eta^5\text{-}Cp_2W(Ph)(H)$

W^{+4}, 18e $\qquad$ W^{+2}, 16e $\qquad$ W^{+4}, 18e *cis*

(d) $\eta^5\text{-}Cp(CO)_3Re + Br_2 \longrightarrow \eta^5\text{-}Cp(CO)_2Re(Br)(Br) + CO$

Re^{+1}, 18e $\qquad$ Re^{+3}, 18e *cis*

(e) $(PPh_3)_2Rh(CO)(COCH_2CH_2R) + H_2 \longrightarrow (PPh_3)_2Rh(CO)(H) + RCH_2CH_2CHO$

Rh^{+1}, 16e $\qquad$ Rh^{+3}, 18e *cis*

(f) $(PPh_3)_4Pd + PhBr \longrightarrow (PPh_3)_2Pd(Ph)(Br) + 2PPh_3$

Pd^0, 18e → Pd^{+2}, 16e *trans*

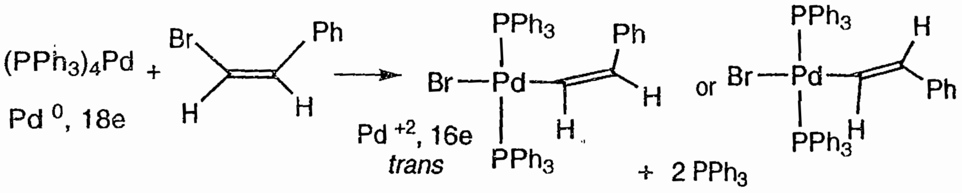
(g) $\eta^5\text{-}Cp(CO)_2Ir + H\text{-}CH_3 \longrightarrow \eta^5\text{-}Cp(CO)Ir(H)(CH_3) + CO$

Ir^{+1}, 18e → Ir^{+3}, 18e *cis*

(h) $\eta^5\text{-}Cp(CO)_2RuCH_3 + Br_2 \longrightarrow \eta^5\text{-}Cp(CO)RuCH_3(Br)(Br) + CO$

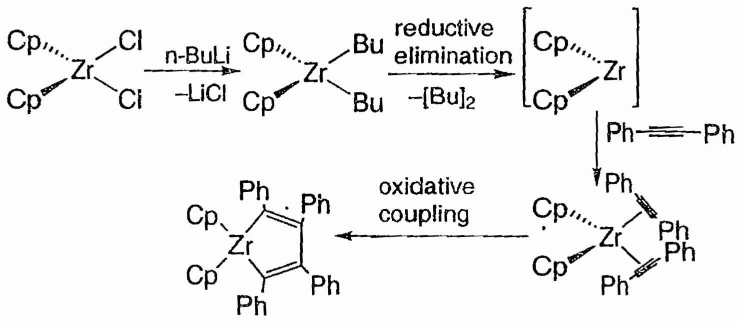
Ru^{+2}, 18e → Ru^{+4}, 18e *cis*

(i)

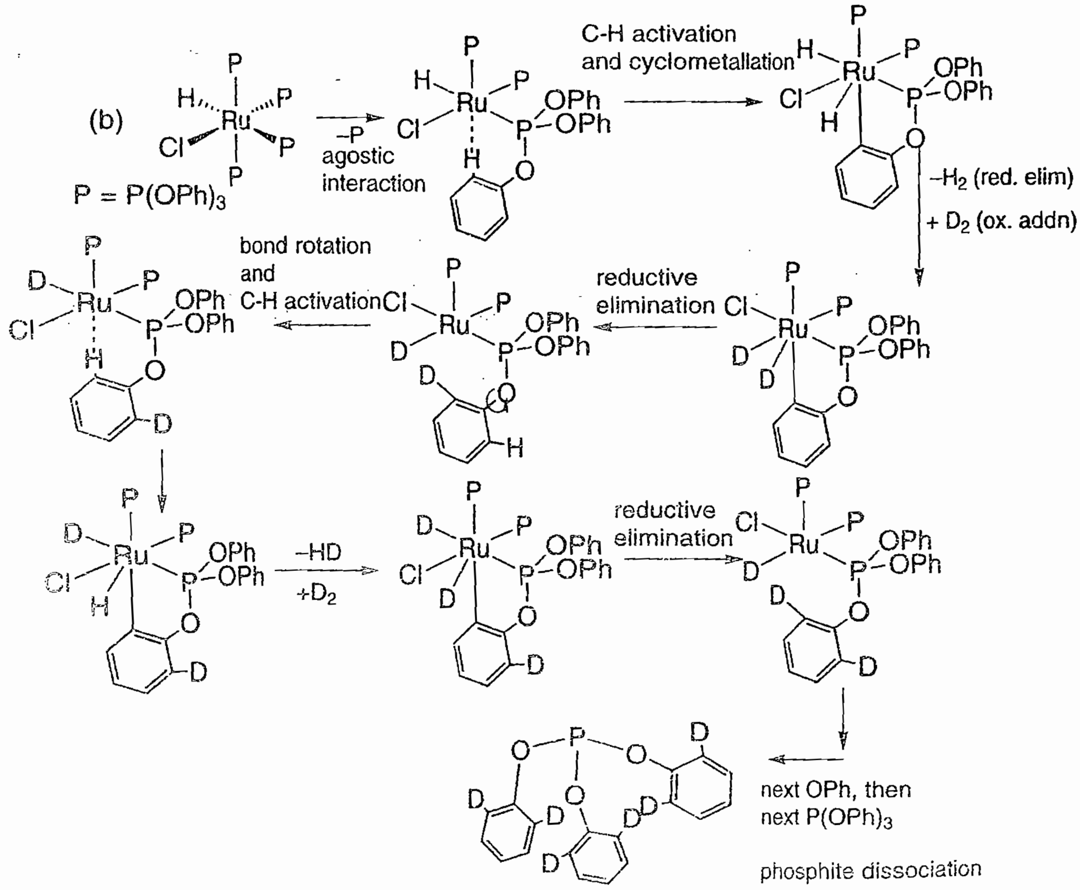


8.13.

(a)

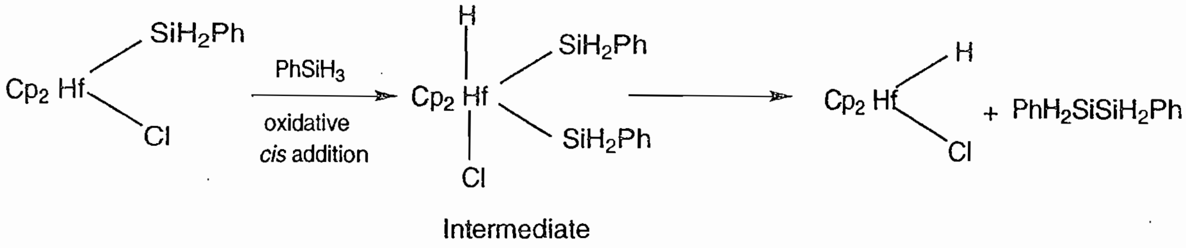


(b)

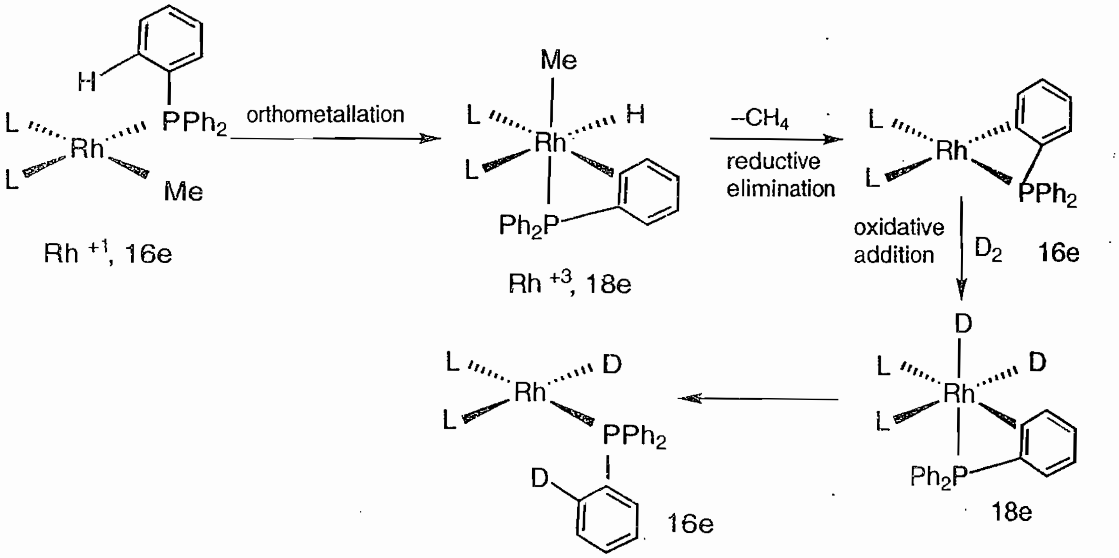


8.14. The answer is (c) because the formal oxidation is Pt^{4+} and the metal is highly electron deficient.

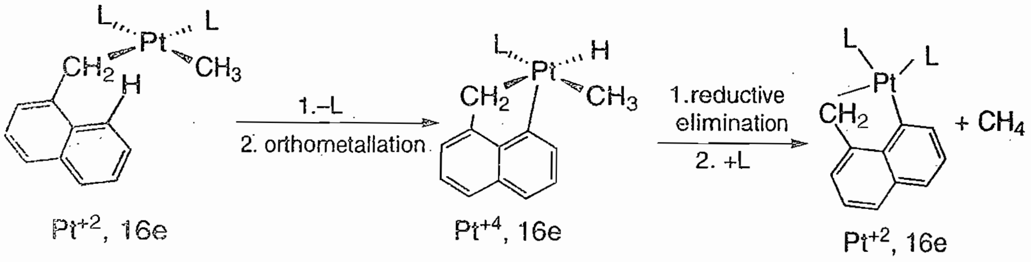
8.15. The *cis* addition of $PhSiH_3$ forms the intermediate which then undergoes reductive elimination of PhH_2SiSiH_2Ph.



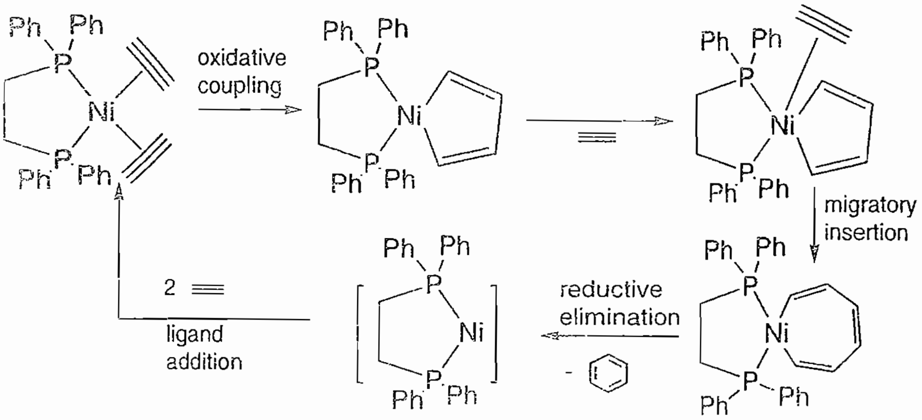
8.16.



8.17.

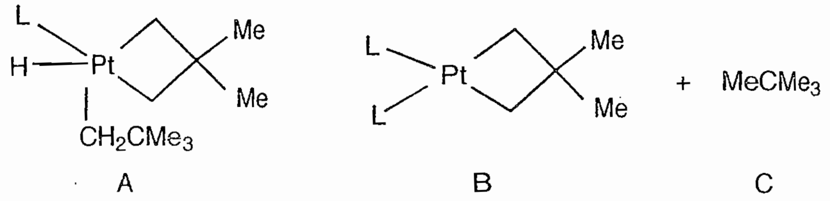


8.18.

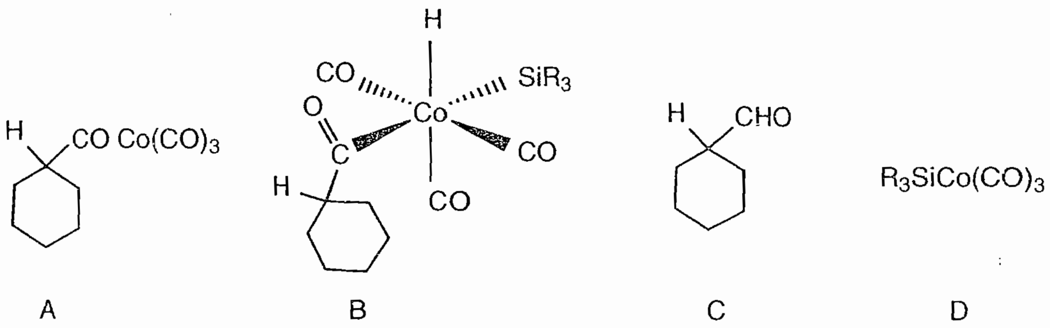


Replacing dppe with dmpe will make the metal more electron rich and it will facilitate the oxidative coupling step thereby increasing the efficiency of the catalyst.

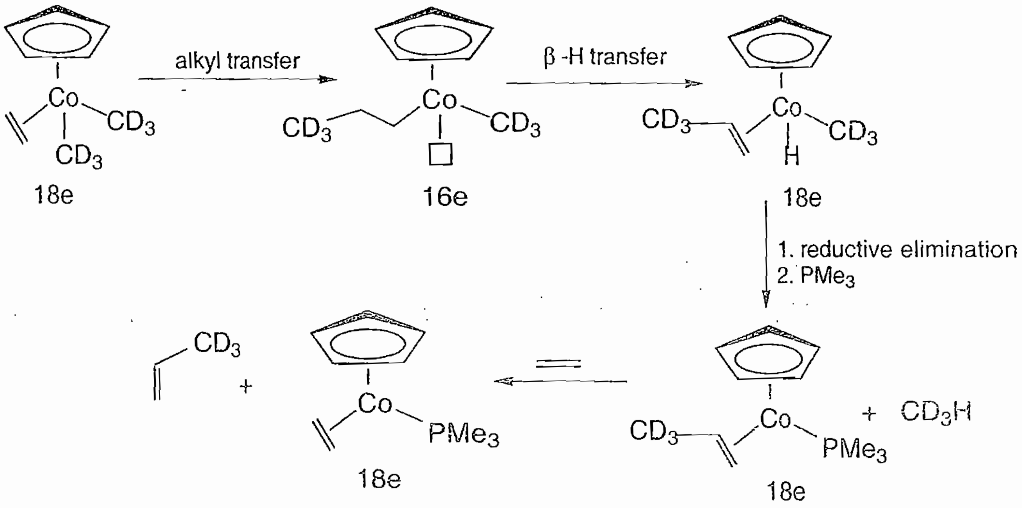
8.19. $L = PEt_3$



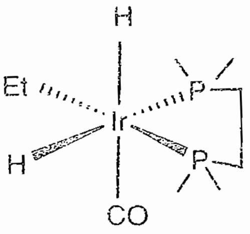
8.20.



8.21.

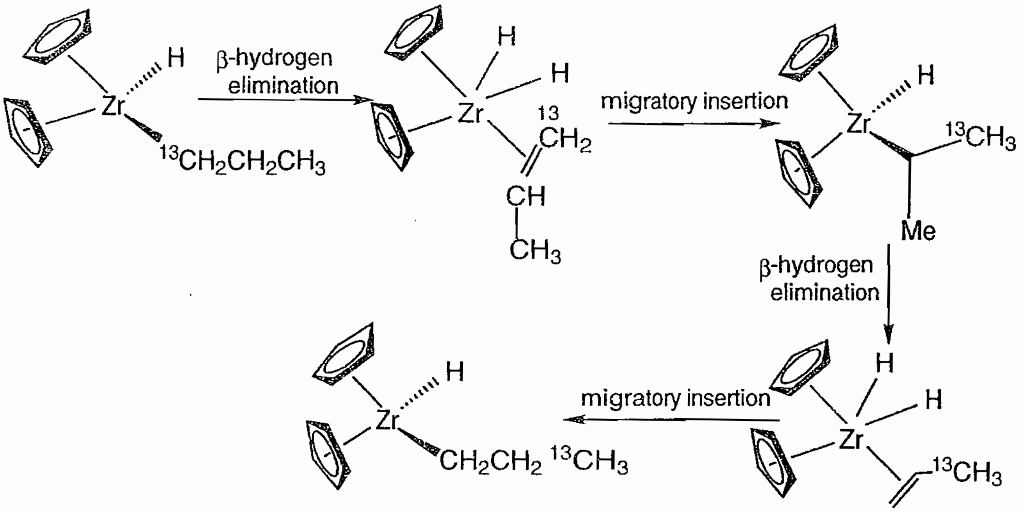


8.22. Since A reductively eliminates H_2 and ethane, it means that the two hydrogens and Et and H must be *cis* to each other. The infrared data corresponds to a CO stretch. The proposed structure is as follows.



The same structure should be given even if the infrared data is not given in the question. This is because the Ir–CO bond is stronger than Ir–alkene bond in $Ir(C_2H_4)(Et)(CO)(dppe)$. The alkene is loosely bound and would come off easily in the presence of H_2.

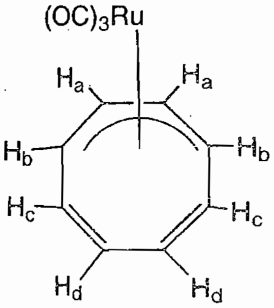
8.23.



8.24. $Os(CO)_5$ (I) should react faster than $L_2Os(CO)_3$ (II) (*trans*). Both are 18e complexes. Therefore one ligand has to dissociate before it can accommodate the incoming ligand, dihydrogen. Since no rate data is given, the dissociation of the same ligand should be considered, CO in both cases. In II, the Os–CO bond is stronger because of the higher back bonding. The presence of two neutral mono dentate non π acid ligands in II will increase the electron density on Os and hence lead to stronger back bonding. Therefore, the oxidative addition will be faster in I.

CHAPTER 9

9.1. The negative entropy of activation is consistent with an associative (A) type of mechanism. The fact that the rate of the reaction depends on the concentration of the incoming ligand is also indicative of an A type mechanism.



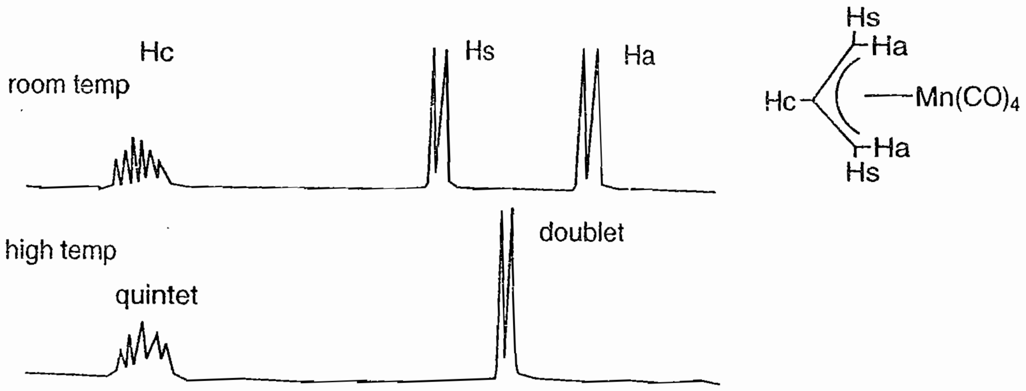
9.2. The figure depicts what is observed at low temperature. At room temperature, the ring is whizzing around the metal atom rapidly so the average signal is observed. At low temperature, the motion of the ring is slower and the distinct conformation exists long enough to be resolved.

9.3. $Mo(CO)_2[P(OMe)_3]_3(CH_3)$ is a 17 electron species while $Mo(CO)_3(PMe_3)_3$ is an 18 electrons species. 17 electrons species undergoes associative substitution and the weakly coordinating ligands can easily dissociate also.

9.4. (i) η^5 to η^3 hapticity change.
(ii) CO ligand addition.
(iii) PMe_3 ligand dissociation.
(iv) η^3 to η^5 hapticity change.

9.5. Reaction (a) will be faster. The reaction involves η^5 to η^3 hapticity change. This happens readily for the pentadienyl ligand. For cyclopentadienyl, as it is in a resonance stabilised aromatic form, more energy will be required for the hapticity change.

9.6. The new compound will be (η^3-allyl)Mn(CO)$_4$. The room temperature and high temperature spectra will be as given below.



9.7. The acac complex (I) is 16e and the Cp complex (II) is 18e. In the former, the reaction proceeds by an associative mechanism while a dissociative mechanism operates in the latter. The dissociative mechanism in general is significantly slower than the associative mechanism for similar complexes. The difference in rate in the present complexes will be particularly large since CO is the leaving group.

9.8. The large negative entropy of activation points to an associative mechanism. This is supported by the fact that the rate depends upon the concentration and nature of the phosphine.

9.9. The two terms in the rate law imply parallel pathways for the formation of the product, Mo(CO)$_5$L. The first term is consistent with the dissociative mechanism.

$$\mathrm{Mo(CO)_6} \xrightarrow{k_1} \mathrm{Mo(CO)_5} + \mathrm{CO} \quad \text{(slow)}$$

$$\mathrm{Mo(CO)_5} + \mathrm{L} \longrightarrow \mathrm{Mo(CO)_5L} \quad \text{(fast)}$$

$$\mathrm{Rate_1} = k_1[\mathrm{Mo(CO)_6}]$$

The second term in the rate law is consistent with an associative mechanism and involves a molecular reaction of Mo(CO)$_6$ and L to form an intermediate which then loses a CO.

$$\mathrm{Mo(CO)_6} + \mathrm{L} \xrightarrow{k_2} [\mathrm{Mo(CO)_6}\text{-------}\mathrm{L}]$$

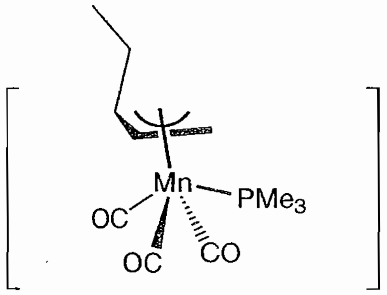
$$[\mathrm{Mo(CO)_6}\text{-------}\mathrm{L}] \longrightarrow \mathrm{Mo(CO)_5L} + \mathrm{CO}$$

The formation of the intermediate is the rate limiting step in the mechanism. Therefore, the rate law is Rate$_2$ = k_2[Mo(CO)$_6$][L].

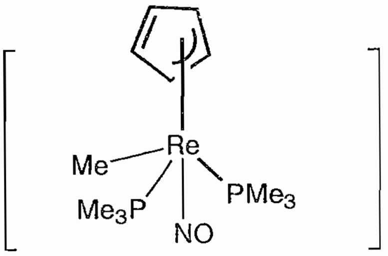
Because of the two pathways, the overall rate of formation of $Mo(CO)_5L$ is the sum of these two rates, $Rate_1$ and $Rate_2$.

9.10.

(a)

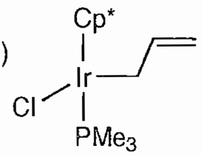


(b)

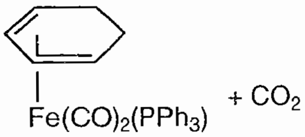


9.11.

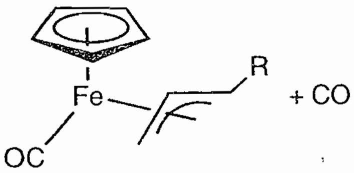
(a)



(b)



(c)

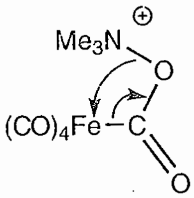


(a) The substrate is an 18e species. To avoid going via a 20e intermediate, the η^3 to η^1 allyl transformation occurs.

(b) Me_3NO attacks the carbon of a coordinated CO and leads to the eventual loss of CO_2.

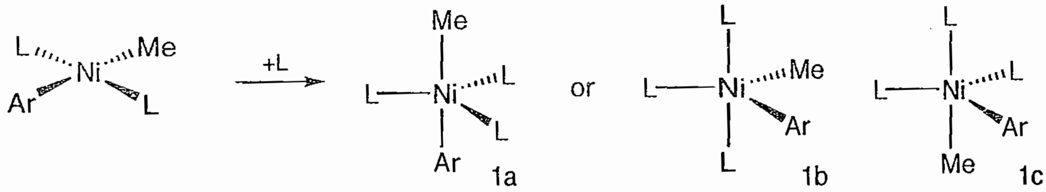
(c) To maintain the 18e count, η^1 allyl changes to η^3 allyl.

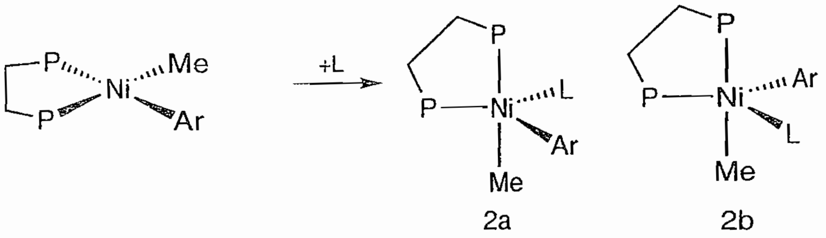
9.12. Me_3NO attacks the carbon of the CO group.



9.13. The faster rate of decomposition in the *cis* isomer may be attributed to the *cis* disposition of Me and Ar, appropriate for the reductive elimination process. In the *trans* isomer, the two eliminating groups must isomerise to the *cis* position before reductive elimination can occur. In the first instance, the data given under (c) points to an associative mechanism as a trigonal bypyramid intermediate is proposed to be formed during phosphine addition.

The striking difference in the reductive elimination behaviour of *cis* and *trans* isomers may be associated with the kinetic instability of the intermediate five coordinate TBP towards intramolecular pseudorotation. If we assume that the psuedorotation of TBP, which is causing the isomerisation, is a slow process, then the difference in the thermolysis behaviour can be explained by the following mechanism.





In 2a or 2b, because of the chelating phosphine ligand which will be strained in *trans* or equatorial *cis* geometries, the Me and Ar are positioned in adjacent equatorial and apical positions in the intermediate TBP geometry. In each case, the reductive elimination is symmetry allowed. However, in 1a or 1b, the Ar and Me are present either in the *trans* position (1a) or in the equatorial *cis* position (1b). The reductive elimination of Ar–Me is not allowed in both the cases. Only when it is in the 1c geometry during pseudorotation, is there a possibility of reductive elimination.

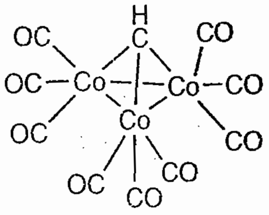
The formation of the reductive elimination product in the *trans* isomer can also be explained considering the dissociative pathway. It occurs through the formation of an unsaturated three-coordinate species that isomerises to the *cis* isomer by polytopal rearrangement which then undergoes reductive elimination of the Me–Ar product.

CHAPTER 10

10.1. $Co_3CH(CO)_9$ TEC = 50. We will consider two options.

(a) If CH is on the vertex then PEC = 50 – (12 × 3) – 2 = 6e pairs: (n + 2). It is a *nido* of a TBP which is a tetrahedron.

(b) If CH is not on the vertex then PEC = 50 – (12 × 3) = 7e pairs—*hypho* of octahedron (not a known structure).



10.2. (a) $[Ni_5(CO)_{12}]^{2-}$ TEC = 76, PEC = 76 – 60 = 8e pair (n + 3). Predicted structure: *arachno* of pentagonal bipyramid.

(b) $Os_6(CO)_{17}[P(OMe)_3]_3$ TEC = 88, PEC = 88 – 72 = 8e pair (n + 2). Predicted structure: *nido* of a seven vertex pentagonal bipyramid cluster.

(c) $[Ru_5N(CO)_{14}]^-$ TEC = 74; PEC = 7e pair (n + 2). Predicted structure: *nido* of a six vertex cluster octahedron.

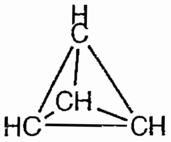
(d) $Os_4(CO)_{12}(\mu^4\text{-}C_2Me_2)$ TEC = 62; PEC = 62 – 48 = 7e pair (n + 3). Predicted structure: *arachno* of a six vertex octahedron cluster; butterfly structure capped with μ^4-alkyne group.

10.3. $Os_6(CO)_{18}$ TEC = 84, PEC = 6e pair ($n = 0$). Predicted structure: 5 vertex cluster with one cap, that is, monocapped TBP. On adding two electrons it becomes $[Os_6(CO)_{18}]^{2-}$; TEC becomes 86e and the structure is octahedral.

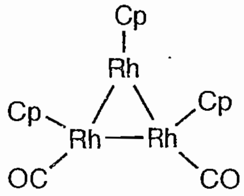
10.4. (a) = $(FeCpCO)_4$

$$FeCpCO \underset{O}{\longleftrightarrow} [Fe(CO)_4]^+ \underset{O}{\longleftrightarrow} \underset{d^7ML_4}{Mn(CO)_4} \underset{O}{\longleftrightarrow} CH$$

The organic fragment is



(b) = after removing the bridge it becomes

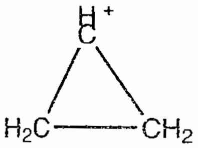


Now

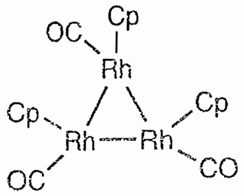
$$CpRh \underset{O}{\longleftrightarrow} [Rh(CO)_3]^+ \underset{O}{\longleftrightarrow} \underset{d^8ML_3}{Fe(CO)_3} \underset{O}{\longleftrightarrow} CH^+$$

$$CpRhCO \underset{O}{\longleftrightarrow} [Rh(CO)_4]^+ \underset{O}{\longleftrightarrow} \underset{d^8ML_4}{Fe(CO)_4} \underset{O}{\longleftrightarrow} CH_2$$

The organic fragment is

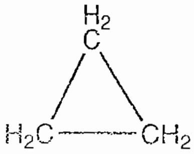


(c) = after removing the bridge it becomes



$$CpRhCO \underset{O}{\longleftrightarrow} [Rh(CO)_4]^+ \underset{O}{\longleftrightarrow} \underset{d^8ML_4}{Fe(CO)_4} \underset{O}{\longleftrightarrow} CH_2$$

The organic fragment is



10.5. Between (a) and (b), only $Pt(CO)(PMe_2Ph)$and Cu–Cp* are to be considered. The rest of the molecule is the same. Therefore PtL_2 and CuCp are to be considered for isolability.

$$PtL_2 \underset{\circ}{\longleftrightarrow} d^8ML_4 \underset{\circ}{\longleftrightarrow} CH_2$$

$$CuCp \underset{\circ}{\longleftrightarrow} \overset{+}{Cu}\,Cp^{-} \underset{\circ}{\longleftrightarrow} [\overset{+}{Cu}(CO)_3] \underset{\circ}{\longleftrightarrow} \underset{d^{10}ML_3}{[Ni(CO)_3]} \underset{\circ}{\longleftrightarrow} CH_2$$

Both are isolobal to each other.

Similarly comparing (b) and (c), the only fragment to be compared is $W(CO)_2Cp$ and CR as rest of the molecule is isolobally the same.

$$\overset{+}{W}(CO)_2\overset{-}{Cp} \underset{\circ}{\longleftrightarrow} [W(CO)_5]^{+} \underset{\circ}{\longleftrightarrow} \underset{d^5ML_5}{[Cr(CO)_5]^{+}} \underset{\circ}{\longleftrightarrow} CH_3^{2+}$$

since $Cr(CO)_5 \underset{\circ}{\longleftrightarrow} CH_3^{+}$

Now $CH_3^{2+} \underset{\circ}{\longleftrightarrow} CH_2^{+} \underset{\circ}{\longleftrightarrow} CH$

Therefore $W(CO)_2Cp \underset{\circ}{\longleftrightarrow} CR$

Hence (b) and (c) are isolobal

10.6.

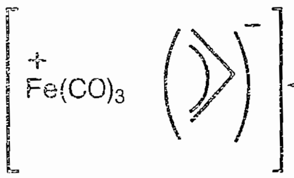
(a) $Fe(CO)_4 \underset{\circ}{\longleftrightarrow} Cp(CO)Rh$ because

$$Cp(CO)Rh \underset{\circ}{\longleftrightarrow} (CO)\overset{+}{Rh}\overset{-}{Cp} \underset{\circ}{\longleftrightarrow} [(CO)_4Rh]^{+} \underset{\circ}{\longleftrightarrow} Fe(CO)_4$$

(b) $\underset{d^8ML_4}{Os(CO)_4} \underset{\circ}{\longleftrightarrow} Fe(CO)_4 \underset{\circ}{\longleftrightarrow} CH_2$

$(CO)_4Os{-}Os(CO)_4 \underset{\circ}{\longleftrightarrow} CH_2{=}CH_2$

(c)
$$\begin{tikzcd}
NiCp(CO) \arrow[r, leftrightarrow, "\circ"'] & \overset{+}{Ni}\overset{-}{Cp}(CO) \arrow[r, leftrightarrow, "\circ"'] & {[Ni(CO)_4]^{+}} \arrow[r, leftrightarrow, "\circ"'] & Co(CO)_4 \\
 & & & d^9ML_4 \arrow[dl, leftrightarrow, "\circ"] \\
 & CH_3 \arrow[r, leftrightarrow, "\circ"'] & d^7ML_5 &
\end{tikzcd}$$

(d)  $\underset{\circ}{\longleftrightarrow} [Fe(CO)_5]^{+} \underset{\circ}{\longleftrightarrow} Mn(CO)_5 \underset{\circ}{\longleftrightarrow} CH_3$

10.7. The isolability of $Pt(PMe_3)_2$ to CuCp is to be considered. The rest of the molecule is the same.

$Pt(PMe_3)_2$ d^{10} ML_2 $\underset{\circ}{\longleftrightarrow}$ d^8 ML_4 $\underset{\circ}{\longleftrightarrow}$ CH_2

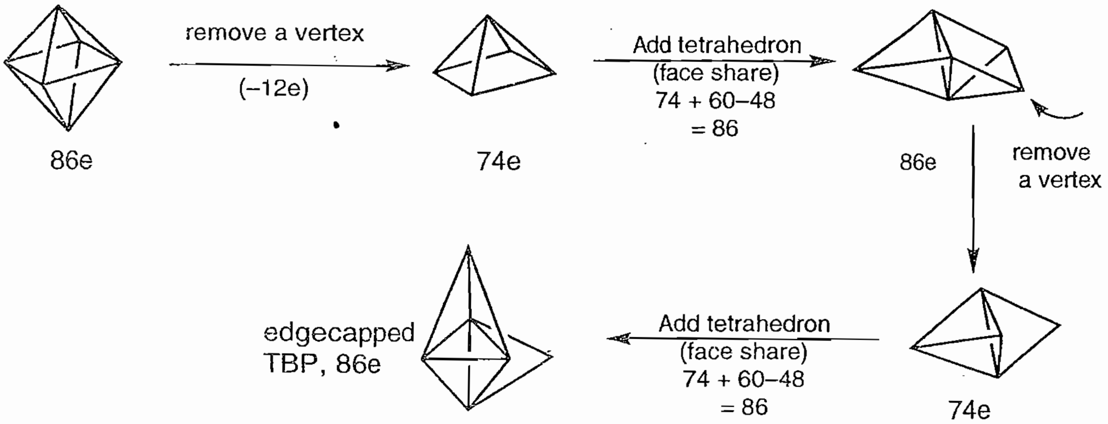
$CuCp$ $\underset{\circ}{\longleftrightarrow}$ $\overset{+}{Cu}\overset{-}{Cp}$ $\underset{\circ}{\longleftrightarrow}$ $[Cu(CO)_3]^+$ $\underset{\circ}{\longleftrightarrow}$ $[Ni(CO)_3]$ $\underset{\circ}{\longleftrightarrow}$ CH_2

d^{10} ML_3
18e

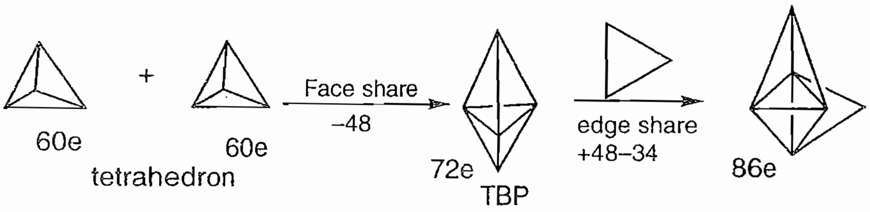
Both are isolobal to each other

10.8. (a), (b), (d), (e) true; (c) is false and $[Cr(CO)_5]$ should be correct instead of $Cr(CO)_5^-$.

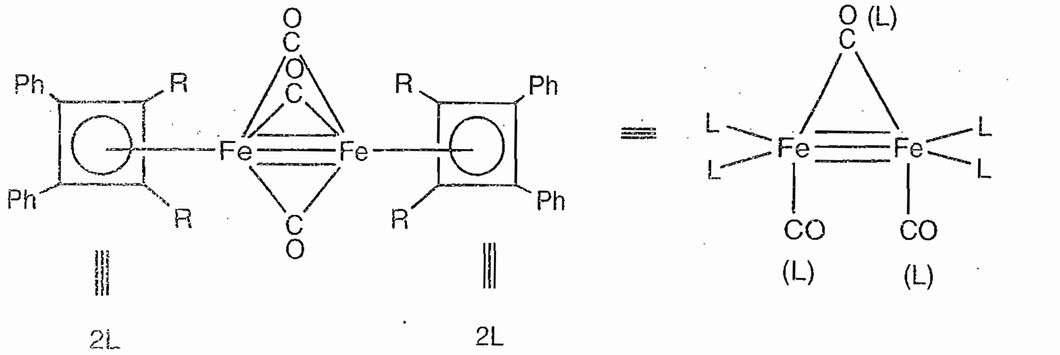
10.9.



The same can be constructed from a four atom cluster also (tetrahedron).



10.10.



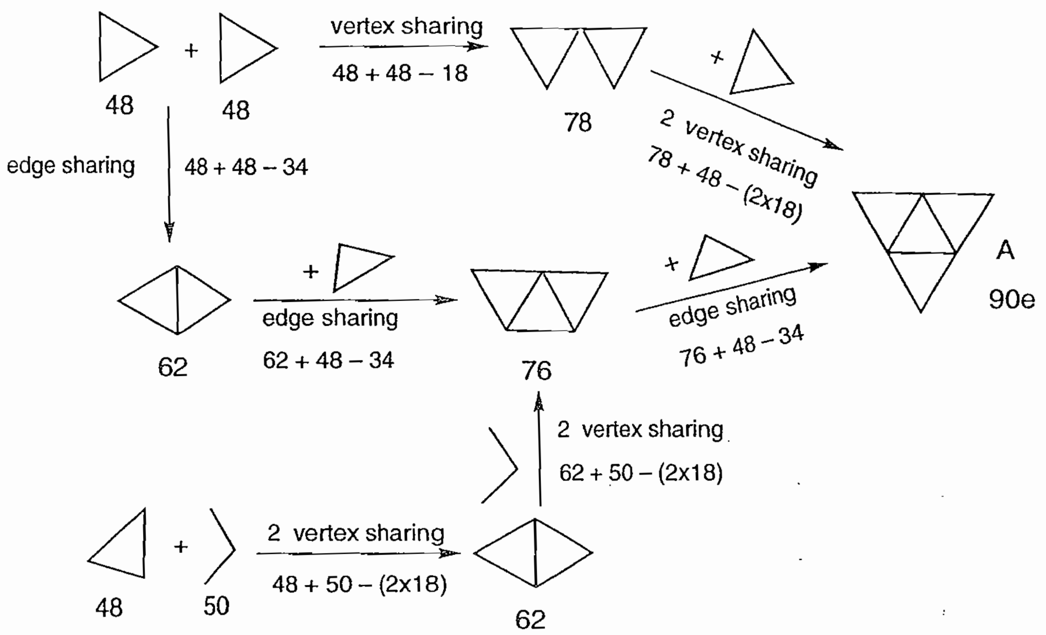
Considering the remaining bridging CO as a one electron donor to each metal, we can write

$\overset{+}{Fe}L_4 \equiv \overset{+}{Fe}L_4$

d^7 ML_4 d^7 ML_4

Since d^7ML_4 is isolobal to CH, we can see that the given complex is isolobal to acetylene.

10.11.



CHAPTER 11

11.1. Entry 6 has the highest TON; 210,000,000. Entry 7 has the highest TOF; 5,000,000.

11.2.

Substrate	Catalyst	Cat/sub (mol%)	Temp (°C)	Time (h)	Conversion (%)	TOF (h^{-1})
Cyclohexene/Et_3SiH	A	0.5	80	3	81	54
PhCOMe/Ph_3SiH	A	0.1	70	2	100	500
PhCOMe/Ph_3SiH	B	0.5	70	2	100	100
PhCOMe/Et_3SiH	A	0.5	70	0.25	100	800
PhCOMe/Et_3SiH	B	0.5	70	0.25	100	800

11.3. The role of the catalyst is to lower the energy of the transition state by coordination. Since only a small fraction of molecules is present at or near the transition state, in principle, we require only a very small number of molecules of the catalyst.

11.4. The substrate S initially binds to catalyst C. The binding should not be too strong otherwise C–S will be too stable. In that case, the activation energy required to get to C–TS (transition state) will be just as large as it is in going from S→TS in an uncatalysed reaction. The substrate should not bind too weakly also since it may otherwise be excluded from the metal and fail to be activated by the metal. Similarly, the product P, usually formed as a C–P complex, must be least strongly bound to C. If it is not, S will not be able to displace P and the catalyst will effectively be poisoned by the products of the reaction.

In reality, the situation is not as simple as described above. The mechanism and nature of the TS changes completely on going from the uncatalysed to the catalysed reaction in which there are several intermediates and transition states on going from S to P. It is therefore required that none of the intermediates be too strongly bound otherwise these will be very stable and will not react further. Similarly none of the transition states shall be of very high energy. The entire reaction profile must remain within a narrow range of free energies and these should be accessible at the reaction temperature.

Even if all this is arranged, a catalyst may undergo a few catalytic cycles and then lose its activity. This will happen if the undesired deactivation reactions are faster than the product forming reactions of the catalyst cycle. This is why a catalyst can fail in more than one way.

11.5. *TOF*: In homogeneous catalysis, the turnover frequency (TOF) is defined as the rate of formation of product, given in moles/L/h, divided by the concentration of catalyst in mol/L. This will give the TOF in h^{-1}. In heterogeneous catalysis, the TOF is the amount of product formed per unit time, given in h^{-1} divided by the number of moles of catalyst present. The final units are h^{-1}, the same as in homogeneous catalysis.

Since one mole of a finely divided homogenous catalyst is more active than one mole of the same catalyst with a small surface area, TOF is sometimes expressed as the amount of product formed per unit time divided by the surface area of the catalyst. This gives the TOF in units of mol $h^{-1}cm^{-2}$. The TOF of commercial heterogeneous catalysts is expressed in rate per gram of catalyst.

Selectivity: A measure of how much desired product is formed relative to the undesired product is referred to as selectivity. Man made catalysts are rarely 100% selective since the process is often faced with difficulties such as separation of the products.

Catalyst: A general definition is, 'a catalyst is a substance that increases the rate of a reaction but is not consumed in the reaction'. This does not mean that nothing happens to the catalyst during the course of the reaction. Many a time, the compound that is added to the reaction mixture as a catalyst, may in fact be a catalyst precursor and the active form of the catalyst gets generated during the reaction.

Catalytic cycle: This comprises a sequence of reactions which ultimately convert the reactants to the products in the presence of a catalyst. The term *cycle* is used because the actual catalytic species that is involved in the first step gets generated in the last step.

11.6. (a) Since all the reactants as well as the products are in the same phase – the gas phase – the reaction is homogeneous.

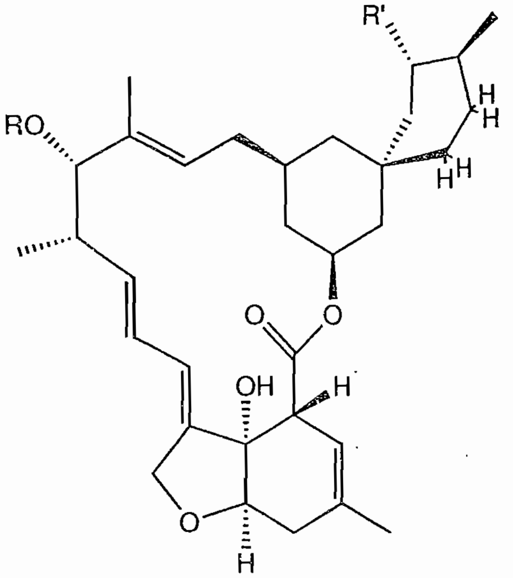
Here the reactants and the products are in the liquid phase (H_2 is dissolved in liquid vegetable oil) but the catalyst is in the solid phase and hence the reaction is heterogeneous.

The reactant, D-glucose, and the product (D, L mixture) dissolve in aqueous HCl and are in one phase and the reaction is homogeneous.

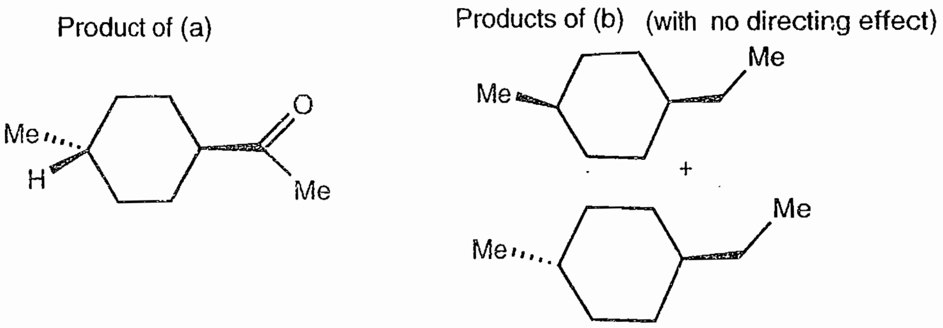
11.7. The working of the converter may get affected as oxidation products of CO and VOC in the first stage can in principle get reduced when they come in contact with the reduction catalyst.

CHAPTER 12

12.1. The least substituted and non-conjugated *cis* alkene is hydrogenated preferentially.

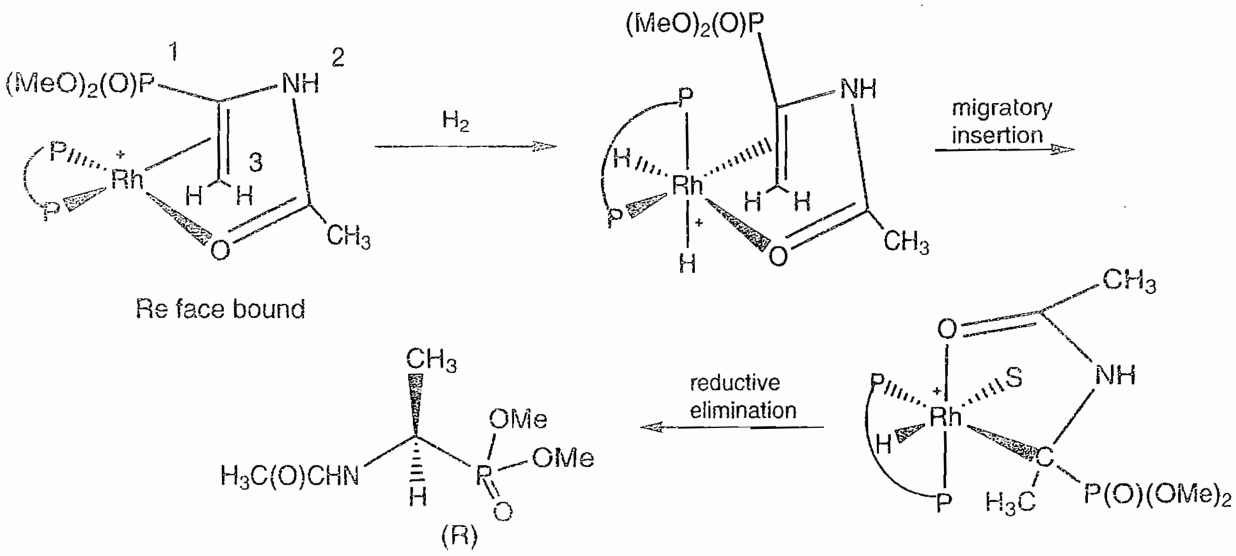


12.2.

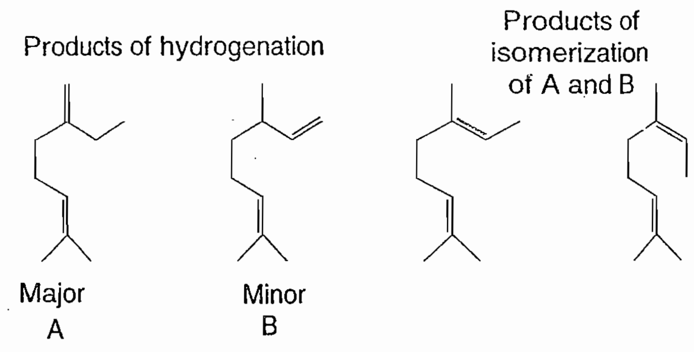

Product of (a)

Products of (b) (with no directing effect)

12.3.

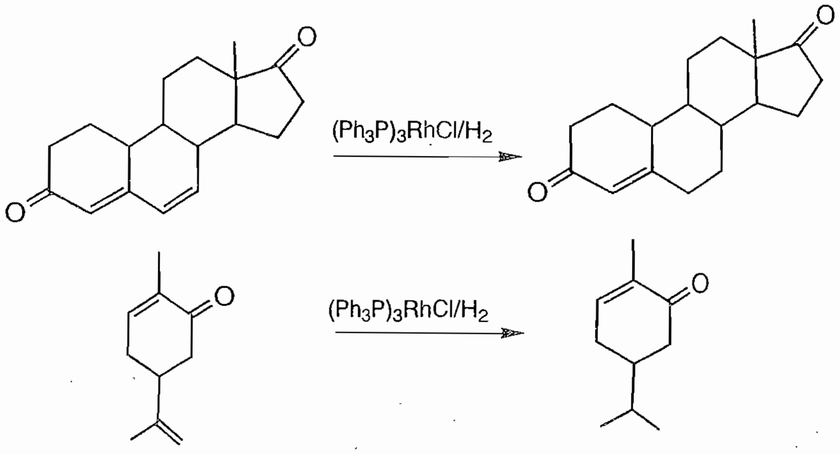


12.4.



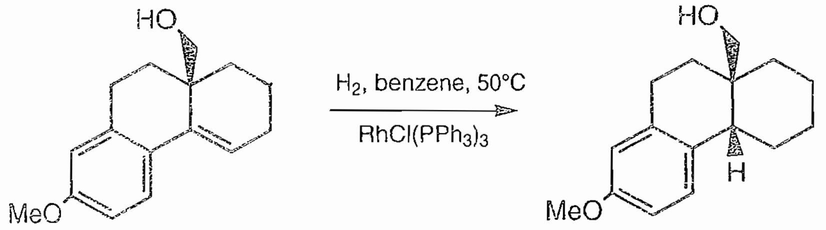
12.5. The cationic complexes are, in general, more active than Wilkinson's or its related complexes because the cationic metal centre is more electrophilic and favours alkene coordination. Therefore (a), (b) and (e) are more active as hydrogenation catalyst than (c) and (d). PEt_3 being a strong donor does not dissociate from the complex and so the activity for (d) is almost negligible and so (d) < (c). The chelating bisphosphine is favoured as it provides two active *cis* sites. So, the order becomes (d) < (c) < (b) < (a), (e). Between (e) and (a), the hydrogenation of norbornadiene is more favoured due to, the release in ring strain on the molecule. Such a strain is not there in COD complexes. Therefore the overall order becomes (d) < (c) < (b) < (e) < (a).

12.6.



The least substituted alkene is hydrogenated first.

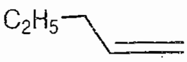
12.7.



12.8. (a)

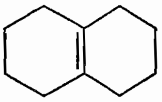
(b)

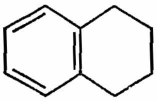
(c)



(d)

(e)

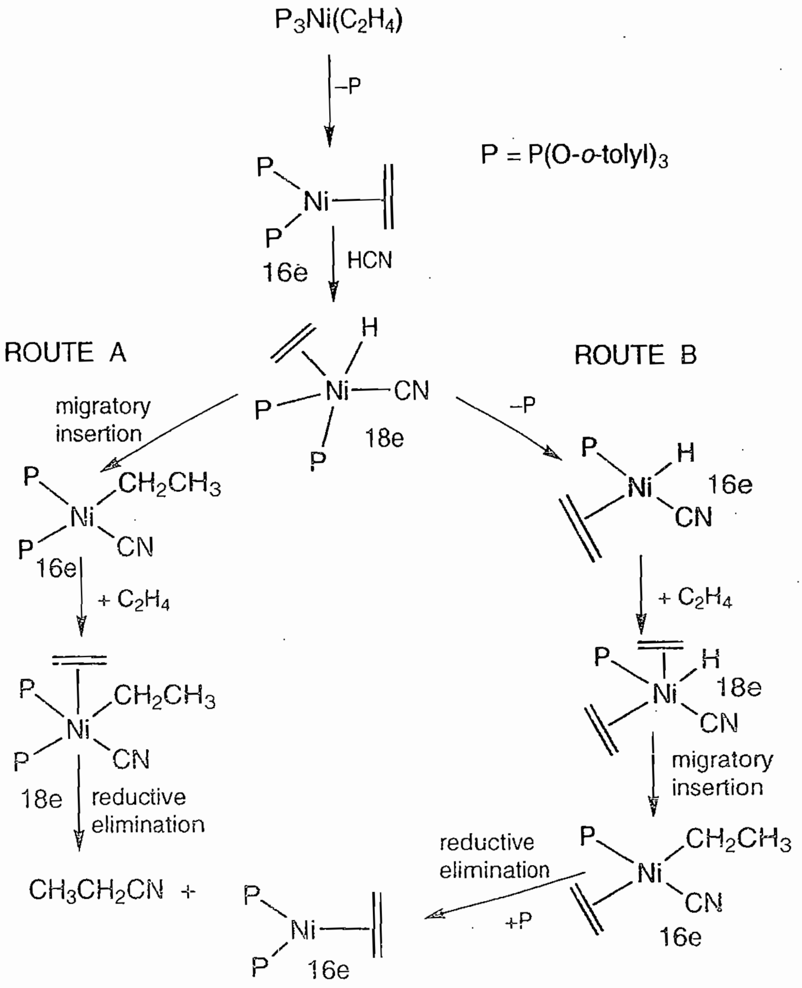
12.9. The hydrogenated product formed (major) is .

The isomerised product (minor) is .

12.10. The important differences are as follows.

- While migratory insertion is the rate determining step for Wilkinson's catalyst, oxidative addition of H_2 is the rate determining step as well as the enantioselecti determining step for the cationic catalyst. Also, addition of the alkene is the step for the cationic catalyst while oxidative addition of H_2 is the first step for Wilkinson's catalyst.
- The presence of polar substituents on the alkene is a prerequisite for chiral catal to occur.

12.11.

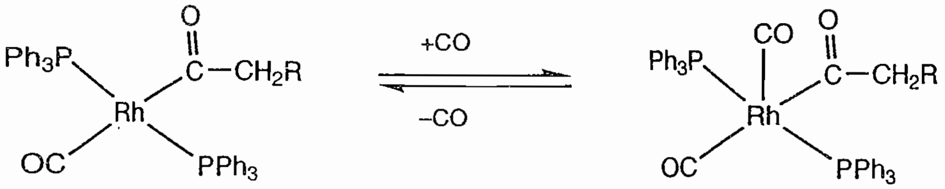


Both routes A and B are acceptable

CHAPTER 13

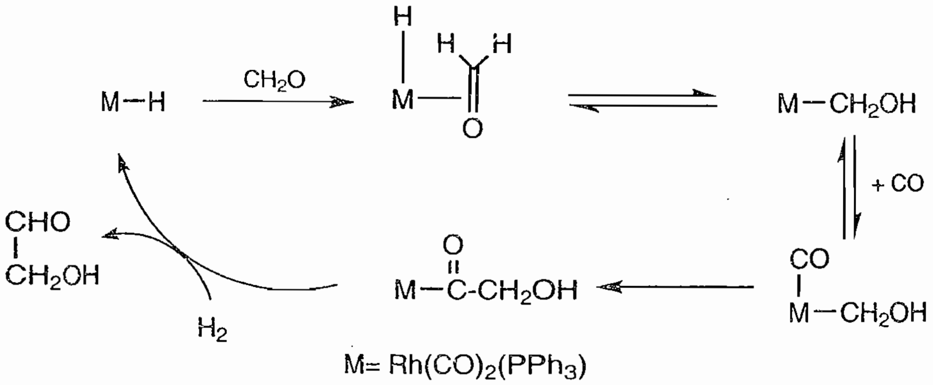
13.1. (a) $RhH(CO)(PPh_3)_2$.

(b) During the catalytic cycle, the five coordinate dicarbonyl complex $Rh(CO)_2(COCH_2R)(PPh_3)_2$ is formed by the reaction of $Rh(CO)(COCH_2R)(PPh_3)_2$ with excess CO. The dicarbonyl complex does not react further with dihydrogen.

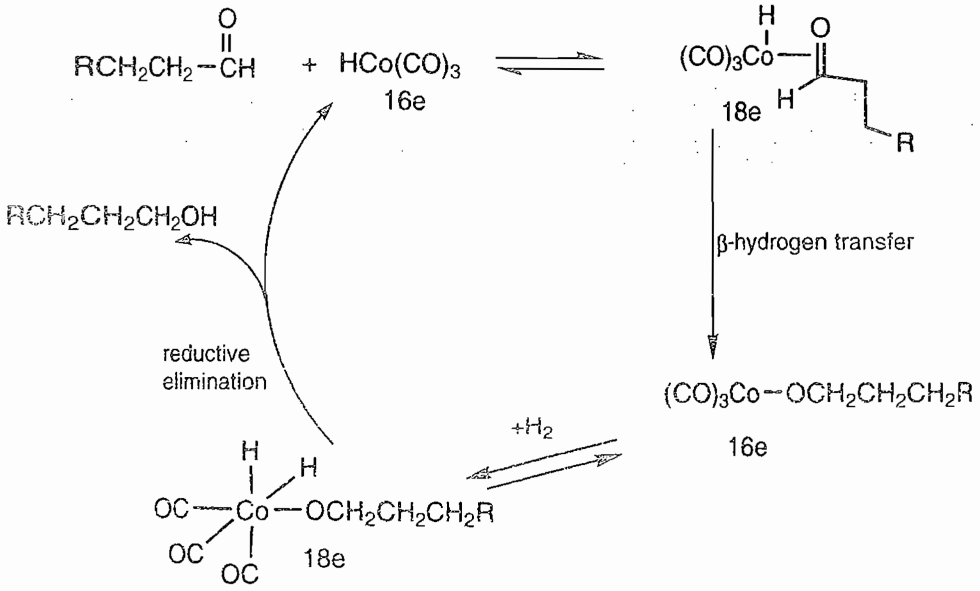


(c) The oxidative addition of H_2 to $Rh(CO)(COCH_2R)(PPh_3)_2$ is the rate determining step. This is the only step in the catalytic cycle where the formal oxidation state of Rh changes from +1 to +3.

13.2. It is believed that the following sequence of reactions occurs.



13.3



13.4. In the cobalt catalysed reaction, $HCo(CO)_3$ is the actual active catalyst and it is produced by the following equilibrium reaction. $HCo(CO)_4$ is an 18e complex and it must lose one CO before it enters into the catalytic cycle.

$HCo(CO)_4 \rightleftharpoons HCo(CO)_3 + CO$

An increase in CO pressure will push the reaction equilibrium to the reactant side and will decrease the concentration of $HCo(CO)_3$.

13.5. Since product A is identified during catalysis, it means that its formation must be faster than its conversion to the end product. If this were not true, a spectroscopically observable amount of A would not build up. Therefore, the conversion of A to the end products, 1-pentanal and $HCo(CO)_4$, must be the rate limiting reaction. However, in the presence of Bu_3P, neither A nor its phosphine substituted product is formed which means that their formation must be slower than their conversion to the end products. Hence their formation is the rate determining reaction.

13.6. The active catalyst in the hydroformylation reaction is $HRh(CO)(PPh_3)_2$ which is generated in situ by the loss of PPh_3.

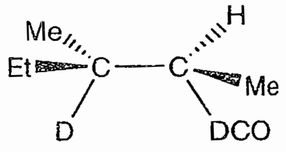
$HRh(CO)(PPh_3)_3 \rightleftharpoons HRh(CO)(PPh_3)_2 + PPh_3$

The addition of PPh_3 will shift the equilibrium to the reactant side and will retard the rate of reaction with alkene.

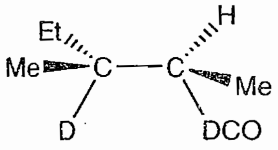
13.7. $CH_3CH_2CH{=}CH_2 > CH_3CH{=}CHCH_3$ (*cis*) $> CH_3CH{=}CHCH_3$ (trans) $> (CH_3)_2C{=}CH_2$

13.8. The stereospecific *cis* addition of D and DCO groups to the alkene occurs, that is, the addition of these two groups occurs on the same face of the alkene. The products formed are as follows.

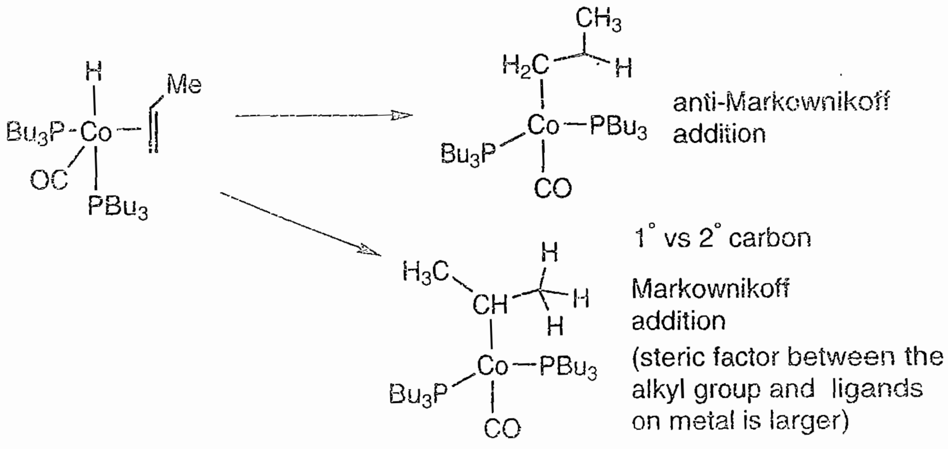
A



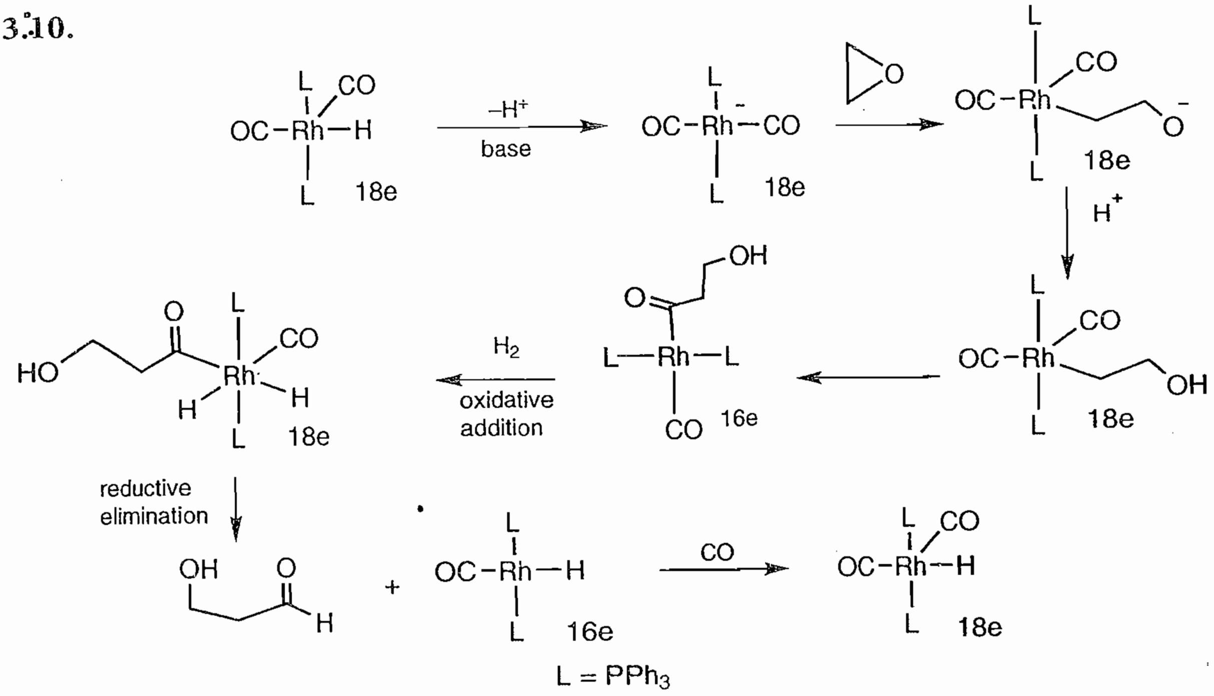
B



13.9. When the hydrogen is transferred to the carbon bearing the most hydrogen atoms, the resulting secondary alkyl group will have a larger steric bulk close to the ligands on cobalt. If the ligands already present on the metal are bulky say, Bu_3P, then the steric factor would even be larger. Therefore, a mixed carbonyl-phosphine combination of ligands on cobalt will offer a better selectivity for the formation of the normal aldehyde. The formation of the normal aldehyde is preferred because of lesser steric crowding around the metal.

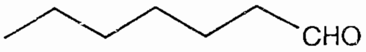


13.10.

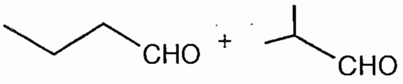


13.11.

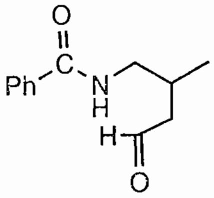
(a)



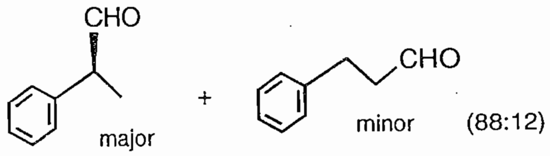
(b)



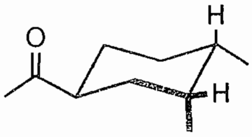
(c)



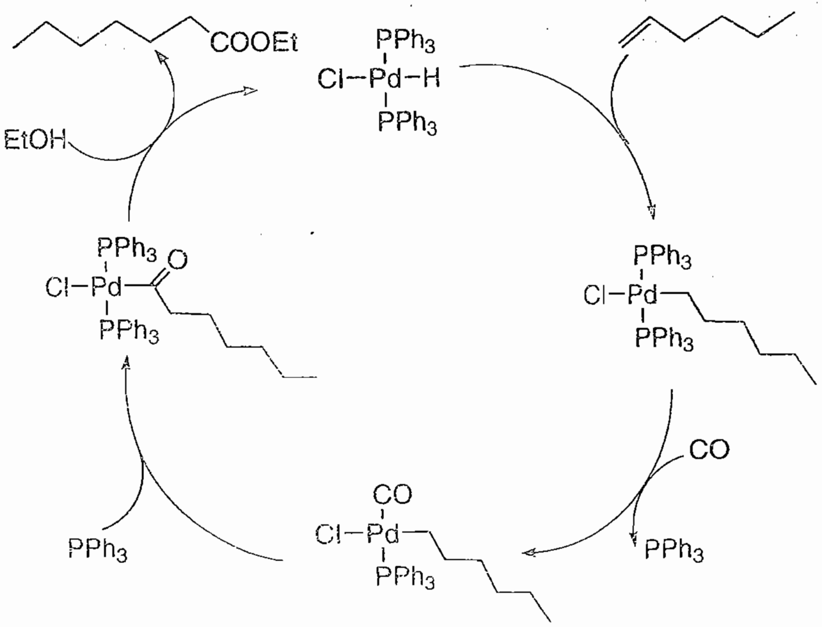
(d)



(e)



13.12.



13.13. Since Bu_3P is sterically bulkier than CO, the linear alkyl complex is preferentially formed. The secondary Co–alkyl intermediate if formed is not stable. Electronically, Bu_3P being an alkyl phosphine, is a good σ donor while CO is a poor σ donor but a good π acceptor ligand. The hydrogen is relatively acidic in $HCo(CO)_4$ while it has more hydridic character in $HCo(CO)_3PBu_3$ and consequently the former has lesser preference for Markownikoff type of addition to the alkene. So the primary Co–alkyl complex is also electronically preferred over the secondary alkyl.

CHAPTER 14

14.1. For the rhodium catalyst, oxidative addition of MeI is slow and is the rate determining step. Oxidative addition is much more facile in electron rich anionic complexes compared to neutral complexes. Hence the rate of the reaction is higher when the anionic complex is used.

14.2. The actual active catalyst is *cis* $[Ir(CO)_2I_2]^-$.

14.3. (i) It is less expensive than rhodium.

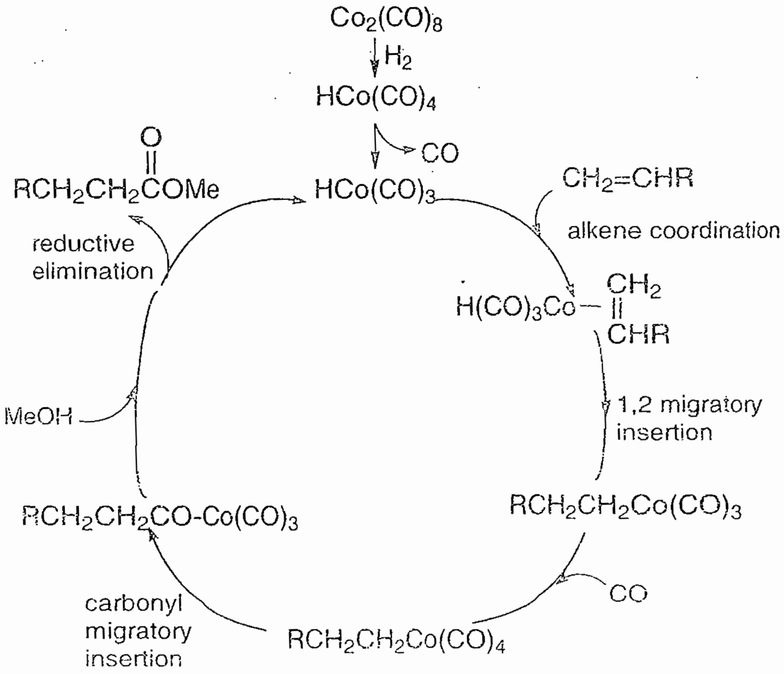
(ii) The process allows the use of less water in the reaction mixture. This reduces the number of drying columns, reduces the formation of byproducts and suppresses the water gas shift reaction.

(iii) A higher catalyst loading can be done.

(iv) Less propionic acid byproduct is produced as compared with the Monsanto process.

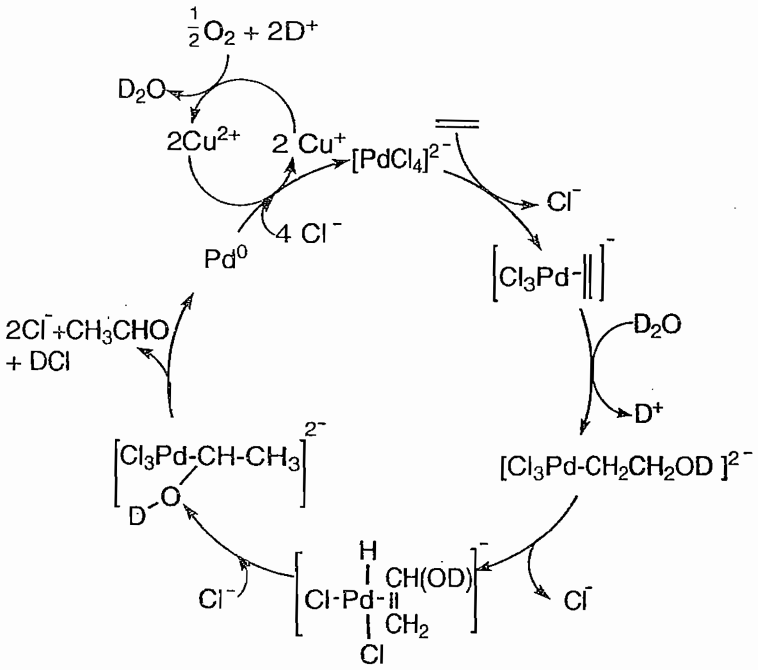
(v) The oxidative addition of MeI to the Ir complex is about 150 times faster than the same reaction with the Rh complex. The oxidative addition step is no longer the rate determining step as in the Rh complex.

14.4.



14.5.

(a)



(b) No. The fact that deuterium is not incorporated in the product molecule does not support falling off of the vinyl alcohol from the metal centre, as the free alcohol would then have tautomerised to $CH_3C(O)D$ (see the above scheme, step 3, for part (a). The β-elimination product does not leave the metal centre before rearrangement as shown in the scheme.

14.6. Similar to the formation of vinyl acetate when acetic acid is used as the medium with methanol as solvent; the product formed will be a vinyl ether $CH_2=CH(OMe)$. When a hydrocarbon is used as solvent, the chlorine itself ends up in the product resulting in vinyl chloride.

14.7. The role of the promoter is to facilitate the loss of I^- from the anionic catalyst at the second step of the reaction. So it has to be an iodine containing Lewis acid which can get converted to an anion readily or a metal complex able to add an I^- easily. GaI_3 and ZnI_2 can easily add iodide because of Lewis acidity and are therefore good promoters. Both $[Ru(CO)_3I_3]^-$ and $[Ru(CO)_2I_4]^{2-}$ are already coordinatively saturated and are anions themselves and therefore won't be able to abstract iodide. SiI_4 is not a Lewis acid which can expand its coordination sphere and LiI is a source of I^- and therefore will act not as a promoter but as a poison for the catalyst.

14.8. CH_3I is produced by the reaction of methylacetate with LiI, an iodide promoter.

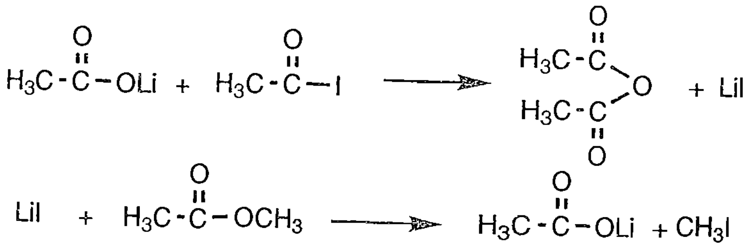
$$H_3C\text{-}\overset{\overset{\displaystyle O}{\|}}{C}\text{-}OCH_3 + LiI \longrightarrow CH_3I + H_3C\text{-}\overset{\overset{\displaystyle O}{\|}}{C}\text{-}OLi$$

14.9. The following modifications were made.

(i) Methyl acetate is used as reactant instead of methanol.

(ii) LiI is used as iodide promoter instead of HI.

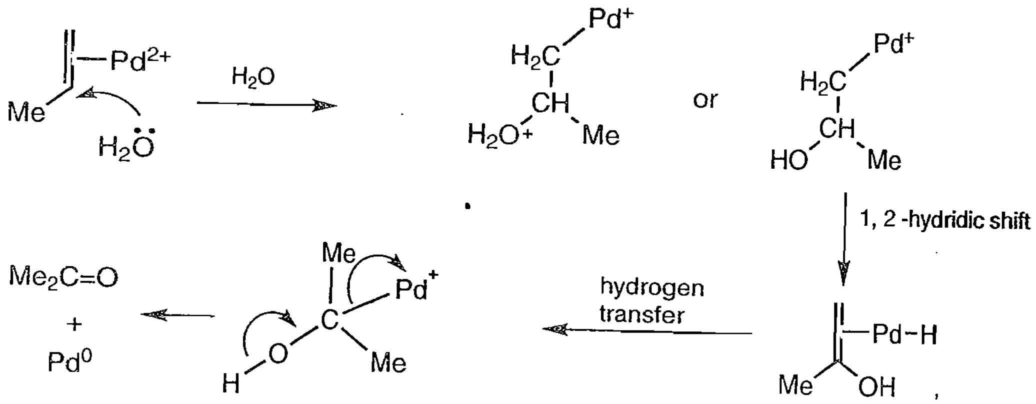
Acetic anhydride was produced by the following reactions.



$$H_3C-\overset{O}{\overset{\|}{C}}-OLi + H_3C-\overset{O}{\overset{\|}{C}}-I \longrightarrow (H_3C-\overset{O}{\overset{\|}{C}})_2O + LiI$$

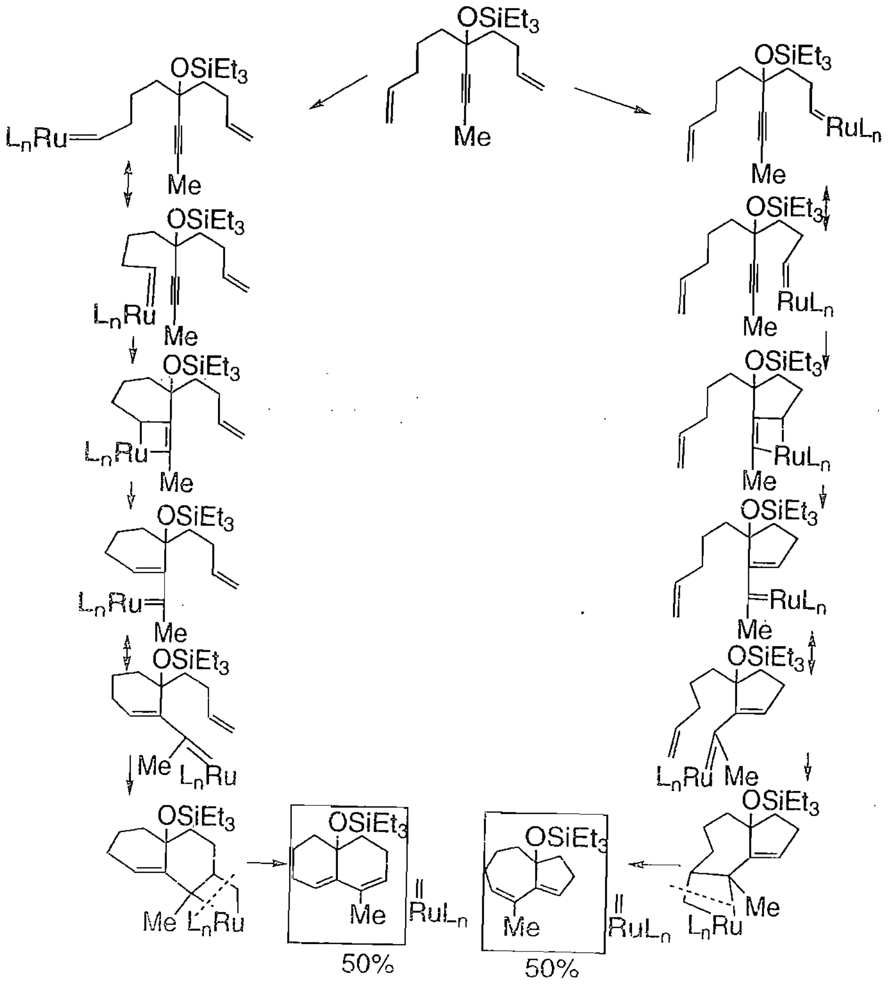
$$LiI + H_3C-\overset{O}{\overset{\|}{C}}-OCH_3 \longrightarrow H_3C-\overset{O}{\overset{\|}{C}}-OLi + CH_3I$$

14.10.

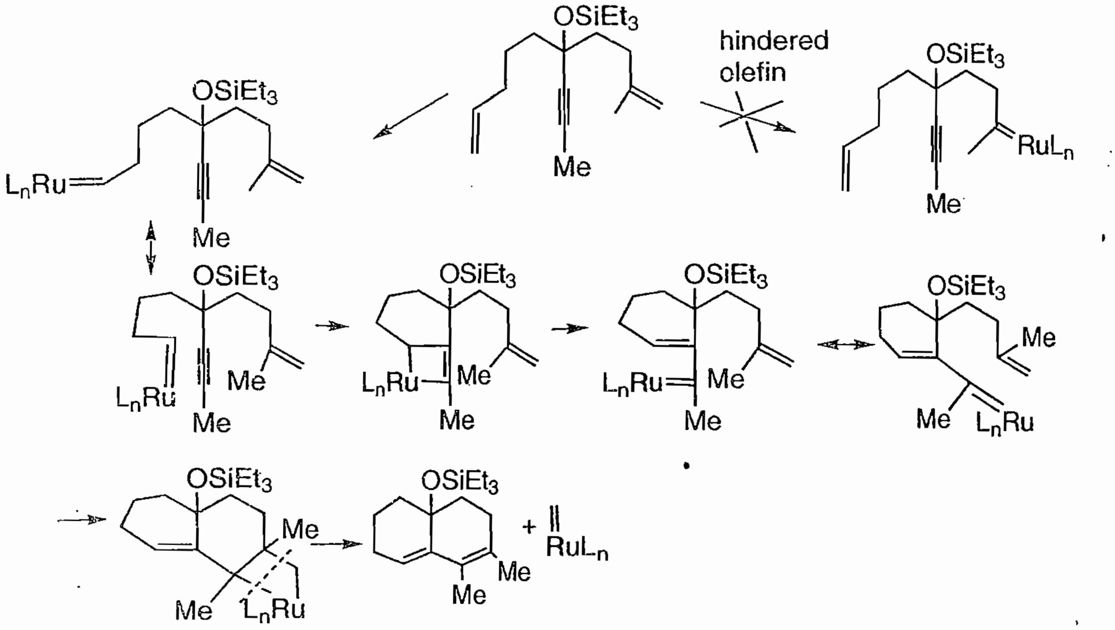


CHAPTER 15

15.1. (a)

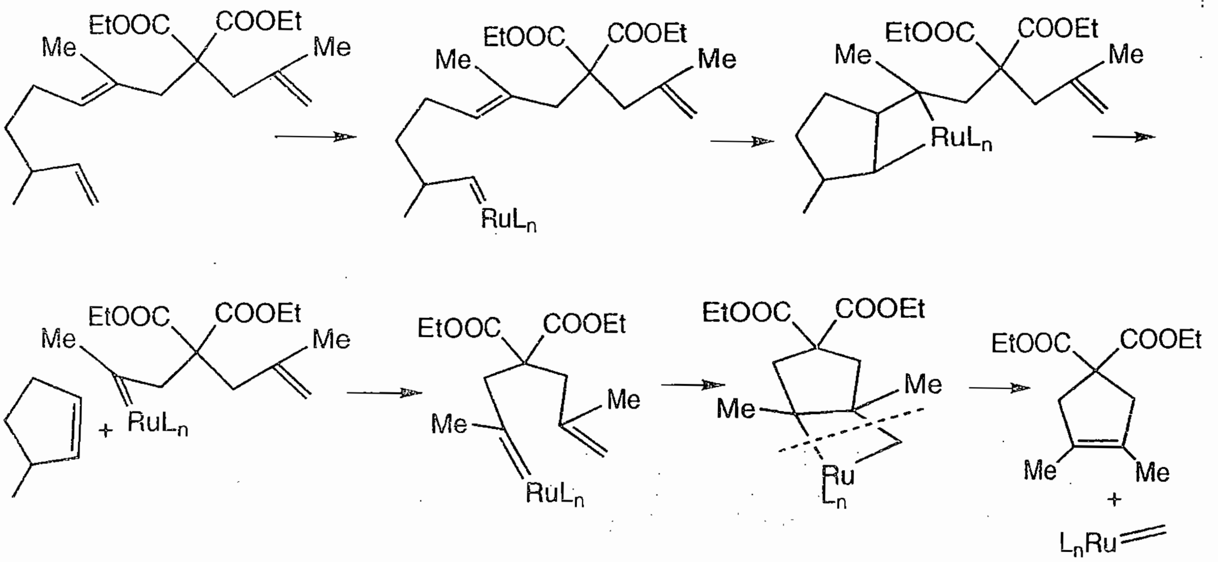


(b)



15.2.

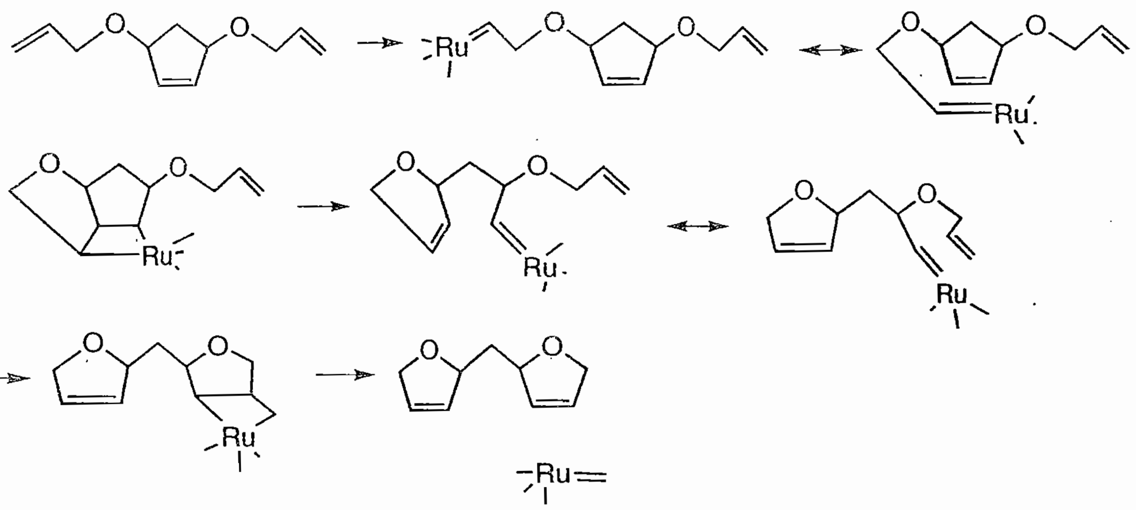
B



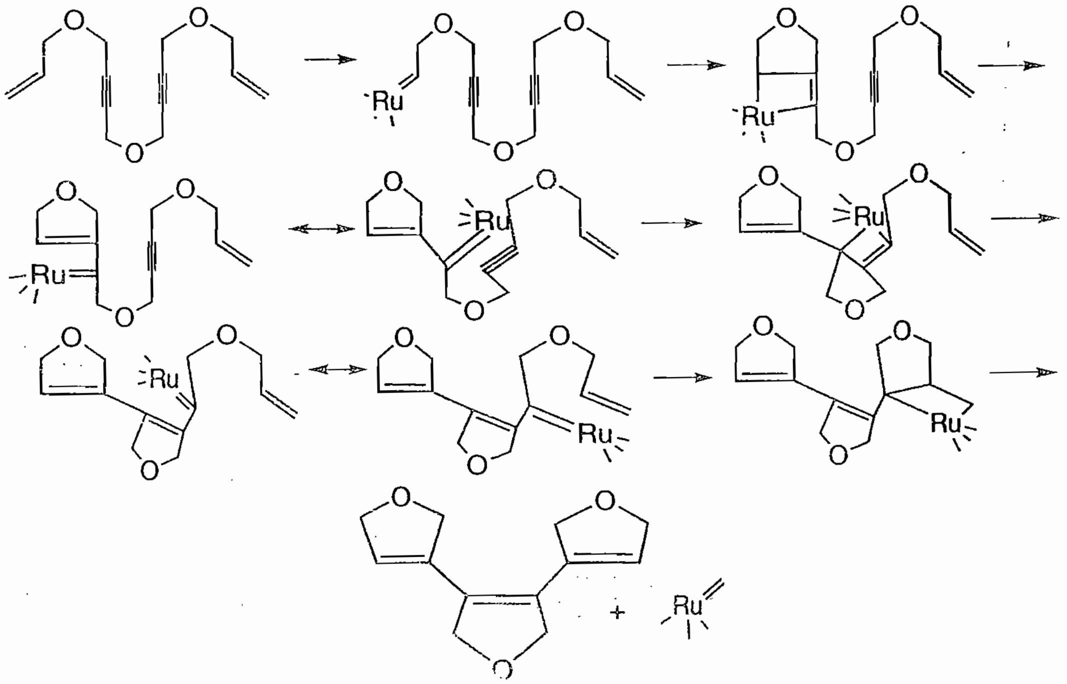
A does not react with Grubbs' I generation catalyst as there are no unhindered alkene units present in the molecule.

15.3. Ideally the mechanism can be written in each case and the product can be arrived at. However, an easier method may be to count the number of carbon atoms in the reactant and product. As all the compounds have terminal unhindered alkenes, the expected loss will be one ethylene for each reactant. So the correct product will have two carbon atoms less than the reactant. So the match becomes (b) – 1, (c) – 5 and (e) – 3. However, for (a) and (d), the number of carbons is the same in both the products. Therefore, the mechanism has to be worked out for one of them to assign the product.

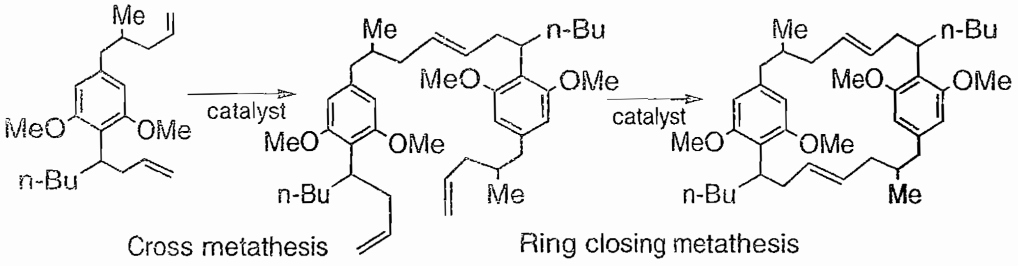
(a)


O
Ru

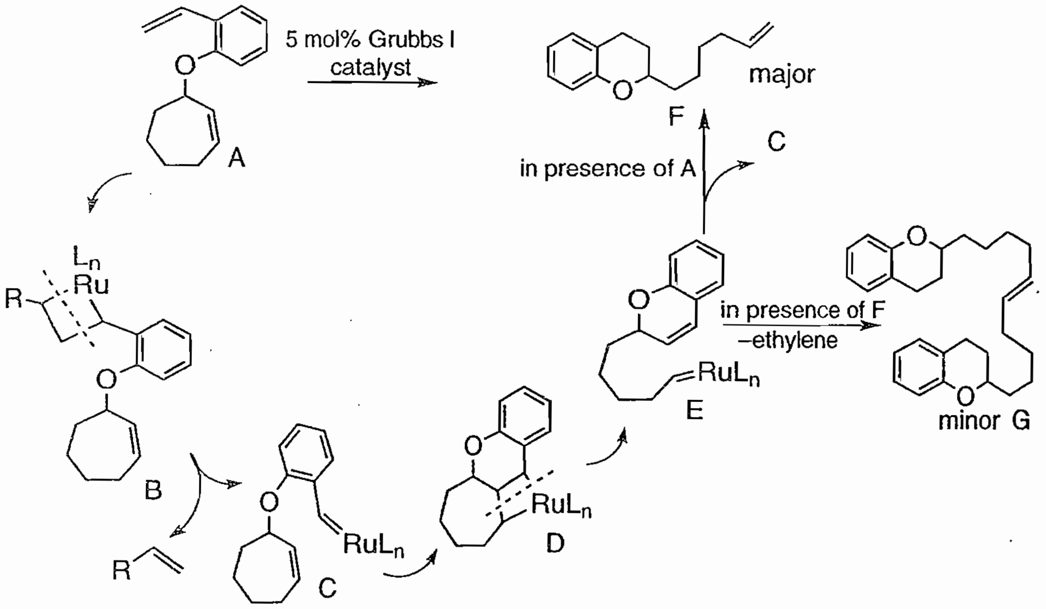
15.4.


O
Ru
+

15.5.


Me
MeO
OMe
n-Bu
catalyst
Cross metathesis
Ring closing metathesis

15.6.



15.7. Product (a) is the result of RCM of the alkene and alkyne moieties present on the starting material. The role of the metal carbene is only catalytic in this reaction. Product (a) undergoes a stoichiometric metathesis of the side arm alkene moiety with equivalent amount of tungsten carbene resulting in product (b) along with $(CO)_5W{=}CH(Me)$ as the side product.

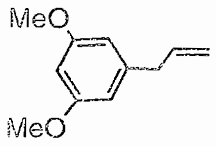
15.8. For Grubbs I and II, the dissociation of a PCy_3 unit from the catalyst is the first step towards the formation of the active catalyst. CuCl is a phosphine scavenger and will thus facilitate this process and increase the efficiency of the catalyst. However, this will not have any effect on the phosphine-free Schrock's molybdenum catalyst or the Grubbs–Hoveyda catalyst.

15.9. The Grubbs' catalyst is not tolerant to amines and thioethers while Schrock's catalyst is not tolerant to aldehydes, alcohols and acids. Also, highly sterically hindered dienes undergo RCM only in the presence of Schrock's catalyst. Based on these facts for (a), (c) and (d), the catalyst is Schrock's molybdenum catalyst while for (b) it is Grubbs II catalyst.

CHAPTER 16

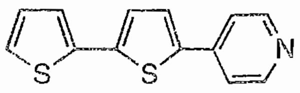
16.1.

(a)



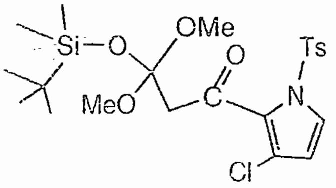
Suzuki coupling

(b)



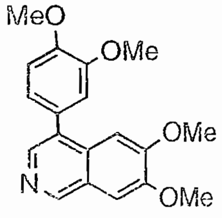
Kumada coupling

(c)



Negishi coupling

(d)



Kumada coupling

16.2.

(i) For Stille coupling, the alkyl halide used should not have β-hydrogens as it wi initiate β-hydrogen elimination instead of reductive elimination.

(ii) No activation of the oragnostannyl group is required in Stille coupling an therefore no base is required, while an activation using a base is required fc boronic acids.

(iii) The side product formed in Suzuki coupling (borates) is not toxic while it is tox in Stille coupling (organostannanes) and therefore the former is preferred fc the synthesis of pharmaceutical products.

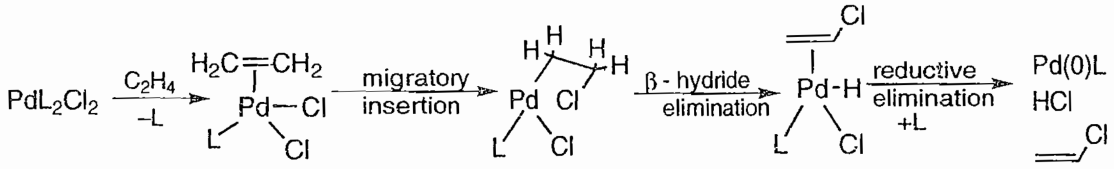
(iv) Separation of the organic product from organostannanes is difficult in Stil coupling while the borate side products formed in Suzuki coupling can be easi separated from the organic product.

16.3. The C–C bond forming reaction is a migratory insertion in Heck coupling and not reductive elimination as in others. The transmetallation step is not present in Hec coupling while this is a major step in other Pd catalysed coupling reactions.

16.4. Transmetallation from tetracoordinate, tetralkyl substituted tin to palladiu is possible while transmetallation from silicon to palladium occurs only fro hypervalent pentacoordinate silicon.

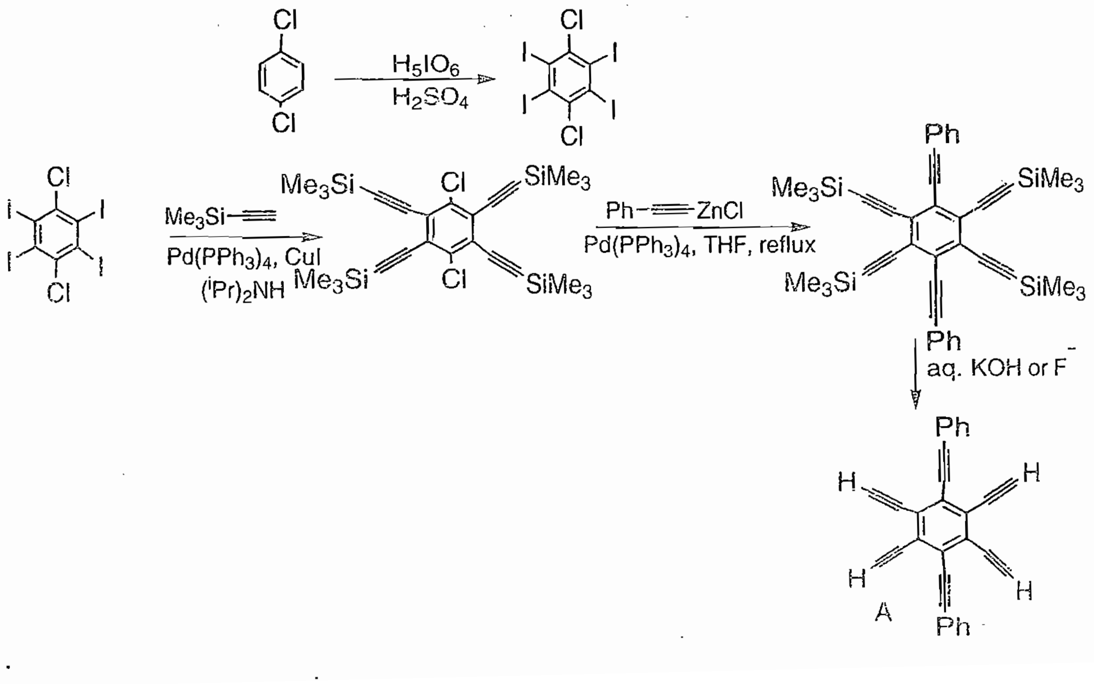
16.5. Kumada, Negishi and Stille coupling do not require a base for the coupling reactio to occur.

16.6.



L = R_3P

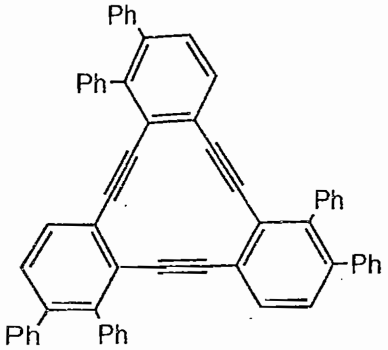
16.7.



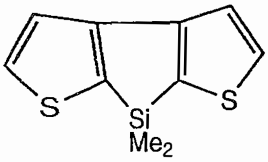
Compound (b) can be prepared in a similar way by carrying out Sonogashira coupling with phenyl acetylene followed by Negishi coupling with trimethylsilyl acetylene and final removal of the silyl groups.

16.8.

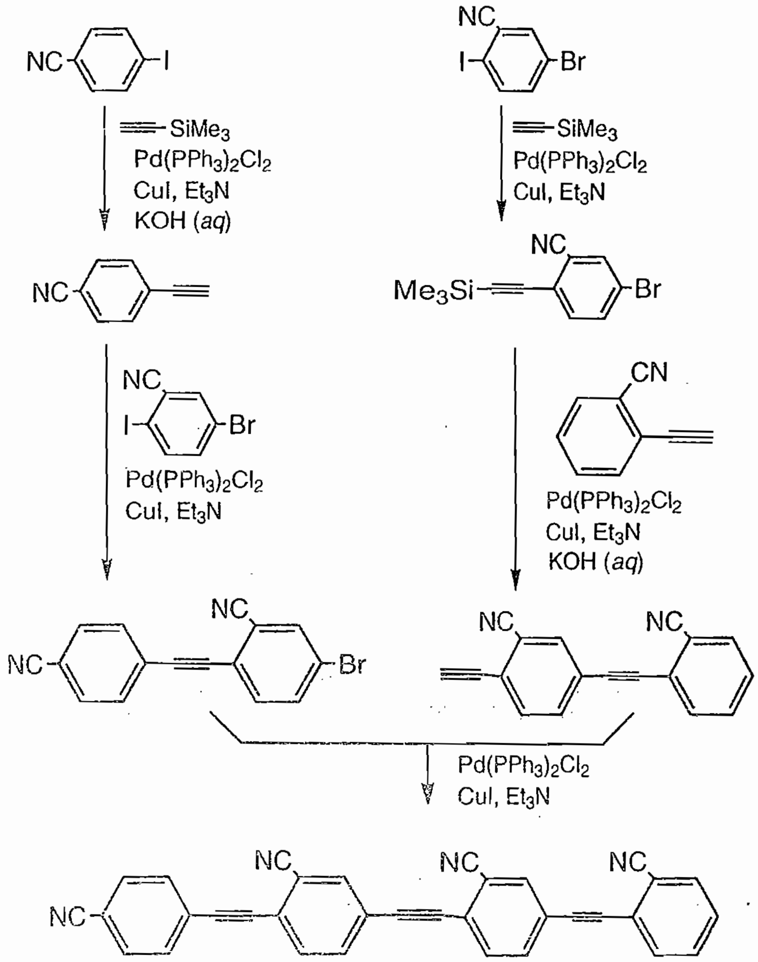
(a)



(b)



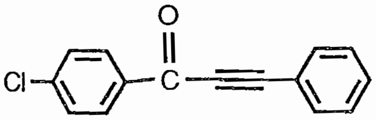
16.9.



16.10. (a) Suzuki coupling (b) Kumada coupling (c) Sonogashira coupling
(d) Suzuki followed by Heck coupling (e) Buchwald–Hartwig coupling
(f) Negishi followed by Heck coupling *(Note that rings formed in Heck reactions are five membered when the double bond is five atoms away from palladium and six membered when the double bond is six atoms away from palladium).*

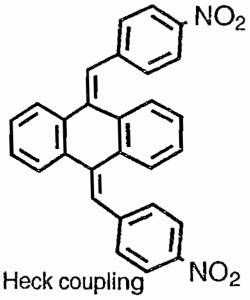
16.11.

(a)



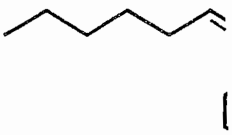
Stille coupling

(b)



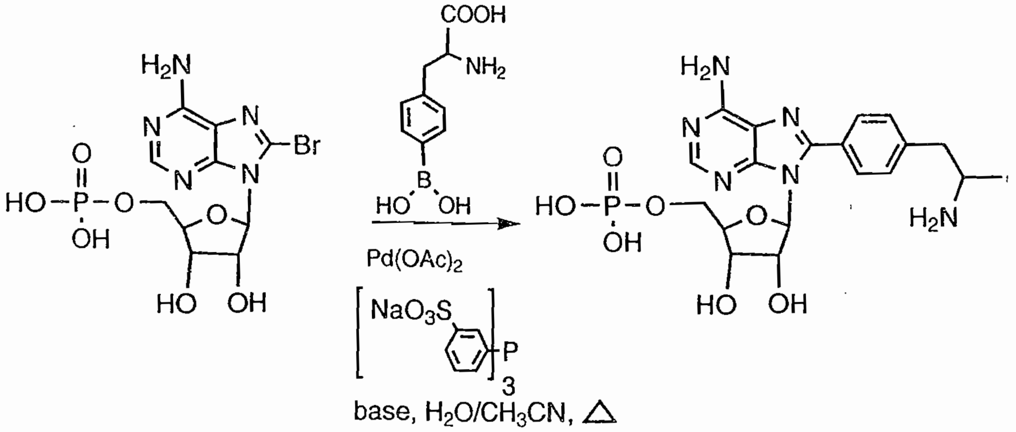
Heck coupling

(c)

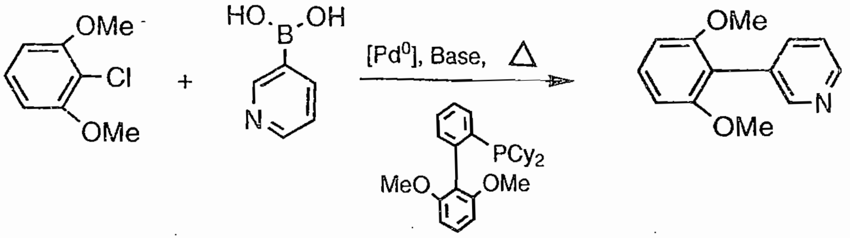


Hiyama Coupl

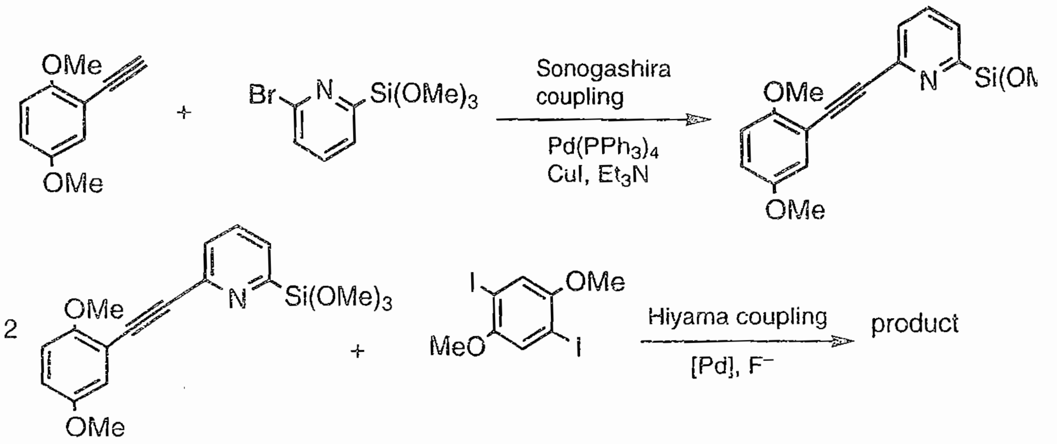
16.12. (a)



(b)



16.13.



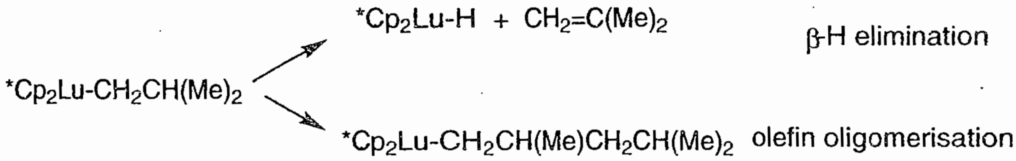
CHAPTER 17

17.1. (i) Green's pathway requires a formal oxidation step at the metal centre whereas Cossee's pathway does not.

(ii) Cossee's mechanism is operating here. Lu(III) cannot undergo 2e oxidation reaction and hence Green's mechanism does not take place. β-hydride elimination and olefin oligomerisation are the competing side reactions.

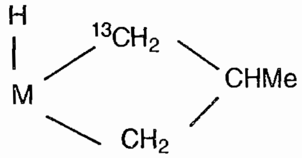
Olefin oligomerisation

$$*Cp_2Lu\text{-}Me + CH_2{=}CHMe \longrightarrow *Cp_2Lu\text{-}CH_2CH(Me)_2$$

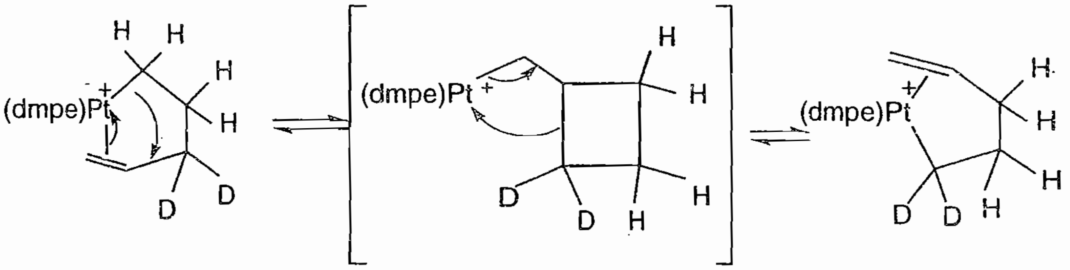


17.2.

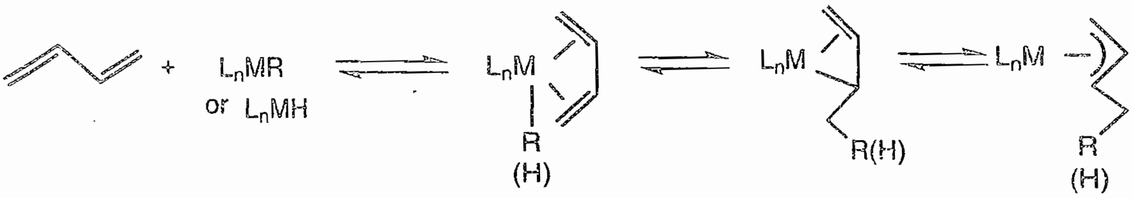
(a) $M\text{-}CH_2\text{-}CH\,(^{13}CH_3)(CH_3)$ (b)



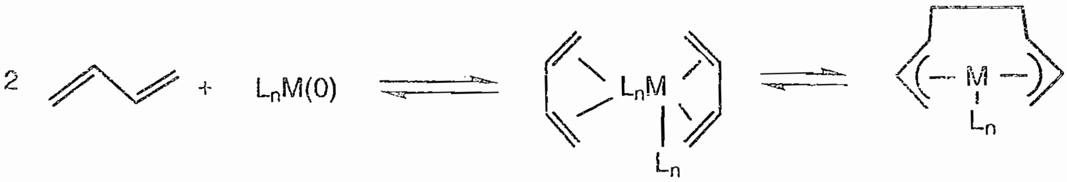
17.3.



17.4.

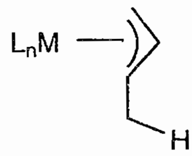


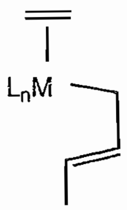
The equilibrium between η^1 and η^3 depends upon the nature of other ligands present on the metal. It is major factor in deciding the course of the reaction.

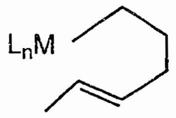


Ni(0) and Pd(0) reductively dimerise butadiene to the corresponding η^3 complex.

17.5.

A = 

B = 

C = 

D = β hydride elimination

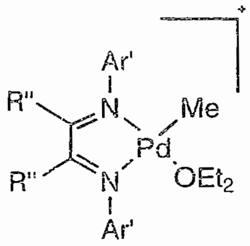
17.6. (a) High cost (due to the high cost of $AlMe_3$ from which it is prepared), requirement of large amounts (typically Al:Zr ratio of 10^3–10^4 M is used), high residual content of catalyst residues (alumina) in the final product and intrinsic danger associated with the use of extremely pyrophoric $AlMe_3$.

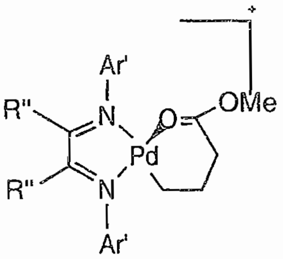
(b) MAO surrogates have been used, for example MAO/$Al(^iBu)_3$. To save the amount of cocatalyst, generally a small amount of AlR_3 [such as $Al(^iBu)_3$ and $AlEt_3$] is added to the reaction system. This helps to scavenge the impurities and also to alkylate the metallocene dichloride.

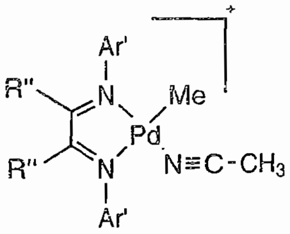
17.7.

Differences	Metallocene	FI catalyst
Geometry around active site	tetrahedral	octahedral
M–L bonds	M–C and M– halogen	M–N, M–O and M–halogen
Effect of catalyst on stereochemistry of α-olefin polymerisation	catalyst symmetry controls stereochemistry (site control)	no control on stereochemistry by the catalyst (chain end control)
Similarities		
Orientation of halogens	*cis*	*cis*
Oxidation state	+4	+4
Mode of activation by cocatalyst	similar	similar

17.8. Since one of the monomers is polar, early TM based catalysts cannot be used. Ideally the Pd bisimine catalysts of the type shown below will be suitable for polymerisation As chain walking is bound to occur with this catalyst, there will be significant amoun of branching and the density of the polymer will be very low.

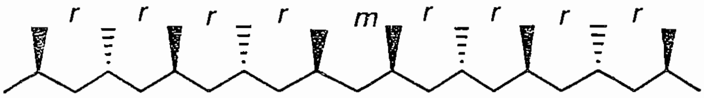






17.9. From the fact that the major peak corresponds to [*rrrr*], the tactictiy of the polyme can be assigned as syndiotactic. To assign, if the mechanism has proceeded by control or chain end control mechanism, the expected pentad errors in the po chain for syndiotactic polypropylene can be assigned as follows.

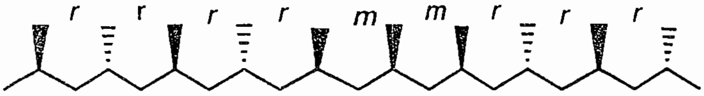
chain-end control mechanism (syndiotactic)



errors expected

rrrm *rrmr*

site control mechanism (syndiotactic)



errors expected

rrrm *rrmm* *rmmr*

As the minor peaks in the spectra are assigned as *rmrr* (*rrmr*) and *rrrm* (*mrrr*), the mechanism of polymerisation is of chain end control.

17.10. Both are syndiotactic since the [*rrrr*] values are 90% and 91%.

(a) The microstructure analysis indicates that polymer A has as main errors [*rmrr*] and [*rrrm*] (ignoring pentads having ≤1% content). Hence it must have been formed by chain end control mechanism.

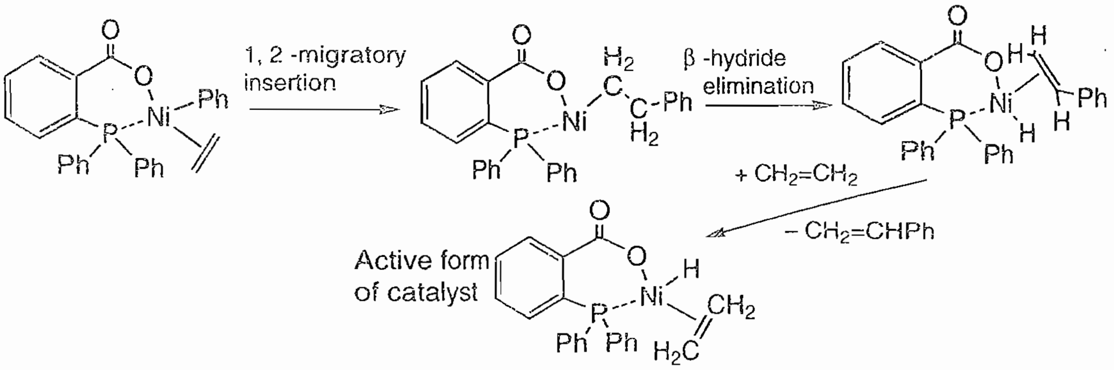
(b) For polymer B there are three major errors [*mmrr*], [*rrrm*] and [*rmmr*]. These are typical defects of site control mechanism (having *m* triads). Therefore the polymer must have been formed by site control mechanism.

(c) As B has been found to form by site control mechanism, it must be the polymer prepared using the metallocene catalyst. Since the polymer is syndiotactic, the metallocene catalyst used must have had C_s symmetry.

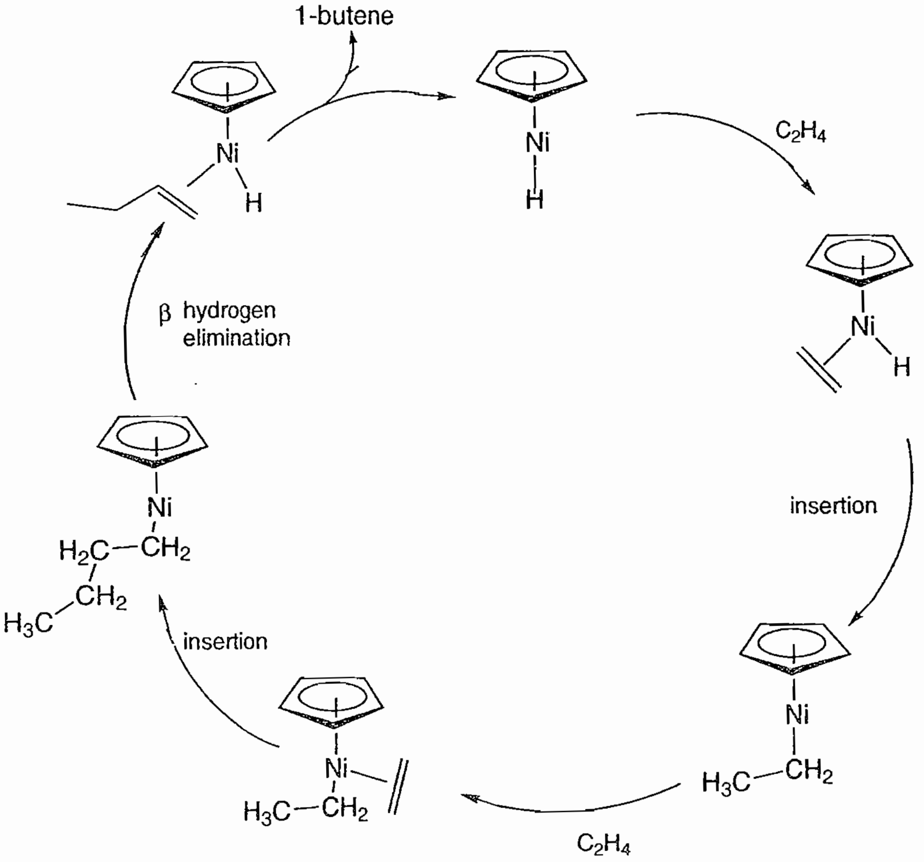
17.11.

Catalyst used	**Reactant**	**Product**
Cp_2ZrCl_2	Ethylene	no product
$Cp_2ZrCl_2/R_3Al/H_2O$	Ethylene	polyethylene
Cp_2ZrCl_2/MAO/No water	Ethylene	polyethylene
*Cp_2ZrCl_2/MAO	Propylene	polypropylene
*CpCpZrCl(Me)	Propylene	aPP
$CpTiCl_3$	Styrene	Syndiotactic polystyrene

17.12.

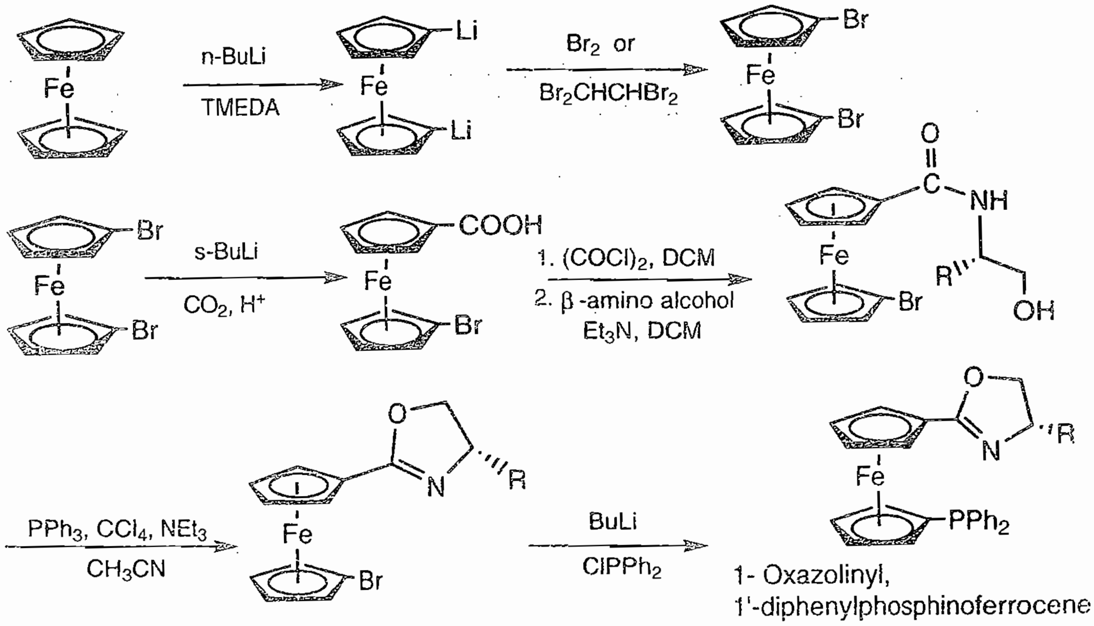


17.13.



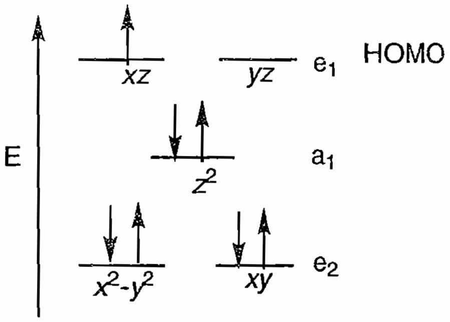
CHAPTER 18

18.1.



1- Oxazolinyl,
1'-diphenylphosphinoferrocene

18.2.



18.3. The valence orbitals of staggered metallocenes based on the ferrocene MO picture are e_{2g}, a_{1g} and e_{1g*}. The magnetic moments indicate the number of unpaired electrons in each. For Cp_2Mn, the magnetic moment corresponds to 5 unpaired electrons. Similarly the rest can be determined.

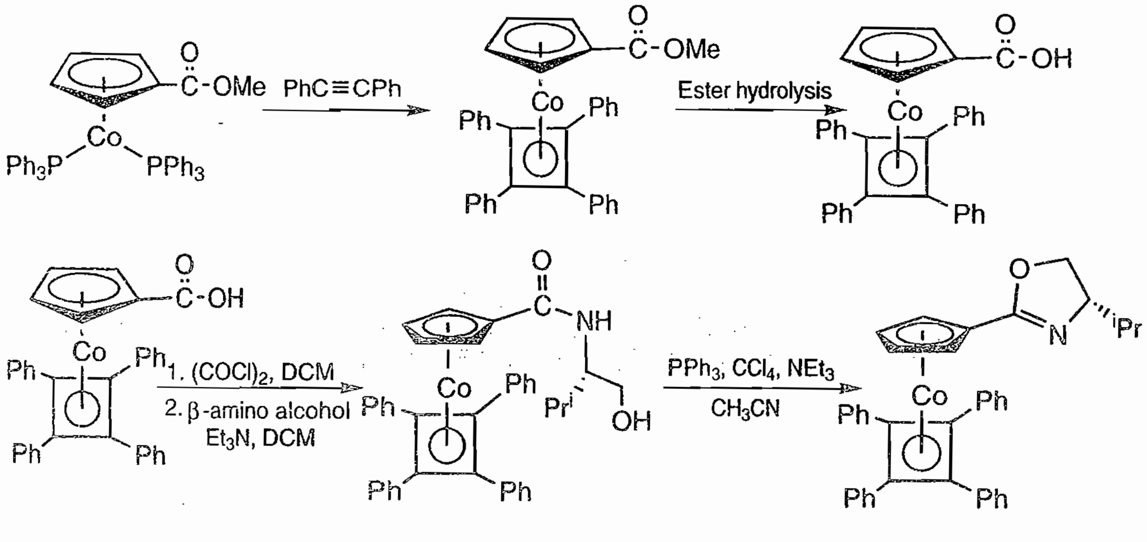
$Cp_2Mn = (e_{2g})^2, (a_{1g})^1\ (e_{1g*})^2$

$Cp_2V\ = (e_{2g})^2, (a_{1g})^1\ (e_{1g*})^0$

$Cp_2Co = (e_{2g})^4, (a_{1g})^2\ (e_{1g*})^1$

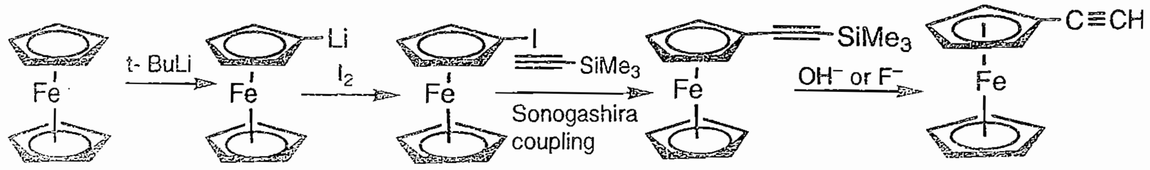
$Cp_2Ni\ = (e_{2g})^4, (a_{1g})^2\ (e_{1g*})^2$

18.4.

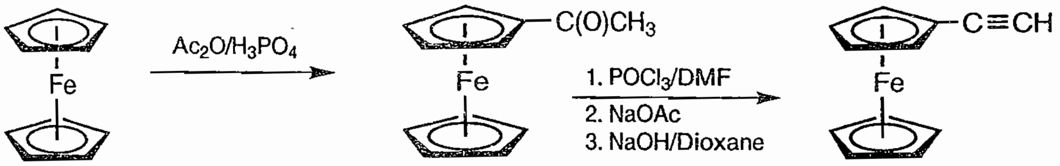


Note for the first step: See chapter 7 for synthesis of η^4-cyclobutadiene complexes.

18.5. (a) Via cross coupling reaction:

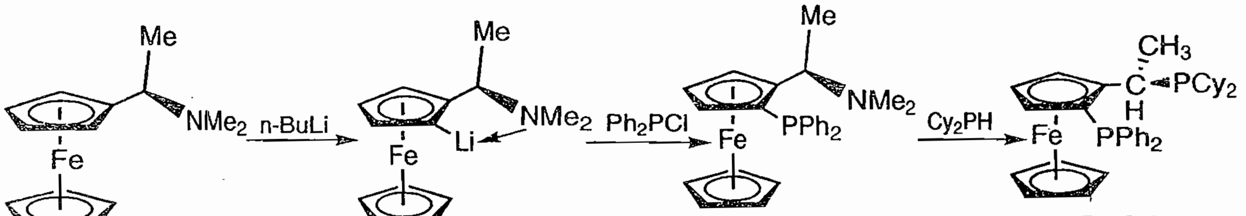


(b) Via acetyl ferrocene:



The procedure based on acetylferrocene is better because it involves less number of steps and does not require monolithiation which is cumbersome. Also, there is no requirement of an expensive palladium catalyst.

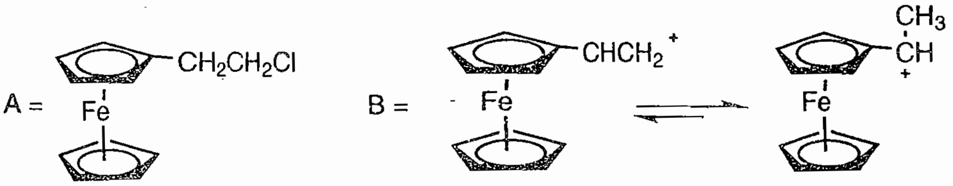
18.6.



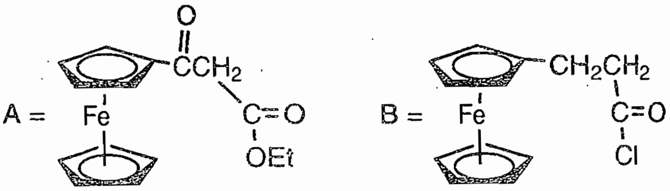
JOSIPHOS

18.7. It has eclipsed conformation because of the presence of intermolecular hydrogen bonding between two carboxylic acid molecules forming a dimer.

18.8.

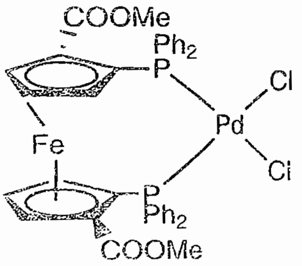


18.9.



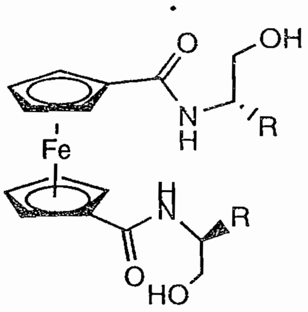
18.10. The electrophilic substitution will be more facile on ferrocene. Since Cp is a poor π-acceptor ligand than CO, the electron density on Cp will be less in η^5-$CpMn(CO)_3$.

18.11. Only planar chirality is observed.

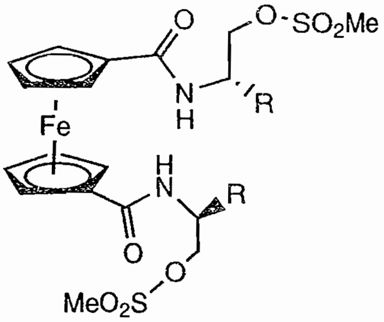


18.12.

A



B

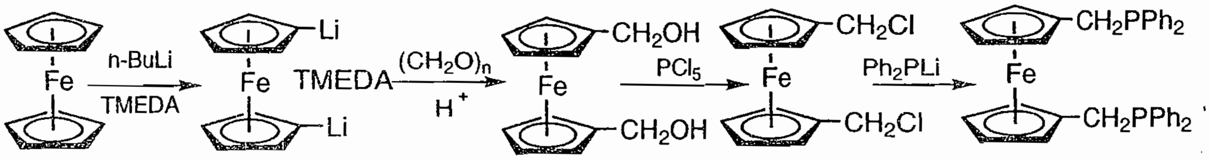


18.13. (a) Planar chiral: R_p (shortest path from I to CHO) (b) Not planar chiral

(c) Planar chiral: S_p (d) Planar chiral: R_p

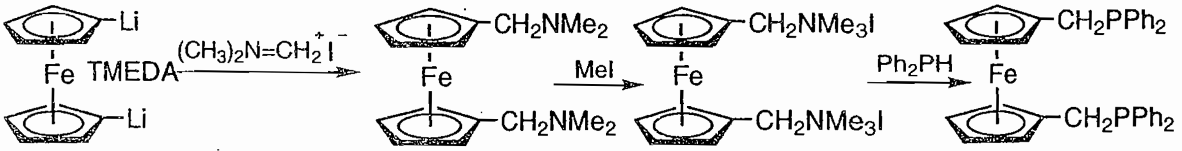
18.14.

Method 1



$|\ \mathrm{Ph_2PH} + n\text{-BuLi} \longrightarrow \mathrm{Ph_2PLi}\ |$

Method 2

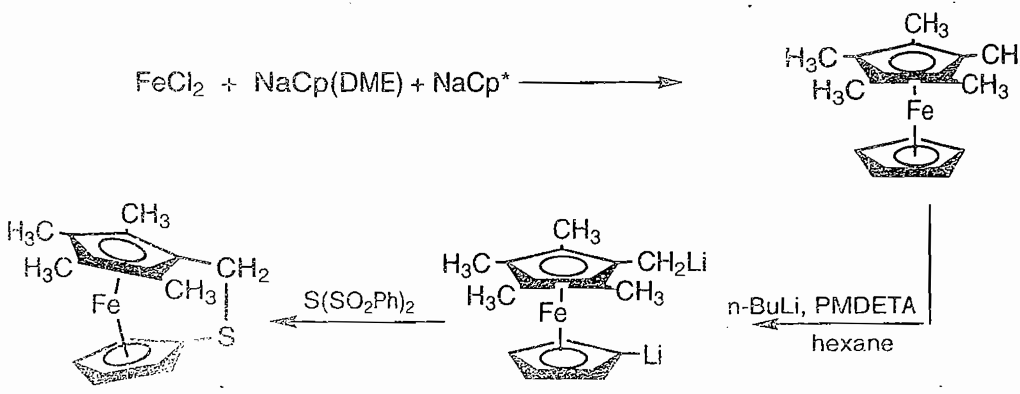


CHAPTER 19

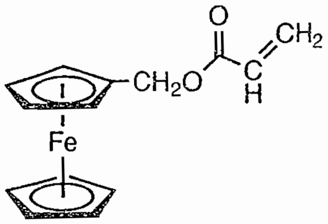
19.1. (c) < (a) < (b)

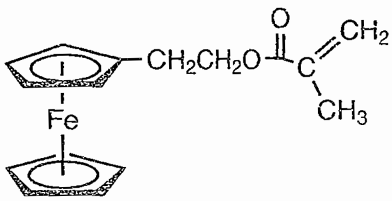
The metal will be close to the radical centre in (c) and so the electron transfer from the metal to the radical centre occurs. Thus, the chain termination process is fast. The ferrocenylmethyl cation can form in (a) which can result in chain breaking. B should be stable and so should have a higher molecular weight.

19.2. Only compound (b) will undergo ROP as it has a significantly high tilt angle above 15°.



19.3. We require a monomer which has the propagating radical centre away from and out of conjugation with the iron centre. So an appropriate group should be inserted between ferrocene and the vinyl group, for example the following compounds should be ideal for this.

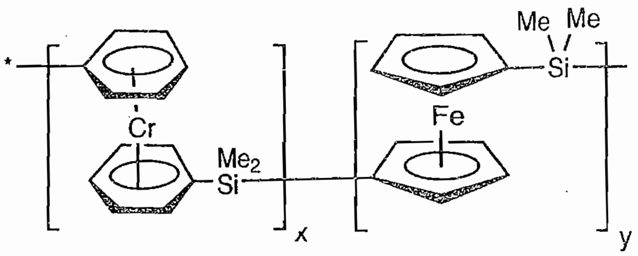




19.4. (a) The resulting polymeric product lacks regioregularity since it contains three different silicon environments, Cp^H–Si–Cp^H, Cp^{Me}–Si–Cp^{Me} and Cp^H–Si–Cp^{Me} and only single iron environment, Cp^H–Fe–Cp^{Me}. Because of this we expect it to be amorphous.

(b) The product is crystalline because of its highly region-regular character. With the result the compound should be completely insoluble in solvents like dichloromethane, benzene, aniline, DMF.

19.5.

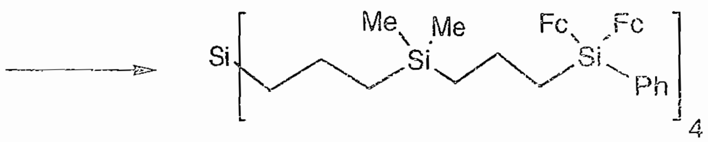


19.6. This failure occurs due to the difficulty in achieving both high purity levels of the reactive organometallic species and precise stoichiometry between the monomers. Such polycondensation reactions, therefore, usually do not proceed to near completion. This causes the formation of low molecular weight macromolecular chains only.

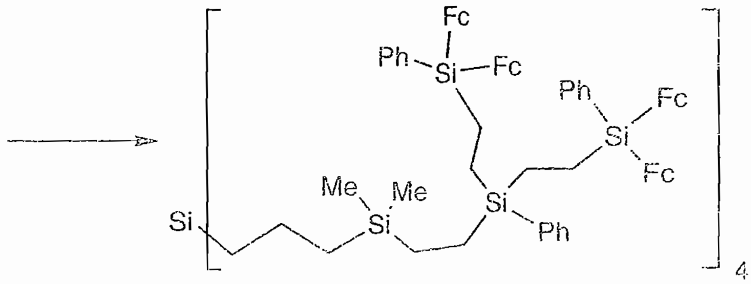
19.7. The role of $^nBu_3P$ is to abstract one equivalent of S (desulphurisation reaction) and it is eliminated as $^nBu_3P{=}S$. It is known to abstract the central S atom in the reactant.

19.8.

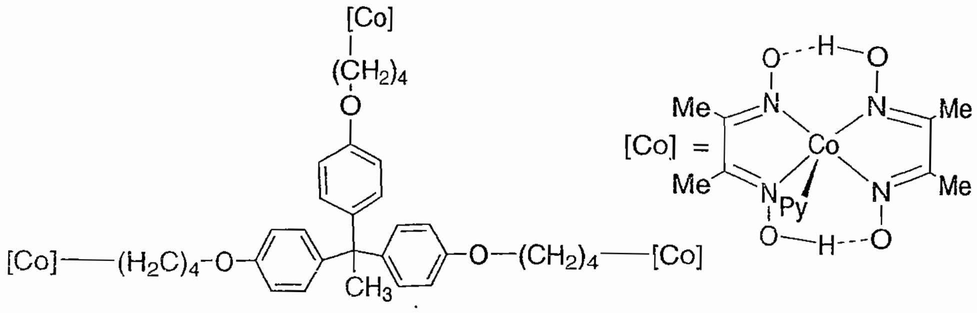
1



2

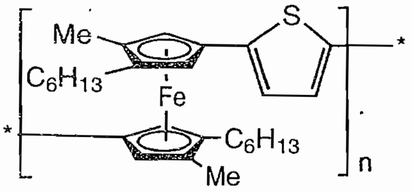


19.9.



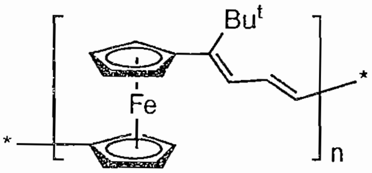
19.10.

(a)



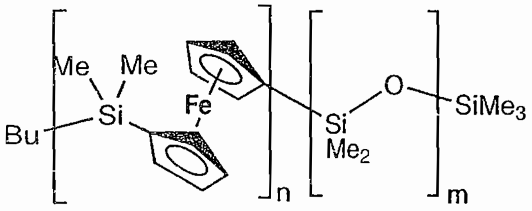
Condensation polymerisation

(b)



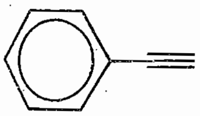
Ring opening metathesis polymerisation

(c)



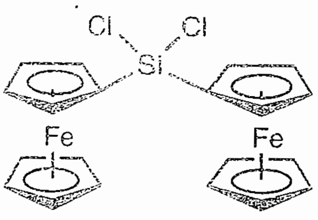
Anionic ring opening polymerisation

19.11. The polymerisation can be brought about by Sonogashira coupling. Additional reactant and reagents required are given below.

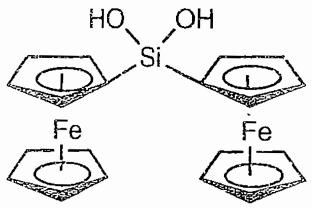


$PdCl_2(PPh_3)_2$ or similar palladium salts CuI Base

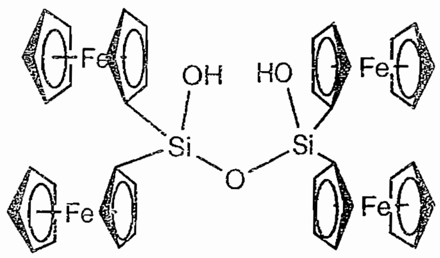
19.12. B and C combine to form the cyclosiloxane.



A



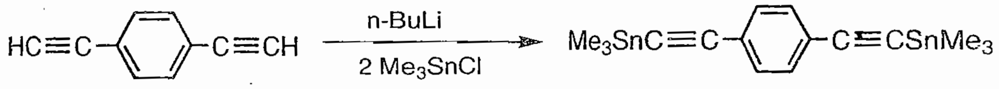
B

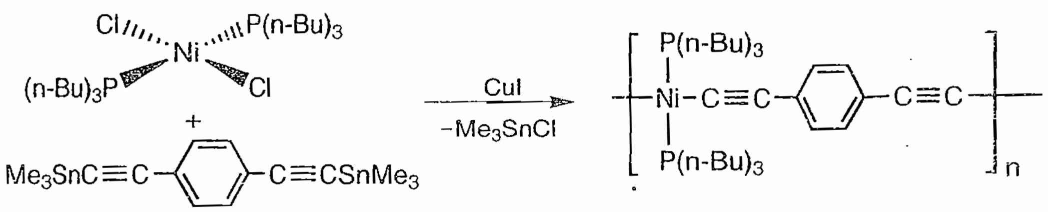


C

19.13. As ruthenium belongs to the second row, its ionic radius (2^+) will be larger than that of iron and hence the tilt angles of ruthenocenophanes will be higher than that of the analogous ferocenophanes. For example, the tilt angle of (a) (20.6°) is about 5.5° higher than that of the analogous ferrocenophane. Compounds (a) and (b) have been found to undergo thermal ring opening polymerisation. [Tilt angle of (b) has been reported as 29.6 while that of (c) is 14.8.]

19.14. Since dihalo nickel compounds undergo decomposition in amine solvents, a method which does not involve amine solvents has to be used. The best method is by converting the 1,4-dialkynylbenzene to its bis-trimethylstannylated derivative followed by reaction with the nickel halide complex.





The two chlorine atoms on the nickel complex can also be substituted by acetylene units and then reacted directly with the 1,4-dialkynylbenzene.

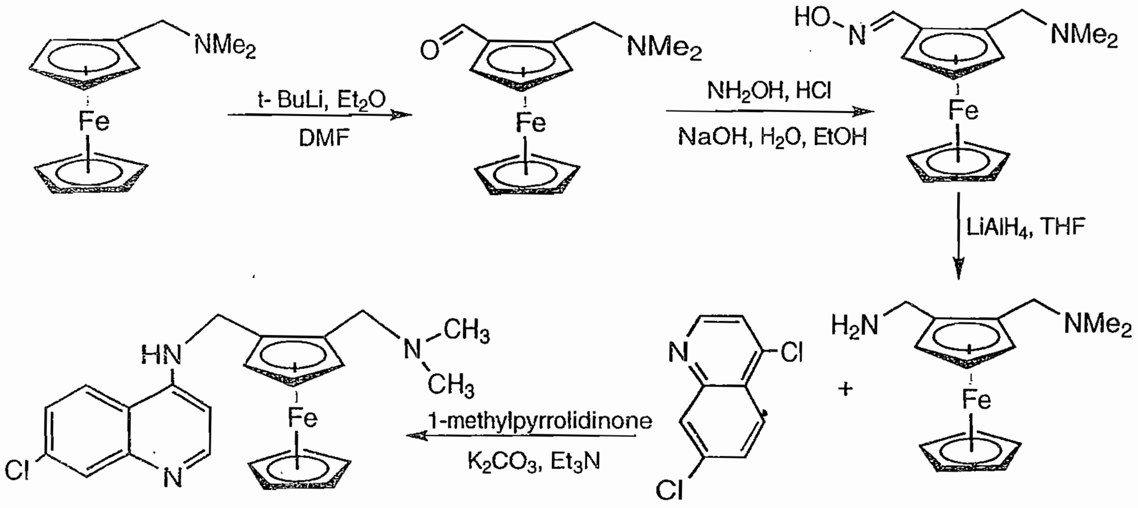
CHAPTER 20

20.1. Corrin is similar to porphyrin but is missing one methyne bridge (=CH−) between one pair of pyrrole rings and has only one NH group at the centre. This imparts flexibility to the macrocycle.

20.2. Cyanocobalamin was formed in the early days in a very facile manner when coenzyme B_{12} (AdoCbl) exposed to light got converted to hydroxycobalamin and the latter exchanged hydroxy groups for cyanide ions present in the charcoal column on which it was purified. So, hydroxycobalamin will be an excellent candidate as an antidote for cyanide poisoning. The product of the reaction (Vit B_{12}) is not only harmless but also beneficial. Hydroxycobalamin will be better than AdoCobl as the latter will require photochemical decomposition and its action will not be instantaneous which is very much required in case of cyanide poisoning.

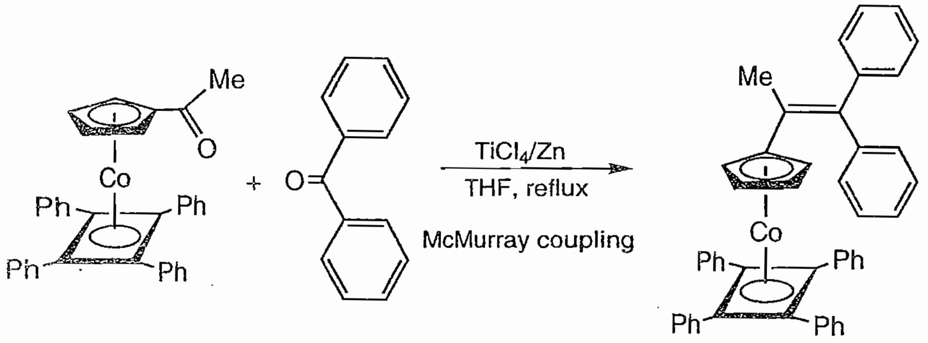
Recent studies carried out on dogs have confirmed the use of hydroxycobalamin as an effective antidote for cyanide poisoning reducing mortality rate very significantly.

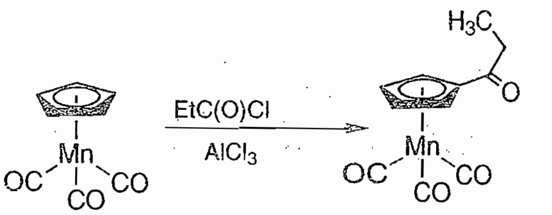
20.3.

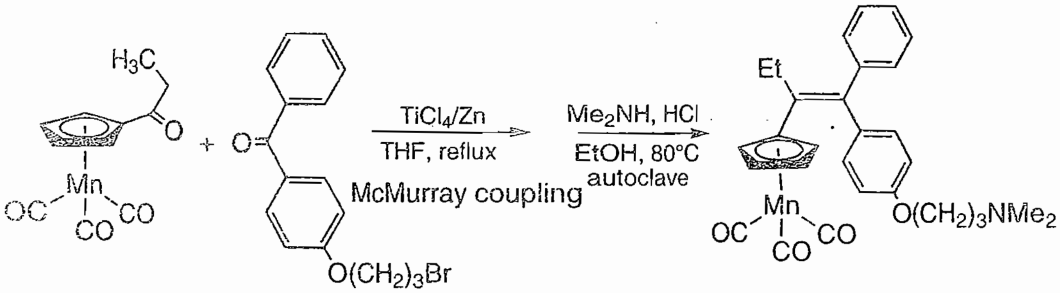


Ferroquine

20.4.







Or, it can also be prepared by direct McMurray coupling of the half-sandwich compound derived ketone with a benzophenone derivative having $O(CH_2)_3NMe_2$.

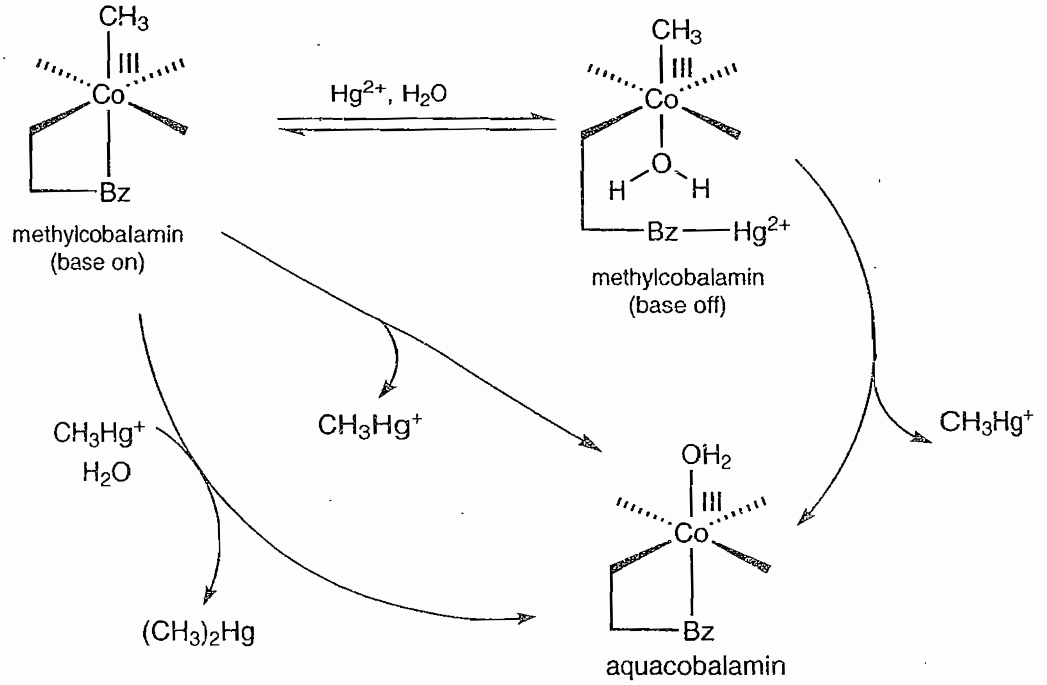
20.5. Thioquinone methides are not that important in biology because oxidation of aromatic thiols immediately leads to dimerisation or reaction with other thiols, thiolates or molecular oxygen. So, one would expect the thio congeners to be non-cytotoxic.

20.6. These values show that despite the presence of the bulkier ligand (Cp*) and the phosphorus containing η^5 ligand, the complexes are still recognised by the two forms of ER and the α form seems to be less able to accommodate them.

20.7. These are named estrogen response element (ERE) and activation protein 1 (AP1).

20.8. In all, there are seven amide groups present; C_2, C_7 and C_{18} bear acetamide (CH_2CONH_2) and C_3, C_8 and C_{13} bear propionamide ($CH_2CH_2CONH_2$) groups. The C_{17} atom is bonded to an N-substituted propionamide of which the $C^{2'}$ is connected to an unusual ribonucleotide in which the base unit is 5,6-dimethylbenzimidazole.

20.9.



20.10. *B_{12r} and B_{12s}*: 1e and 2e reduction product of the coenzyme B_{12} (r stands for reduced species and s stands for super reduced species).

Cofactor and prosthetic group: A cofactor is a non-protein chemical compound that is bound (either tightly or loosely) to a protein and is required for the protein's biological activity. The proteins are commonly enzymes and therefore cofactors can be considered 'helper molecules/ions' that assist in biochemical transformations.

With enzymes, cofactors are often further classified depending on how tightly they bind to the protein. For example, loosely bound cofactors are termed coenzymes and tightly bound cofactors are termed as prosthetic groups. The latter may be lipids, carbohydrates, metal ions (such as iron in hemoglobin), or inorganic groups such as phosphates.

Apoenzyme and holoenzyme: An inactive enzyme without the cofactor is called an apoenzyme, while the complete enzyme with cofactor is the holoenzyme.

APPENDIX
2

Quick Revision Questions

Fill in the Blanks

Chapters 1–5

1. Among $Fe(CO)_4C_2H_4$ and $Fe(CO)_4C_2F_4$, __________ will undergo a more facile electrophilic addition reaction.

2. The P–Cr bond in $(PhO)_3PCr(CO)_5$ is __________ in comparison to the P–Cr bond in $Ph_3PCr(CO)_5$ and the π acidity of $(PhO)_3P$ is __________ than that of Ph_3P.

3. The isoelectronic neutral linear nitrosyl complex for η^5-CpCu(CO) among the first row transition metals is __________.

4. The longest N–N bond among the following, N_2, $(CO)_5Cr–N_2$ and $(CO)_5Cr–N_2–Cr(CO)_5$ will be in __________.

5. $Cp_2Fe_2(CO)_4$ exists in equilibrium in __________ different structures with the carbonyl ligands being terminal or bridging.

6. If $AlMe_3$ is added to $[Cp(CO)_2Fe]_2$, it will coordinate to the __________ carbonyl and the equilibrium will shift to the __________.

7. The total number of M–M bonds in $[\mu\text{-X-}\mu\text{-}CH_2(Os_3(CO)_{10}]^-$ is __________.

8. Consider the molecule η^5-$Cp_2Zr(H)CH_2CH_2CH_3$. The molecule has __________ valence electrons and the formal oxidation state of Zr is __________.

9. $PtCl_2(PPh_3)C_2H_4$ has __________ back bonding than $PtCl_2(PPh_3)C_2(CN)_4$.

10. Consider the back bonding in A = $PtCl_2$ (1,5-cyclooctadiene) and B = Pt(1,5-cyclooctadiene)$_2$. It is higher in __________.

11. *Trans* cyclooctene has more strain than the *cis* isomer. Therefore the one which will bind better with the metal will be the __________ isomer.

12. Consider the dissociation of a phosphine in a complex which has metal in the relatively high oxidation state and the metal is not electron rich. The weak donor phosphine will dissociate __________ than a strong donor phosphine.

13. In Zeise's salt, the alkene is bonded __________ to the metal-L coordination plane. This is to minimise the __________.

14. Alkynes are __________ donors than alkenes.

15. The carbon atoms of C_2F_4 in η^5-$CpRh(C_2H_4)(C_2F_4)$ are __________ to Rh than the carbon atoms in C_2H_4.

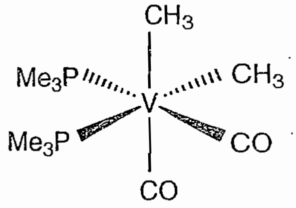
16. Josiphos is a ferrocene derived chiral bisphosphine and has __________ and __________ chirality.

17. N-heterocyclic carbenes are __________ at room temperature (in the absence of oxygen and moisture).

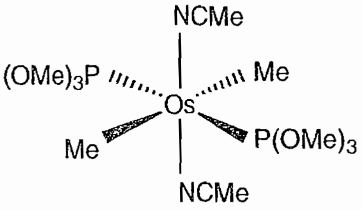
Chapters 6–10

18. Among the given compounds, the one that is most likely to undergo reductive elimination of ethane is __________.

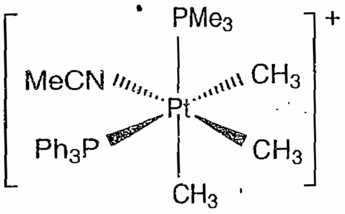
(a)



(b)



(c)



19. Among the following complexes, the one that is likely to oxidatively add dihydrogen the fastest is __________.

(a) $IrCl(CO)(PPh_3)_2$ (b) $RhCl(CO)(PPh_3)_2$ (c) $IrCl(CO)_2(PPh_3)$

20. The oxidative addition of Br_2 to η^5-$Cp(CO)_2RuMe$ forms __________.

21. There is a barrier to rotation around the M–C bond in the Schrock carbenes. Of the following molecules, the one which will have higher activation energy for the rotation is __________.

(a) $[Cp(CO)_2(PPh_3)W{=}CH_2]^+$ (b) $[Cp(CO)_2(PEt_3)W{=}CH_2]^+$

22. $Pd(PPh_3)_4$ + PhBr on oxidative addition forms __________.

23. Among $W(CO)_6$ and $IrCl(PPh_3)_2CO$, the one which will undergo faster exchange with ^{13}CO is __________.

24. The structure of the possible product/s when $IrCl(PMe_3)_3$ reacts oxidatively with Cl_2 is/are __________.

25. $W(CO)_5[C(OMe)Me]$ is __________ stable than $W(CO)_5(CMe_2)$.

26 Between the compounds $[(P(OMe)_3]_2Ir(CO)Cl$ and $(PMe_3)_2Rh(CO)Br$, the one which will undergo oxidative addition of dihydrogen the fastest will be __________.

27. $(PhNH_2)Cr(CO)_3$ is a __________ base than free aniline and $PhCOOH)Cr(CO)_3$ is a __________ acid than benzoic acid.

28. Tebbe's reagent is an example of a bridging carbene. In its reactions, it always forms a 16e active species with the formula __________.

29. $(CO)_5Cr{=}C(Me)(OMe)$ on reaction with RNH_2 forms __________.

30. The rate of alkene substitution by an incoming alkene in (acac)Rh(C_2H_4)$_2$ and η^5-CpRh(C_2H_4)$_2$ is 10^4/sec and 10^{-10}/sec respectively. The mechanism of substitution in these complexes is __________ and __________ respectively.

31. The substitution of CO by PPh_3 is __________ in $V(CO)_6$ than in $[V(CO)_6]^-$.

32. The substitution of CO by a phosphine (PMe_2Ph) in η^5-pentadienylMn$(CO)_3$ occurs by an associative mechanism. The same reaction in η^5-CpMn$(CO)_3$ is expected to be slower because __________.

33. In alkyl migratory reactions between two alkyl groups, the electron __________ alkyl group will migrate preferentially.

34. The $H_2Os_3(CO)_{10}$ cluster has __________ valence electrons and the complex is categorised as a __________ cluster.

35. Using Wade's rules, $Ru_6(CO)_{17}C$ is predicted to have a __________ structure.

36. $Os_7(CO)_{21}$ has a __________ structure.

37. The organic unit isolobal to d^9 ML_3 is __________.

Chapters 11–15

38. For the synthesis of $CH_3CH_2CH(Me)CH_2CHO$ via the hydroformylation reaction using $RhH(CO)(PPh_3)_3$ as catalyst, the alkene required is __________.

39. If in a particular reaction, 0.05 mol% of the catalyst is used and the yield of the product is 75%, then the TON is __________.

40. Conjugated dienes are hydrogenated __________ than the terminal alkenes when Wilkinson's catalyst is used.

41. The hydroformylation reaction of alkenes in the presence of a phosphine-modified cobalt catalyst works at lower pressure compared to $HCo(CO)_4$. This is because of the __________ of the modified catalyst.

42. Celanese catalyst for the conversion of methanol to acetic acid uses __________ as promoter.

43. Tennessee Eastman process is used to convert synthesis gas to __________ and the process uses __________ as iodide promoter.

44. Monsanto process for the production of acetic acid uses HI, methanol and H_2O as reactants. The reactants used in the Tennessee Eastman process for the production of acetic anhydride are __________ and __________.

45. Ferrocenophanes are a class of compounds in which the two Cp rings in ferrocene are __________.

46. In the Wacker process, oxidation of alkenes to aldehydes is achieved in the presence of Pd(II). However, this is a stoichiometric reaction. To make this reaction catalytic, it must be carried out in the presence of __________.

47. η^1-Aryl complexes do not undergo β-hydrogen elimination reaction because __________ is too unstable to form.

48. A nitro or chloro group cannot be introduced directly in ferrocene because __________.

49. Schwartz's reagent can be prepared from Cp_2ZrCl_2 by __________.

50. Olefin metathesis is a 2 + 2 cycloaddition reaction between a transition meta __________ and __________ and goes via a metallacyclobutane intermediate.

51. When the groups on an olefin are not sufficiently different, olefin metathesis afford three products out of which __________ is/are cross product/products.

52. The trans-alkylidenation of two terminal olefins accompanied by the release of ethan is defined as __________.

53. Strained ring olefins undergo ring opening metathesis in the presence of a catalyst an another olefin, but in the absence of another olefin it prefers to undergo __________.

54. Self metathesis of 1-octene using Grubbs' second generation catalyst forms __________ and __________.

Chapters 16—20

55. In the olefin polymerisation using Cp_2ZrCl_2/MAO, the actual active center responsibl for catalysis is __________.

56. In propylene polymerisation catalysed by metallocene based catalysts, the active catalys is a __________ cation and __________ is the widely used cocatalyst.

57. A very high percentage of *mmmm* or *rrrr* indicates a polymer of higher __________ o __________ respectively.

58. Isotactic polypropylene has successive monomer units with the __________ configuration and syndiotactic polypropylene has successive monomer units with th __________ configuration.

59. Suzuki coupling is a Pd catalysed cross coupling reaction between a __________ an __________, and forms a C–C bond.

60. Sonogashira coupling is a reaction between __________ and halides and uses a P catalyst, __________ as cocatalyst and a __________.

61. Most of the water soluble phosphines used in olefin metathesis either have __________ or __________ bound at a distance from phosphorus centre.

62. The coupling of an aryl halide with __________ forms an aromatic amine in th presence of a Pd catalyst. This reaction is referred to as __________.

63. Friedel Crafts acetylation of ferrocene using acetyl chloride and $AlCl_3$ forms 1,1′-diacety ferrocene. The formation of a single isomer of the compound shows __________.

64. Ferrocene is __________ reactive to Friedel–Crafts acetylation than mesitylene.

65. Lateral chirality in ferrocene derivatives arises due to __________.

66. The combination of __________ with __________ is called adenosine.

67. The metal in coenzyme B_{12} is __________ and its oxidation state is __________.

68. B_{12s} is a powerful __________ agent.

69. Ferroquin is an __________ drug and contains __________, an organometallic moiety.

70. The radionuclide used in the myocardial imaging agent Cardiolite (sestamibi) is__________.

INDICATE IF THE GIVEN STATEMENTS ARE TRUE OR FALSE

Chapters 1–5

1. The ability of a ligand to accept electron density into low lying σ^* and π^* orbitals is referred to as π acidity.
2. Ligands that are both strong σ donors and π acceptors are most effective at forcing adherence to the 18-electron rule.
3. For bonding in metal carbonyls, the metal must have an empty σ and π orbital.
4. η^5-Cp_2TiH_3 is used as a catalyst for the conversion of benzene to hexadeutrobenzene.
5. In Zeise's salt, the Pt–Cl bond *trans* to ethylene is longer than the other Pt–Cl bonds.
6. $Ni(CO)_4$ is diamagnetic and square planar in shape.
7. Both $HCo(CO)_4$ and $HRh(CO)(PPh_3)_3$ are equally excellent catalysts for the hydroformylation reaction.
8. The C–C bond length in $Pd(PPh_3)_2(CH_2{=}CH_2)_2$ is longer than in $PdCl_2(CH_2{=}CH_2)_2$.
9. The number of ν_{CO} bands shown by $Cr(CO)_6$ and *trans* $(PMe_3)_2Cr(CO)_4$ are the same.
10. Consider $[Cp_2Zr(CO)Cl]^+$ and $Cp_2Zr(CO)_2$ complexes. The latter is a more stable complex than the former.
11. Tolman's parameter (χ) helps one to classify phosphines as good σ and π acceptors.
12. Tolman's cone angle indicates the approximate amount of space that the ligand occupies about the metal center.
13. Grubbs' first generation catalyst is synthesised by replacing the PPh_3 ligand in the precursor Ru complex by PCy_3 because the latter has a higher Tolman's cone angle and is more electron donating that PPh_3.
14. Alkyl phosphines and alkyl phosphites are both good σ donors and good π acceptor ligands.

Chapters 6–10

15. The Cr–C bond in $(CO)_5Cr{=}C(OMe)Ph$ is longer than in $(CO)_5Cr{=}C(OMe)(NMe_2)$.
16. The tendency of the oxidative addition reaction decreases as one moves down the group.

17. The substitution of CO by a phosphine in (η^5-pentadienyl)Mn(CO)$_3$ complex occurs by an associative mechanism and is expected to be faster than the same reaction in [η^5CpMn(CO)$_3$].

18. The oxidative addition of dihydrogen is less facile in [Ir(dppe)$_2$]$^+$ than in the corresponding cobalt complex.

19. Methyl iodide adds oxidatively faster in ClIr(CO)(PPh$_3$)$_2$ than in the corresponding Rh complex.

20. A highly upfield NMR signal is characteristic of the hydride ligand in group 8 and 9 organometallic compounds.

21. Fischer carbenes are synthesised from carbonyl compounds of the early *d* block elements.

22. Consider the complex L$_n$M (η^4-1,3 butadine). If the L ligands are made more electron releasing it will result in more of metallacycle (type II) form and it will also make the C2–C3 bond shorter.

23. Co(CO)$_3$, CH and CpNi are isolobal to one another.

24. In terms of isolobal analogy, the statement 'molecular fragments with frontier orbitals of approximately the same energy are always isolobal' is __________.

25. Isolobal fragments have frontier orbitals with approximately the same symmetry.

26. The orthometallation reactions are intermolecular and the formal oxidation state of the metal always increases by two units.

27. Both cobaltocene and ferrocene react with I$_2$ with equal ease.

28. Electron rich metal favours oxidative addition while the reverse is true for reductive elimination.

29. Oxidative addition of alkane (RCH$_2$–H) is less common while reductive elimination of alkane from M(H)CH$_2$R) is very often observed.

30. The orthometallation reaction involves C–H bond cleavage and can result in a metallacycle intermediate or compound.

31. The formal oxidation state of the metal does not change during the insertion reaction (unless the inserting group is alkylidene or alkylidyne).

32. Oxidative additions are quite facile in complexes with a d^0 metal.

33. With all other factors being the same, the oxidative addition reaction is equally favourable in the isolectronic Fe^0, Co^I and Ni^{+2} complexes.

34. When ferrocene is oxidised to the ferrocenium cation, the Fe–C bond length changes significantly.

35. An important condition for β-hydrogen transfer to occur is that the M–C–C–H unit must attain a roughly coplanar conformation.

36. NaCp is prepared by cracking dicyclopentadiene and reacting it immediately with sodium metal.

37. Cp* is a stronger π donor but weaker π acceptor ligand than Cp.
38. The π acceptor ability of 1,3-butadiene is poorer than CO but better than Cp.
39. A chromium complex with a five-fold bond has been prepared.
40. $[\eta^5\text{-CpMo(CO)}_3]_2$ has two Mo–Mo bonds.
41. In Wade's treatment of metal carbonyl clusters, the $M(CO)_3$ unit is treated analogous to the B–H unit in boron hydrides.
42. d^7ML_5 is isolobal to the CH_3 radical.
43. $Fe(CO)_4$ and CpRh(CO) are isolobal fragments.

Chapters 11–15

44. Both Wilkinson's catalyst and Vaska's complex are equally effective catalysts for the hydrogenation of alkenes.
45. RhX_3 in the presence of CO and iodide source forms $[Rh(CO)_2I_2]^-$ as a single isomer. The *cis* isomer is thermodynamically more stable than the *trans* isomer.
46. A highly active catalyst is one that results in a fast reaction even in low concentrations and has a large turnover frequency.
47. A catalyst increases the rates of processes by introducing new pathways with lower Gibbs free energies of activation, and the reaction profile contains no high peaks and no deep troughs.
48. Internal and branched chain alkenes are hydrogenated faster than terminal ones when Wilkinson's catalyst is used.
49. Replacing the COD in the Schrock–Osborn catalyst by norbordiene results in more facile hydrogenation.
50. Oxidative addition of H_2 to the Lu complex is one of the steps involved in the catalytic cycle of the alkene hydrogenation by $(^*Cp_2LuH)_2$ as catalyst.
51. In the hydroformylation reaction, the *n/iso* ratio is improved when the Rh catalyst has chelating phophine ligands.
52. Terminal and less substituted alkenes react slower in the hydroformylation reactions as compared to the internal or more substituted alkenes.
53. The hydroformylation reactions using $Co_2(CO)_8$ as catalyst has inverse dependence on [CO] concentration.
54. Hydrogenation of alkenes is a competing side reaction in the hydroformylation of alkenes. The thermodynamics of these two reactions suggest that the hydroformylation reaction is kinetically controlled rather than thermodynamically controlled.
55. Using Arrhenius equation, K is large when both E_a and T are large.
56. Bite angle in biphosphines affects the *n/iso* ratio in the hydroformylation reaction and natural bite angles around 120° favour a high *n/iso* ratio.

57. A high *n/iso* ratio of the aldehyde product is preferred for enantioselective hydroformylation.
58. One of the factors favouring ROMP is the release of ring strain in the cyclic olefin.
59. Cyclohexene and norbornene can be polymerised with equal ease.
60. Though the Grubbs' second generation catalyst is 16e, the active catalyst is only 14e.
61. Grubbs' olefin metathesis catalysts are more sensitive to air and moisture than Schrock's catalysts.

Chapters 16–20

62. Pentad content or the percentage of *rrrr* or *mmmm* in a steroisomeric polymer, which can be measured by ^{13}C-NMR, provides a more accurate description of the microstructure than does the dyad or triad content.
63. Heck reaction is a Pd catalysed reaction in which the vinylic hydrogen of an alkene is substituted with a vinyl, aryl or benzyl group.
64. Heck reaction is an intramolecular reaction and uses Pd(0) catalyst.
65. The use of a base such as an amine, is necessary for the Heck reaction.
66. Stille coupling is Pd catalysed and uses a tin–based reagent.
67. Kumada coupling is a cross coupling reaction between an organic halide and a Grignard reagent whereas Negishi coupling uses an organozinc complex.
68. Both Kumada and Negishi are cross coupling reactions between an organic halide and a Grignard reagent.
69. One of the requirements to achieve a cross coupling reaction in aqueous medium is to have water soluble phosphines.
70. Ferrocene with n-BuLi and tBuLi forms only the monolithiated product.
71. Three kinds of chirality, planar, lateral and axial are present in ferrocene based ligands. When both lateral and planar chirality are present in a molecule, the first chiral descriptor indicates the lateral chirality.
72. Since direct bromination of ferrocene cannot be done, bromoferrocene can be prepared by the reaction of $CuBr_2$ with ferrocene boronic acid.
73. The electrochemical studies in poly(vinylferrocene) gives a single oxidation potential. This means that all the pendant ferrocene units are independent and do not interact with each other.
74. Condensation polymerisation of 1,1′-dilithiated ferrocene and Me_2SiCl_2 in polar solvents affords a high molecular weight polymer.
75. Metal polyyne based polymers show MLCT transition and the optical gap corresponding to the lowest energy transition varies with the metal centre and its coordination geometry.

76. The base group attached to cobalt in vitamin B_{12} coenzyme is benzimidazole.
77. In vitamin B_{12} coenzyme, the sixth ligand is a cyanide group.
78. *Methylmalonylcoenzyme A mutase* catalyses the conversion of methyl malonyl coenzyme into succinyl coenzyme A. This is an example of an isomerase reaction.
79. The standard SERM, Tamoxifen, is effective only against the estrogen receptor ER positive breast cancer cells.
80. Salvarsan (Arspehenamine), the first modern chemical therapeutic agent used for the treatment of syphilis is a cyclic organo-arsenic hexamer $[(ArAs)_6]$.

Solutions to Quick Revision Questions

Fill in the Blanks

Chapters 1–5

1. $Fe(CO)_4C_2H_4$
2. shorter, higher
3. η^5-CpNi(NO)
4. $(CO)_5Cr{-}N_2{-}Cr(CO)_5$
5. three
6. bridging; right
7. 2
8. 16e; +4
9. lower
10. B
11. *trans*
12. faster
13. perpendicular; steric interactions
14. better
15. closer
16. central; planar
17. stable

Chapters 6–10

18. (c)
19. (a)
20. η^5-Cp(CO)RuMe(Br(Br) + CO
21. (b)
22. *trans* $Pd(PPh_3)(Ph)(Br)$ and 2 PPh_3
23. $IrCl(PPh_3)_2CO$
24. *Fac* and *Mer* $IrCl_3(PMe_3)_3$
25. more
26. $(PMe_3)_2Rh(CO)Br$
27. weaker; stronger
28. $[\eta^5$-$Cp_2Ti{=}CH_2]$
29. $(CO)_5Cr{=}C(Me(NHR) + MeOH$
30. associative; dissociative
31. faster

32. hapticity change from η^5-Cp to η^3-Cp will disrupt the aromaticity of the Cp ring.

33. rich

34. 46; unsaturated

35. octahedral

36. monocapped octahedron

37. CH

Chapters 11—15

38. $\mathrm{Et(Me)CH{=}CH_2}$

39. 1500 40. Slower

41. higher thermal stability

42. LiI 43. acetic anhydride; LiI

44. methyl acetate; LiI

45. linked by a bridging group

46. $\mathrm{Cu^{2+}}$ and $\mathrm{O_2}$

47. benzyne intermediate

48. the electrophile is oxidising in nature and will oxidise ferrocene

49. reduction with $\mathrm{LiAlH_4}$

50. carbene complex; olefin

51. two

52. cross metathesis

53. ROMP

54. 7-tetradecene

Chapters 16—20

55. $\mathrm{[Cp_2Zr(Me)]^+}$

56. metallocene alkyl; MAO

57. isotacticity; syndiotacticity

58. same; opposite

59. boronic acid; aryl/alkyl halide

60. terminal alkyne; CuI; base

61. sodium sulphonate group; amine hydrochloride group

62. amine; Buchwald–Hartwig C–N cross coupling

63. free rotation of Cp rings

64. more

65. chiral carbon is directly bonded the Cp ring

66. ribose; adenine

67. Co; +3 68. reducing

69. antimalarial; ferrocene

70. ^{99m}Tc

INDICATE TRUE OR FALSE

Chapters 1–5

1. F 2. T 3. F 4. F 5. T 6. F 7. F
8. T 9. T 10. T 11. T 12. T 13. T 14. F

Chapters 6–10

15. F 16. F 17. T 18. F 19. T 20. T 21. F 22. T 23. T 24. F
25. T 26. F 27. F 28. T 29. T 30. T 31. T 32. F 33. F 34. F
35. T 36. T 37. T 38. T 39. T 40. F 41. T 42. T 43. T

Chapters 11–15

44. F 45. T 46. T 47. T 48. F 49. T 50. F 51. T 52. F 53. T
54. T 55. F 56. T 57. F 58. T 59. F 60. T 61. F

Chapters 16–20

62. T 63. T 64. F 65. T 66. T 67. T 68. F 69. T 70. F 71. T
72. T 73. T 74. F 75. T 76. F 77. F 78. T 79. T 80. F

INDEX

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1 H 1.0079																	2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon. 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]			

*Lanthanide series	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm [145]	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]