Contents

About the Author xiii
Preface xv

1 Introduction 1
1.1 The Basics 2
1.2 The Basic Structural Types 2
1.2.1 Phosphines 5
1.2.2 Phosphites 8
1.2.3 N-Heterocyclic Carbenes 9
1.2.4 Other Ligands 10
1.2.5 Quantifying Ligand Effects 10
1.2.6 Heterogeneous Catalysis 10
1.3 Just How Many Ligands Can Fit around a Metal Atom? 10
1.3.1 Method 1: Covalent 11
1.3.2 Method 2: Ionic 11
1.3.3 Examples 12
1.4 Mechanism and the Basic Reaction Steps 13
1.4.1 Coordination and Dissociation 13
1.4.2 Oxidative Addition and Reductive Elimination 15
1.4.3 Transmetallation 15
1.4.4 Alkene and Alkyne Insertion 15
1.4.5 CO Insertion 16
1.4.6 β-Hydride Elimination 16
1.4.7 Oxidative Cyclization 17
1.5 Catalysis 17
References 19

2 Coupling Reactions 21
2.1 Carbon–Carbon Bond Formation 21
2.1.1 The Main-Group Metal, M 22
2.1.2 Limitation 23
2.1.3 Reactivity of the Leaving Group 23
2.1.4 Selectivity 25
2.1.4.1 Selectivity Based on Halogen Reactivity 25
2.1.4.2 Steric Hindrance 25
2.1.4.3 Electronic Effects 26
2.2 Lithium and Magnesium: Kumada Coupling 27
2.3 Zinc: The Negishi Reaction 32
2.4 Aluminium and Zirconium 35
Contents

2.5 Tin: The Stille Reaction 37
  2.5.1 Vinyl Stannanes 41
  2.5.2 Aryl and Heteroaryl Stannanes 42
  2.5.3 The Intramolecular Stille Reaction 42
  2.5.4 Coupling of Acid Chlorides 42
  2.5.5 Stille Coupling of Triflates 44
  2.5.6 Stille Coupling of Alkyl Halides 44
  2.5.7 Stille Reaction Troubleshooting 44

2.6 Boron: The Suzuki Reaction 46
  2.6.1 Alkenyl Borane Coupling Reactions 48
  2.6.2 Alkyl Borane Coupling Reactions 50
  2.6.3 Aryl Borane Coupling Reactions 52
  2.6.4 Suzuki Coupling of Alkyl Halides 56

2.7 Silicon: The Hiyama Reaction 57

2.8 Copper: The Sonogashira Reaction 61

2.9 Other Metals 67
  2.10 Homocoupling 67
  2.11 Enolate and Phenoxyde Coupling 69
  2.12 Heteroatom Coupling 70
    2.12.1 Palladium-Catalysed Synthesis of Amine Derivatives 72
    2.12.2 Palladium-Catalysed Synthesis of Ethers 76
    2.12.3 Ullmann Coupling 78
    2.12.4 Formation of Other C–X bonds 81

References 82

3 C–H Activation 89
  3.1 Arenes and Heteroarenes 91
    3.1.1 Fujiwara–Heck Reaction 91
    3.1.2 Biaryl Coupling 93
  3.2 Aldehydes 100
  3.3 Borylation and Silylation 102
  3.4 Allylic Functionalization 103
  3.5 Unfunctionalized C–H Bonds 105
    3.5.1 Carbon–Heteroatom Bond Formation 105
    3.5.2 Carbon–Carbon Bond Formation 109

References 115

4 Carbonylation 117
  4.1 Carbonylative Coupling Reactions: Synthesis of Carbonyl Derivatives 117
  4.2 Carbonylative Coupling Reactions: Synthesis of Carboxylic Acid Derivatives 122
  4.3 Carbonylation of Alkenes and Alkynes 127
    4.3.1 The Carbonylative Heck Reaction 127
    4.3.2 Other Carbonylation Reactions of Allenes and Alkynes 129
  4.4 Hydroformylation 130
    4.4.1 Directed Hydroformylation 135
    4.4.2 Asymmetric Hydroformylation 138
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>4.5.1</td>
<td></td>
</tr>
<tr>
<td>4.5.2</td>
<td></td>
</tr>
<tr>
<td>4.5.3</td>
<td></td>
</tr>
<tr>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>5.1.1</td>
<td></td>
</tr>
<tr>
<td>5.1.2</td>
<td></td>
</tr>
<tr>
<td>5.1.3</td>
<td></td>
</tr>
<tr>
<td>5.1.4</td>
<td></td>
</tr>
<tr>
<td>5.1.5</td>
<td></td>
</tr>
<tr>
<td>5.1.6</td>
<td></td>
</tr>
<tr>
<td>5.1.7</td>
<td></td>
</tr>
<tr>
<td>5.1.8</td>
<td></td>
</tr>
<tr>
<td>5.1.9</td>
<td></td>
</tr>
<tr>
<td>5.1.10</td>
<td></td>
</tr>
<tr>
<td>5.1.11</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>5.2.1</td>
<td></td>
</tr>
<tr>
<td>5.2.2</td>
<td></td>
</tr>
<tr>
<td>5.2.3</td>
<td></td>
</tr>
<tr>
<td>5.2.4</td>
<td></td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>6.1.1</td>
<td></td>
</tr>
<tr>
<td>6.1.2</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>6.2.1</td>
<td></td>
</tr>
<tr>
<td>6.2.2</td>
<td></td>
</tr>
<tr>
<td>6.2.3</td>
<td></td>
</tr>
<tr>
<td>6.2.4</td>
<td></td>
</tr>
<tr>
<td>6.2.5</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>6.3.1</td>
<td></td>
</tr>
<tr>
<td>6.3.2</td>
<td></td>
</tr>
<tr>
<td>6.3.3</td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
</tbody>
</table>
Contents

7 Reactions of Alkyne Complexes 241
7.1 Alkyne Cobalt Complexes 241
7.2 Propargyl Cations: The Nicholas Reaction 244
7.3 The Pauson–Khand Reaction 246
  7.3.1 Asymmetric Pauson–Khand Reaction 248
  7.3.2 The Hetero-Pauson–Khand Reaction 249
7.4 Synthesis Using Multiple Cobalt Reactions 250
References 251

8 Carbene Complexes 253
8.1 Fischer Carbenes 253
  8.1.1 Demetallation 258
  8.1.2 The Dötz Reaction 258
  8.1.3 Not the Dötz Reaction 263
  8.1.4 Fischer Carbene Photochemistry 267
8.2 Vinylidene Complexes 269
8.3 Metathesis Reactions Involving Carbene Complexes 273
  8.3.1 Tebbe’s Reagent 274
  8.3.2 Alkene (Olefin) Metathesis 278
  8.3.3 Ring-Closing Metathesis 279
  8.3.4 Cross-Metathesis 291
  8.3.5 Ring-Opening Metathesis 296
  8.3.6 Asymmetric Metathesis 297
  8.3.7 Ene–Yne Metathesis 300
  8.3.8 Ene–Yne–Ene Metathesis 303
  8.3.9 Tandem Reactions 306
  8.3.10 Metathesis Side Reactions 306
8.4 Carbyne Complexes 310
  8.4.1 Alkyne Metathesis 310
8.5 Carbene Complexes from Diazo Compounds 312
  8.5.1 Nucleophilic Trapping 313
  8.5.2 C–H Insertion Reactions of Carbene Complexes 315
  8.5.3 C–H Insertion Reactions of Nitrene Complexes 316
References 319

9 η3- or π-Allyl Complexes 325
9.1 Stoichiometric Reactions of π-Allyl Complexes 325
9.2 Catalysis: Mostly Palladium 328
  9.2.1 Regioselectivity 331
  9.2.2 Internal versus Terminal Attack 333
  9.2.3 Stereoselectivity 335
  9.2.4 Asymmetric Allylation 337
  9.2.5 Synthesis Using Palladium Allyl Chemistry 341
  9.2.6 Base-Free Allylation 343
  9.2.7 Allylation with Decarboxylation 347
  9.2.8 Allyl as a Protecting Group 350
  9.2.9 Other Routes to η3- or π-Allyl Palladium Complexes 352
9.3 Propargyl Compounds 357
References 357
Contents  xi

10  Diene, Dienyl and Arene Complexes 361
    10.1  \(\eta^1\)-Diene Complexes 361
         10.1.1  Electrophilic Attack 364
         10.1.2  Nucleophilic Attack 366
         10.1.3  Deprotonation 370
    10.2  \(\eta^5\)-Dienyl Complexes 371
         10.2.1  Nucleophilic Attack 372
    10.3  \(\eta^6\)-Arene Complexes 377
         10.3.1  Nucleophilic Attack 380
         10.3.2  Deprotonation 385
    10.4  \(\eta^2\)-Arene Complexes 387
    References 389

11  Cycloaddition and Cycloisomerization Reactions 391
    11.1  Formal Six-Electron, Six-Atom Cycloadditions 391
         11.1.1  The \([4 + 2]\) Cycloaddition 391
         11.1.2  The \([2 + 2 + 2]\) Cycloaddition 394
    11.2  Cycloadditions Involving Fewer than Six Atoms 402
         11.2.1  Four-Membered Rings 402
         11.2.2  Five-Membered Rings through TMM Methods 402
         11.2.3  Other Five-Membered Ring Formations 405
    11.3  Cycloadditions Involving More than Six Atoms 407
         11.3.1  The \([5 + 2]\) Cycloaddition 407
         11.3.2  The \([4 + 4]\) Cycloaddition 410
         11.3.3  The \([6 + 2]\) and \([6 + 4]\) Cycloadditions 411
    11.4  Isomerization 414
    11.5  Cycloisomerization and Related Reactions 415
    References 426

Abbreviations 431

Index of Principle Transition Metal Catalysts and Reagents 433

Index 437