

Volume 25: Aldehydes

Preface	V
Volume Editor's Preface	VII
Table of Contents	XIII
Introduction	
R. Brückner	1
25.1 Product Class 1: Aliphatic and Alicyclic Aldehydes	
25.1.1 Synthesis by Oxidative Cleavage	
J. Podlech	17
25.1.2 Synthesis by Oxidation	
J. Podlech	25
25.1.3 Synthesis by Isomerization	
A. Gansäuer and K. Muñiz	57
25.1.4 Synthesis by Reduction or by Reduction Followed by Hydrolysis	
C. Harcken	65
25.1.5 Synthesis by Elimination or Rearrangement	
M. Kalesse	137
25.1.6 Synthesis by Protonation	
M. Kalesse	147
25.1.7 Synthesis by Hydrolysis	
B. Plietker	151
25.1.8 Synthesis by Hydration of Alkynes	
M. Oestreich	199
25.1.9 Synthesis by Formylation of Enolates	
T. J. J. Müller	213
25.1.10 Synthesis by Homologation of Aldehydes	
A. Lindenschmidt	237
25.1.11 Synthesis by Hydroformylation of Alkenes	
B. Breit	277

25.1.12	Synthesis by C₁-Extension of Alkyl Halides	319
	A. S. K. Hashmi	
25.1.13	Synthesis by C₁-Extension of Organometallics	337
	A. S. K. Hashmi	
25.1.14	Synthesis by C₂-Elongation	355
	R. Göttlich	
25.1.15	Synthesis by C₃-Elongation	369
	R. Göttlich	
25.1.16	Synthesis by Diels–Alder Reactions with Enals or Their Acetals	405
	B. Witulski and C. Alayrac	
25.2	Product Class 2: 2-Oxoaldehydes and Heteroatom Analogues	423
	T. Olpp	
25.3	Product Class 3: 2,2-Diheteroatom-Substituted Aldehydes	441
	M. Harmata	
25.4	Product Class 4: 2-Heteroatom-Substituted Aldehydes and Sugar Aldehydes	463
	M. Eckhardt	
25.5	Product Class 5: Ynals	507
	B. Witulski and C. Alayrac	
25.6	Product Class 6: Arenecarbaldehydes	
25.6.1	Synthesis by Oxidative Cleavage of Carbon–Carbon Bonds	523
	K. Ditrich	
25.6.2	Synthesis by Oxidation	531
	K. Ditrich	
25.6.3	Synthesis by Reduction	563
	K. Ditrich	
25.6.4	Synthesis by Hydrolysis of Aldehyde Derivatives	575
	K. Ditrich	
25.6.5	Synthesis by Formylation of Arylmetal Reagents	585
	A. Schall and O. Reiser	
25.6.6	Synthesis by Formylation of Arene–Hydrogen Bonds	605
	A. Schall and O. Reiser	

25.6.7	Synthesis by Carbonylation of Arylpalladium Intermediates	
	A. Schall and O. Reiser	655
25.6.8	Synthesis by C—C Bond Formation	
	M. Oestreich	667
25.6.9	Synthesis by C—X Bond Formation	
	T. Berkenbusch	689
25.7	Product Class 7: Polyenals	
	I. Escher and F. Glorius	711
25.8	Product Class 8: α,β-Unsaturated Aldehydes	
	I. Escher and F. Glorius	733
25.9	Product Class 9: 3-Heteroatom-Substituted Aldehydes	
	A. Lindenschmidt	779
	Keyword Index	803
	Author Index	841
	Abbreviations	897

Table of Contents

Introduction

R. Brückner

Introduction	1
---------------------	---

25.1 Product Class 1: Aliphatic and Alicyclic Aldehydes

25.1.1 Synthesis by Oxidative Cleavage

J. Podlech

Synthesis by Oxidative Cleavage	17
25.1.1.1 Method 1: Oxidative Cleavage of Alkenes	17
25.1.1.1.1 Variation 1: By Ozonolysis	17
25.1.1.1.2 Variation 2: By Dihydroxylation/Glycol Cleavage	19
25.1.1.2 Method 2: Oxidative Cleavage of Glycols and Related Compounds	20
25.1.1.2.1 Variation 1: Using Lead(IV) Acetate	20
25.1.1.2.2 Variation 2: Using Sodium Periodate	21

25.1.2 Synthesis by Oxidation

J. Podlech

Synthesis by Oxidation	25
25.1.2.1 Method 1: Oxidation of Halides and 4-Toluenesulfonates	25
25.1.2.1.1 Variation 1: Oxidation with Dimethyl Sulfoxide and Related Species	25
25.1.2.1.2 Variation 2: Oxidation with N-Oxides	26
25.1.2.2 Method 2: Oxidation of Primary Alcohols	27
25.1.2.2.1 Variation 1: Oxidation with Metal Salts in High Oxidation States	28
25.1.2.2.2 Variation 2: Oxidation with Activated Dimethyl Sulfoxide and Related Species	33
25.1.2.2.3 Variation 3: Oxidation with Hypervalent Iodine Reagents	38
25.1.2.2.4 Variation 4: Oxidation of Alcohols with a Nitroxide and a Co-oxidant	41
25.1.2.2.5 Variation 5: Oxidation with Oxygen and a Catalyst	43
25.1.2.3 Method 3: Oxidation of Primary Silyl Ethers	44
25.1.2.4 Method 4: Oxidation of Sulfur Compounds	46
25.1.2.5 Method 5: Oxidation of Amines	48
25.1.2.6 Method 6: Oxidation at the Terminal Carbon Atom of an Alk-1-ene	49
25.1.2.6.1 Variation 1: Oxidation of Terminal Alkenes with Oxygen under Palladium Catalysis	50
25.1.2.6.2 Variation 2: Hydroboration of Alk-1-enes and Subsequent Oxidation of the Boranes	50

25.1.3	Synthesis by Isomerization	
	A. Gansäuer and K. Muñiz	
<hr/>		
25.1.3	Synthesis by Isomerization	57
25.1.3.1	Method 1: Transition-Metal-Catalyzed Isomerization of Allylic Alcohols	57
25.1.3.1.1	Variation 1: Enantioselective Transition-Metal-Catalyzed Isomerization of Allylic Alcohols	59
25.1.3.2	Method 2: Transition-Metal-Catalyzed Isomerization of Allylic Amines and Subsequent Hydrolysis	59
25.1.3.2.1	Variation 1: Enantioselective Transition-Metal-Catalyzed Isomerization of Allylic Amines and Subsequent Hydrolysis	61
<hr/>		
25.1.4	Synthesis by Reduction or by Reduction Followed by Hydrolysis	
	C. Harcken	
<hr/>		
25.1.4	Synthesis by Reduction or by Reduction Followed by Hydrolysis	65
25.1.4.1	Reduction of Carboxylic Acid Chlorides	66
25.1.4.1.1	Method 1: Rosenmund Reduction	67
25.1.4.1.2	Method 2: Reduction Using Complex Aluminum Hydrides	67
25.1.4.1.3	Method 3: Reduction Using Complex Borohydrides	69
25.1.4.1.4	Method 4: Reduction Using Triethylsilane	70
25.1.4.1.5	Method 5: Reduction Using Tributyltin Hydride	70
25.1.4.2	Reduction of Carboxylic Acids	71
25.1.4.2.1	Method 1: Reduction Using Complex Aluminum Hydrides	71
25.1.4.2.1.1	Variation 1: Using Lithium Aluminum Hydride	71
25.1.4.2.1.2	Variation 2: Using Lithium Bis(<i>N</i> -methylpiperazinyl)aluminum Hydride	72
25.1.4.2.1.3	Variation 3: Using Lithium <i>Tri-tert</i> -butoxyaluminum Hydride	73
25.1.4.2.2	Method 2: Reduction Using Boranes	75
25.1.4.2.3	Method 3: Reduction Using Formic Acid or Formates	76
25.1.4.2.4	Method 4: Reduction Using Alkali Metals	76
25.1.4.2.5	Method 5: Reduction Using Two-Step, One-Pot Procedures	76
25.1.4.2.5.1	Variation 1: Reduction of Carboxylic Acids through Silyl Esters	76
25.1.4.2.5.2	Variation 2: Reduction of Carboxylic Acids through an Imidazolide	77
25.1.4.2.5.3	Variation 3: Reduction of Carboxylic Acids through a Triazinyl Ester	78
25.1.4.2.5.4	Variation 4: One-Pot Reduction–Oxidation of Carboxylic Acids	79
25.1.4.3	Reduction of Esters	79
25.1.4.3.1	Method 1: Reduction Using Diisobutylaluminum Hydride	80
25.1.4.3.2	Method 2: Reduction Using Sodium Bis(2-methoxyethoxy)aluminum Hydride	84
25.1.4.3.3	Method 3: Reduction Using Other Complex Aluminum Hydrides	85
25.1.4.3.3.1	Variation 1: Using Lithium Aluminum Hydride	85
25.1.4.3.3.2	Variation 2: Using Lithium <i>Tri-tert</i> -butoxyaluminum Hydride	86
25.1.4.3.3.3	Variation 3: Using Lithium Bis(diethylamino)aluminum Hydride	86
25.1.4.3.4	Method 4: Reduction Using Alkali Metal Amalgam	87

25.1.4.4	Reduction of Thioesters	87
25.1.4.4.1	Method 1: Reduction Using Raney Nickel	88
25.1.4.4.2	Method 2: Reduction Using Triethylsilane	88
25.1.4.4.3	Method 3: Reduction Using Diisobutylaluminum Hydride	90
25.1.4.5	Reduction of Amides	90
25.1.4.5.1	Method 1: Reduction Using Lithium Aluminum Hydride	92
25.1.4.5.1.1	Variation 1: Reduction of Weinreb Amides	92
25.1.4.5.1.2	Variation 2: Reduction of Other Amides	94
25.1.4.5.2	Method 2: Reduction Using Diisobutylaluminum Hydride	95
25.1.4.5.2.1	Variation 1: Reduction of Weinreb Amides	95
25.1.4.5.2.2	Variation 2: Reduction of Other Amides	96
25.1.4.5.3	Method 3: Reduction Using Other Complex Aluminum Hydrides	97
25.1.4.5.3.1	Variation 1: Using Sodium Bis(2-methoxyethoxy)aluminum Hydride	97
25.1.4.5.3.2	Variation 2: Using Lithium Alkoxyaluminum Hydrides	98
25.1.4.5.3.3	Variation 3: Using Lithium Tris(dialkylamino)aluminum Hydrides	99
25.1.4.5.4	Method 4: Reduction Using Boranes or Complex Borohydrides	99
25.1.4.5.5	Method 5: Reduction Using Chlorobis(η^5 -cyclopentadienyl)-hydridozirconium(IV)	100
25.1.4.6	Reduction of Lactones and Lactams	101
25.1.4.6.1	Method 1: Reduction Using Complex Aluminum Hydrides	101
25.1.4.6.1.1	Variation 1: Using Lithium Aluminum Hydride	101
25.1.4.6.1.2	Variation 2: Using Sodium Bis(2-methoxyethoxy)aluminum Hydride	101
25.1.4.6.1.3	Variation 3: Using Lithium Tri- <i>tert</i> -butoxyaluminum Hydride	102
25.1.4.6.1.4	Variation 4: Using Diisobutylaluminum Hydride	102
25.1.4.6.2	Method 2: Reduction Using Boranes	105
25.1.4.6.3	Method 3: Reduction Using Alkali Metal Amalgam	106
25.1.4.6.4	Method 4: Reduction of Lactams	106
25.1.4.7	Reduction of Heterocyclic Derivatives of Carboxylic Acids	107
25.1.4.7.1	Method 1: Reduction of 5,6-Dihydro-4 <i>H</i> -1,3-oxazines and 4,5-Dihydrooxazoles Using Sodium Borohydride	107
25.1.4.8	Reduction of Nitriles Followed by Hydrolysis	110
25.1.4.8.1	Method 1: Reduction Using Diisobutylaluminum Hydride	111
25.1.4.8.2	Method 2: Reduction Using Complex Aluminum Hydrides	118
25.1.4.8.2.1	Variation 1: Using Lithium Aluminum Hydride	118
25.1.4.8.2.2	Variation 2: Using Lithium Triethoxyaluminum Hydride	118
25.1.4.8.2.3	Variation 3: Using Sodium Tris(dialkylamino)aluminum Hydrides	119
25.1.4.8.3	Method 3: Reduction Using Raney Nickel	119
25.1.4.8.4	Method 4: Reduction Using Tin(II) Chloride	120
25.1.4.9	Reduction of Enals	121
25.1.4.9.1	Method 1: Hydrogenation	121
25.1.4.9.2	Method 2: Hydrostannylation	122
25.1.4.9.3	Method 3: Hydrosilylation	123
25.1.4.9.4	Method 4: Reduction Using Copper Reagents	124
25.1.4.9.5	Method 5: Reduction Using Inorganic Salts	125

25.1.5	Synthesis by Elimination or Rearrangement	
	M. Kalesse	
<hr/>		
25.1.5	Synthesis by Elimination or Rearrangement	137
25.1.5.1	Method 1: Synthesis from Halohydrins	137
25.1.5.2	Method 2: Synthesis from Glycols	139
25.1.5.3	Method 3: Semipinacol Rearrangement	140
25.1.5.4	Method 4: Synthesis from Epoxides	142
<hr/>		
25.1.6	Synthesis by Protonation	
	M. Kalesse	
<hr/>		
25.1.6	Synthesis by Protonation	147
25.1.6.1	Method 1: Protonation of Enol Ethers	147
25.1.6.2	Method 2: Asymmetric Protonation	148
<hr/>		
25.1.7	Synthesis by Hydrolysis	
	B. Plietker	
<hr/>		
25.1.7	Synthesis by Hydrolysis	151
25.1.7.1	Hydrolysis of Imines and Derivatives	151
25.1.7.1.1	Method 1: Hydrolysis of Imines	151
25.1.7.1.2	Method 2: Hydrolysis of Oximes and Derivatives	153
25.1.7.1.3	Method 3: Hydrolysis of Sulfonated Imines	154
25.1.7.1.4	Method 4: Hydrolysis of N-Alkylimines	155
25.1.7.1.5	Method 5: Hydrolysis of Hydrazones	156
25.1.7.1.5.1	Variation 1: Hydrolysis of N-Arylhydrazones	156
25.1.7.1.5.2	Variation 2: Hydrolysis of N-Alkylhydrazones	158
25.1.7.1.6	Method 6: Hydrolysis of Hydrazides and Derivatives	159
25.1.7.1.7	Method 7: Hydrolysis of Semicarbazones and Related Compounds	159
25.1.7.2	Hydrolysis of Acetals and Their Derivatives	160
25.1.7.2.1	Method 1: Hydrolysis of O,O-Acetals and Hemiacetals	160
25.1.7.2.1.1	Variation 1: Hydrolysis of Acyclic Hemiacetals	160
25.1.7.2.1.2	Variation 2: Hydrolysis of Carbohydrates and Higher Cyclic Hemiacetals	161
25.1.7.2.1.3	Variation 3: Hydrolysis of Acyclic Dialkyl Acetals	164
25.1.7.2.1.4	Variation 4: Hydrolysis of <i>gem</i> -Diacetates	165
25.1.7.2.1.5	Variation 5: Hydrolysis of Alkoxytetrahydrofurans and -pyrans	166
25.1.7.2.1.6	Variation 6: Hydrolysis of Cyclic Acetals	167
25.1.7.2.2	Method 2: Hydrolysis of O,S-Acetals	169
25.1.7.2.2.1	Variation 1: Hydrolysis of α -Hydroxy Sulfonic Acids	169
25.1.7.2.2.2	Variation 2: Hydrolysis of Hemithioacetals	169
25.1.7.2.2.3	Variation 3: Hydrolysis of Acyclic O,S-Acetals	170
25.1.7.2.2.4	Variation 4: Hydrolysis of Alkyl Thiolactols or Alkoxythiopyrans and Related Compounds	172
25.1.7.2.3	Method 3: Hydrolysis of O,N-Acetals	174

25.1.7.2.3.1	Variation 1:	Hydrolysis of Acyclic O,N-Hemiacetals	174
25.1.7.2.3.2	Variation 2:	Hydrolysis of Cyclic O,N-Hemiacetals	175
25.1.7.2.3.3	Variation 3:	Hydrolysis of Acyclic O,N-Acetals	176
25.1.7.2.3.4	Variation 4:	Hydrolysis of Cyclic O,N-Acetals	176
25.1.7.2.4	Method 4:	Hydrolysis of S,S-Acetals	177
25.1.7.2.4.1	Variation 1:	Hydrolysis of Acyclic S,S-Acetals	177
25.1.7.2.4.2	Variation 2:	Hydrolysis of Cyclic S,S-Acetals	180
25.1.7.2.5	Method 5:	Hydrolysis of S,N-Acetals	183
25.1.7.2.6	Method 6:	Hydrolysis of N,N-Acetals	184
25.1.7.3		Hydrolysis of Enol Ethers and Their Heteroatom Analogues	185
25.1.7.3.1	Method 1:	Hydrolysis of Enol Ethers and Their O-Derivatives	185
25.1.7.3.1.1	Variation 1:	Hydrolysis of O-Alkyl and O-Silyl Enol Ethers	185
25.1.7.3.1.2	Variation 2:	Hydrolysis of Vinyl Carboxylates	187
25.1.7.3.2	Method 2:	Hydrolysis of Enamines and Derivatives	188
25.1.7.3.2.1	Variation 1:	Hydrolysis of N,N-Dialkylenamines	188
25.1.7.3.2.2	Variation 2:	Hydrolysis of Enamides	189
25.1.7.3.3	Method 3:	Hydrolysis of Vinyl Halides	190
25.1.8		Synthesis by Hydration of Alkynes	
		M. Oestreich	
25.1.8		Synthesis by Hydration of Alkynes	199
25.1.8.1		Synthesis by Direct Hydration	200
25.1.8.1.1	Method 1:	Ruthenium(II)-Catalyzed Hydration	201
25.1.8.1.1.1	Variation 1:	Simple Ruthenium(II) Catalysis	201
25.1.8.1.1.2	Variation 2:	Ruthenium(II) Catalysis Assisted by Hydrogen Bonding	202
25.1.8.1.1.3	Variation 3:	Ruthenium(II) Catalysis Using a Bifunctional Catalyst	204
25.1.8.1.1.4	Variation 4:	Ruthenium(II) Catalysis Using a Self-Assembled Catalyst	205
25.1.8.2		Synthesis by Indirect Hydration	206
25.1.8.2.1	Method 1:	Hydroboration Followed by Oxidation	206
25.1.8.2.1.1	Variation 1:	Hydroboration with Sterically Hindered Boranes	206
25.1.8.2.1.2	Variation 2:	Hydroboration with Catecholborane	207
25.1.8.2.1.3	Variation 3:	Hydroboration with Haloboranes	207
25.1.8.2.2	Method 2:	Hydrosilylation Followed by Oxidation	208
25.1.8.2.3	Method 3:	Hydroamination Followed by Hydrolysis	209
25.1.9		Synthesis by Formylation of Enolates	
		T. J. J. Müller	
25.1.9		Synthesis by Formylation of Enolates	213

25.1.9.1	Method 1:	Crossed Claisen Condensations with Formates	213
25.1.9.1.1	Variation 1:	Using Ketones or Esters and an Alkali Metal Alkoxide as the Base	213
25.1.9.1.2	Variation 2:	Using Ketones or Esters and Sodium Metal as the Base	217
25.1.9.1.3	Variation 3:	Using Ketones or Esters and Sodium Hydride as the Base	219

25.1.9.1.4	Variation 4: Using Preformed Lithium Enolates of Ketones or Esters	222
25.1.9.2	Method 2: Vilsmeier Formylation of Carbonyl Compounds, Enols, or Enol Ethers	223
25.1.9.3	Method 3: Condensation of Ketones, Esters, or Active Methylenic Compounds with Dimethylformamide Acetals	227
25.1.9.4	Method 4: Condensation of Enol Ethers with Orthoformates	229
25.1.9.5	Method 5: Condensation of Esters with Formyl Acetate	229
25.1.9.6	Method 6: Synthesis from Enols by the Reimer–Tiemann Reaction	230
25.1.9.7	Method 7: Synthesis from Enol Ethers and Related Compounds by Mukaiyama Condensation	230
25.1.9.8	Method 8: Formylation of Pyranones with Dichloromethyl Methyl Ether	231
25.1.9.9	Method 9: Synthesis from Reformatsky Enolates	232
25.1.9.10	Methods 10: Additional Syntheses	232
 25.1.10	Synthesis by Homologation of Aldehydes	
	A. Lindenschmidt	
 25.1.10	Synthesis by Homologation of Aldehydes	237
25.1.10.1	Method 1: Homologation via the Darzens Reaction	237
25.1.10.2	Method 2: Homologation via the Nef Reaction	239
25.1.10.3	Method 3: Homologation via the Formation of a Nitrile Intermediate ..	242
25.1.10.4	Method 4: Homologation with Dihalomethane	246
25.1.10.5	Method 5: Homologation with Diazomethane	248
25.1.10.6	Method 6: Homologation with Phosphorus Reagents	249
25.1.10.6.1	Variation 1: Via 1-Heteroatom-Substituted Alkene Intermediates	249
25.1.10.6.2	Variation 2: Via Terminal Acetylene Intermediates	257
25.1.10.7	Method 7: Homologation with Boron Reagents	260
25.1.10.8	Method 8: Homologation with Silicon Reagents	262
25.1.10.8.1	Variation 1: Via 1-Heteroatom-Substituted Alkene Intermediates	262
25.1.10.8.2	Variation 2: Via α,β -Epoxide Intermediates	267
25.1.10.9	Method 9: Homologation with Sulfur Reagents	268
25.1.10.9.1	Variation 1: Via 1-Heteroatom-Substituted Alkene Intermediates	268
25.1.10.9.2	Variation 2: Via Epoxide Intermediates	269
 25.1.11	Synthesis by Hydroformylation of Alkenes	
	B. Breit	
 25.1.11	Synthesis by Hydroformylation of Alkenes	277
25.1.11.1	Method 1: Regioselective Hydroformylation: Substrate Control	283
25.1.11.2	Method 2: Regioselective Hydroformylation: Catalyst Control	290
25.1.11.3	Method 3: Isomerizing Hydroformylation	293
25.1.11.4	Method 4: Diastereoselective Hydroformylation: Passive Substrate Control	294
25.1.11.4.1	Variation 1: Cyclic Alkenes	295
25.1.11.4.2	Variation 2: Acyclic and Exocyclic Alkenes	296

25.1.11.5	Method 5:	Diastereoselective Hydroformylation: Active Substrate Control	297
25.1.11.6	Method 6:	Diastereoselective Hydroformylation: Catalyst Control	304
25.1.11.7	Method 7:	Enantioselective Hydroformylation	306
25.1.11.7.1	Variation 1:	Vinylarenes	307
25.1.11.7.2	Variation 2:	Aliphatic Alkenes and Dienes	311
25.1.11.7.3	Variation 3:	Functionalized Alkenes	313
25.1.12	Synthesis by C₁-Extension of Alkyl Halides		
	A. S. K. Hashmi		
25.1.12	Synthesis by C₁-Extension of Alkyl Halides		319
25.1.12.1	Method 1:	Synthesis from Formyl Anion Equivalents	319
25.1.12.1.1	Variation 1:	Synthesis Using 1,3-Dithiane or Bis(phenylsulfanyl)methane	321
25.1.12.1.2	Variation 2:	Synthesis Using 1,3,5-Trithiane	321
25.1.12.1.3	Variation 3:	Synthesis Using 5-Methyl-1,3,5-dithiazinane	322
25.1.12.1.4	Variation 4:	Synthesis Using Sulfur(VI) Reagents	323
25.1.12.1.5	Variation 5:	Synthesis Using (Diethylamino)acetonitrile	324
25.1.12.1.6	Variation 6:	Synthesis Using Silicon, Selenium, and Tellurium Reagents	325
25.1.12.2	Method 2:	Reductive Carbonylation	326
25.1.12.2.1	Variation 1:	Using Hydrogen and a Platinum Catalyst	326
25.1.12.2.2	Variation 2:	Using Tributyltin Hydride and a Palladium Catalyst	327
25.1.12.2.3	Variation 3:	Using Stoichiometric Amounts of Tetracarbonylhydridoferrate Salts	328
25.1.12.2.4	Variation 4:	Using Stoichiometric Amounts of Carbonylferrate Salts and an Acidic Workup	329
25.1.12.2.5	Variation 5:	Using Stannanes by a Free-Radical Pathway	330
25.1.12.3	Method 3:	Reduction with Lithium Metal in the Presence of N,N-Disubstituted Formamides	331
25.1.12.4	Method 4:	Synthesis Using Triphenylphosphine and Alkyl Formates	332
25.1.13	Synthesis by C₁-Extension of Organometallics		
	A. S. K. Hashmi		
25.1.13	Synthesis by C₁-Extension of Organometallics		337
25.1.13.1	Method 1:	Reaction with Formamides	338
25.1.13.1.1	Variation 1:	Reaction with Dimethylformamide	338
25.1.13.1.2	Variation 2:	Reaction with Piperidine-1-carbaldehyde	342
25.1.13.1.3	Variation 3:	Reaction with N-Methyl-N-phenylformamide	344
25.1.13.1.4	Variation 4:	Reaction with N-Methyl-N-(2-pyridyl)formamide	345
25.1.13.2	Method 2:	Reaction with Ortho Esters	345
25.1.13.2.1	Variation 1:	Reaction with Triethyl Orthoformate	346
25.1.13.2.2	Variation 2:	Reaction with Diethyl Phenyl Orthoformate	347
25.1.13.3	Method 3:	Reaction of Organoboranes with Carbon Monoxide and Hydride Reagents, Followed by Oxidative Workup	349

25.1.13.4	Method 4:	Reaction of Organomagnesium Compounds with Carbon Monoxide from Pentacarbonyliron(0)	349
25.1.13.5	Method 5:	Reaction of Organometallic Compounds with Isocyanides ...	350
25.1.14	Synthesis by C₂-Elongation		
	R. Göttlich		
25.1.14	Synthesis by C₂-Elongation		355
25.1.14.1	Method 1:	Alkylation of Enolates	355
25.1.14.2	Method 2:	Alkylation and Michael Addition of Silyl Enol Ethers	357
25.1.14.3	Method 3:	Alkylation and Michael Addition of Enamines	358
25.1.14.4	Method 4:	Alkylation and Michael Addition of Azaenolates	360
25.1.14.4.1	Variation 1:	Alkylation and Michael Addition of Imine Enolates	360
25.1.14.4.2	Variation 2:	Alkylation of Oxime Enolates	361
25.1.14.4.3	Variation 3:	Alkylation and Michael Addition of Achiral Hydrazone Enolates	362
25.1.14.4.4	Variation 4:	Alkylation and Michael Addition of Enantiomerically Pure Hydrazone Enolates	363
25.1.14.5	Method 5:	Arylation of Heterosubstituted Ethenes	366
25.1.15	Synthesis by C₃-Elongation		
	R. Göttlich		
25.1.15	Synthesis by C₃-Elongation		369
25.1.15.1	Method 1:	1,4-Addition to α,β -Unsaturated Aldehydes	369
25.1.15.1.1	Variation 1:	Base-Induced Michael Addition	369
25.1.15.1.2	Variation 2:	Organocatalytic Michael Addition	372
25.1.15.1.3	Variation 3:	Michael Additions Catalyzed by Metal Complexes	374
25.1.15.2	Method 2:	Conjugate Addition Reactions of Organometallic Compounds	374
25.1.15.2.1	Variation 1:	Addition of Organocupper Reagents	374
25.1.15.2.2	Variation 2:	Addition of Organozinc Reagents	379
25.1.15.2.3	Variation 3:	Addition Reactions of Other Organometallic Reagents	381
25.1.15.2.4	Variation 4:	Transition-Metal-Catalyzed Additions	383
25.1.15.3	Method 3:	Addition to α,β -Unsaturated Aldehydes via Radicals	384
25.1.15.3.1	Variation 1:	Addition of Organoboranes	384
25.1.15.3.2	Variation 2:	The Meerwein Arylation	387
25.1.15.4	Method 4:	Reactions of Homoenolates	388
25.1.15.4.1	Variation 1:	Protected Aldehydes	388
25.1.15.4.2	Variation 2:	Heteroatom-Substituted Allyl Anions	389
25.1.15.4.3	Variation 3:	The Carbamate Approach	392
25.1.15.5	Method 5:	Aldehydes through [3,3]-Rearrangements	395
25.1.15.5.1	Variation 1:	The Claisen Rearrangement	395
25.1.15.5.2	Variation 2:	Aza-Claisen Rearrangement	398
25.1.15.5.3	Variation 3:	Oxy-Cope Rearrangement	398

25.1.16	Synthesis by Diels–Alder Reactions with Enals or Their Acetals	
	B. Witulski and C. Alayrac	
<hr/>		
25.1.16	Synthesis by Diels–Alder Reactions with Enals or Their Acetals	405
25.1.16.1	Method 1: Thermal Diels–Alder Reactions	405
25.1.16.2	Method 2: Lewis Acid Catalyzed Diels–Alder Reactions	406
25.1.16.3	Method 3: Brønsted Acid Catalyzed Diels–Alder Reactions (Cationic Diels–Alder Reactions)	408
25.1.16.4	Method 4: Stepwise Diels–Alder Reactions of π -Complexed 1,3-Dienes	409
25.1.16.5	Method 5: Enantioselective Diels–Alder Reactions Catalyzed by Chiral Lewis Acids	410
25.1.16.6	Method 6: Enantioselective Organocatalytic Diels–Alder Reactions	414
25.1.16.7	Method 7: Heterogeneously Catalyzed and Polymer-Supported Diels–Alder Reactions	417
25.1.16.8	Method 8: Diels–Alder Reactions Accelerated by High Pressure	419
25.1.16.9	Method 9: Diels–Alder Reactions in Aqueous Media	419
<hr/>		
25.2	Product Class 2: 2-Oxoaldehydes and Heteroatom Analogues	
	T. Olpp	
<hr/>		
25.2	Product Class 2: 2-Oxoaldehydes and Heteroatom Analogues	423
25.2.1	Product Subclass 1: 2-Oxoaldehydes	423
25.2.1.1	Synthesis of Product Subclass 1	424
25.2.1.1.1	Method 1: Oxidation of Activated C–H Bonds by Selenium Dioxide	424
25.2.1.1.2	Method 2: Oxidation via Bromomethyl Ketones	426
25.2.1.1.3	Method 3: Oxidation of α -Diazoo Ketones	427
25.2.1.1.4	Method 4: Oxidation of Hydroxymethyl Ketones	428
25.2.1.1.5	Method 5: Hydrolysis of Glyoxal Dialkyl Acetals and Related Compounds	429
25.2.1.1.6	Method 6: Reduction of Glyoxylic Acid Chlorides	430
25.2.1.1.7	Method 7: Cleavage of C=C Bonds	430
25.2.1.1.8	Method 8: C–C Bond Formation	431
25.2.2	Product Subclass 2: 2-Imino-, 2-(Hydroxyimino)-, 2-Hydrazono-, and 2-Diazoaldehydes	431
25.2.2.1	Synthesis of Product Subclass 2	431
25.2.2.1.1	Method 1: Formylation of Imine Derivatives	431
25.2.2.1.2	Method 2: Functionalization of Enamines with N-Electrophiles	432
25.2.2.1.3	Method 3: Addition of Azides to β -Amino Acroleins	433
25.2.2.1.4	Method 4: Nitrosation of Enals and Alkynes	434
25.2.3	Product Subclass 3: 2-Thioxoaldehydes	434
25.2.3.1	Synthesis of Product Subclass 3	434
25.2.3.1.1	Method 1: Retro Pericyclic Reactions	434
25.2.4	Product Subclass 4: 2-Phosphoranylidenealdehydes	435
25.2.4.1	Synthesis of Product Subclass 4	435

25.2.4.1.1	Method 1: Formylation of Phosphoranes	435
25.2.4.1.2	Method 2: Electrophilic Substitution in Phosphoranylideneacetaldehyde	436
25.3	Product Class 3: 2,2-Diheteroatom-Substituted Aldehydes	
	M. Harmata	
<hr/>		
25.3	Product Class 3: 2,2-Diheteroatom-Substituted Aldehydes	441
25.3.1	Product Subclass 1: 2,2-Dihaloaldehydes	441
25.3.1.1	Synthesis of Product Subclass 1	441
25.3.1.1.1	Method 1: Synthesis by Halogenation	441
25.3.1.1.1.1	Variation 1: Bromination of an Acetal	441
25.3.1.1.1.2	Variation 2: Halogenation of Enamines	442
25.3.1.1.1.3	Variation 3: Chlorination of Tetrahydrofuran	442
25.3.1.1.1.4	Variation 4: Chlorination of Aldehydes	442
25.3.1.1.2	Method 2: Synthesis by Acylation	445
25.3.1.1.3	Method 3: Synthesis by Rearrangement	448
25.3.1.1.4	Method 4: Synthesis by Oxidation or Reduction	449
25.3.1.1.5	Method 5: Synthesis by Radical Addition	451
25.3.1.1.6	Methods 6: Miscellaneous Procedures	452
25.3.2	Product Subclass 2: 2,2-Dialkoxyaldehydes and Related Species	453
25.3.2.1	Synthesis of Product Subclass 2	453
25.3.2.1.1	Method 1: Synthesis by Oxidation or Reduction	453
25.3.2.1.2	Method 2: Synthesis by Formation of Acetals or Ketals	454
25.3.2.1.3	Method 3: Synthesis by Rearrangement	455
25.3.3	Product Subclass 3: 2,2-Disulfanylaldehydes and Related Species	455
25.3.3.1	Synthesis of Product Subclass 3	455
25.3.3.1.1	Method 1: Synthesis by Sulfanylation or Selanylation	455
25.3.3.1.2	Method 2: Synthesis by Formylation	456
25.3.3.1.3	Method 3: Synthesis by Substitution and Alkylation	457
25.3.3.1.4	Method 4: Synthesis by Oxidation or Reduction	458
25.4	Product Class 4: 2-Heteroatom-Substituted Aldehydes and Sugar Aldehydes	
	M. Eckhardt	
<hr/>		
25.4	Product Class 4: 2-Heteroatom-Substituted Aldehydes and Sugar Aldehydes	463
25.4.1	Product Subclass 1: 2-Haloaldehydes	463
25.4.1.1	Synthesis of Product Subclass 1	464
25.4.1.1.1	2-Fluoroaldehydes	464
25.4.1.1.1.1	Method 1: Fluorination of Aldehydes	464
25.4.1.1.2	2-Chloroaldehydes	466

25.4.1.1.2.1	Method 1: Chlorination of Aldehydes	466
25.4.1.1.2.1.1	Variation 1: Chlorination under Acidic Conditions	466
25.4.1.1.2.1.2	Variation 2: Amine-Catalyzed Chlorination	467
25.4.1.1.3	2-Bromoaldehydes	468
25.4.1.1.3.1	Method 1: Bromination of Aldehydes	468
25.4.1.1.3.1.1	Variation 1: Bromination under Neutral and Acidic Conditions	469
25.4.1.1.3.1.2	Variation 2: Amine-Catalyzed Bromination	471
25.4.1.1.4	2-Iodoaldehydes	472
25.4.1.1.4.1	Method 1: Iodination of Aldehydes	472
25.4.1.1.4.2	Method 2: Iodination of Preformed Enolates	473
25.4.2	Product Subclass 2: 2-Oxylaldehydes	474
25.4.2.1	Synthesis of Product Subclass 2	474
25.4.2.1.1	Method 1: Aminoxylation of Aldehydes	474
25.4.2.1.2	Method 2: Oxidation of Enol Ethers and Silyl Enol Ethers	477
25.4.2.1.3	Method 3: Oxidative C—C Bond Cleavage of Glycols	477
25.4.2.1.4	Method 4: Oxidation/Aminoxylation of Primary Alcohols	480
25.4.2.1.5	Method 5: Addition of Formyl Anion Equivalents to Aldehydes	481
25.4.2.1.5.1	Variation 1: Via 2-(Trimethylsilyl)thiazole	481
25.4.2.1.5.2	Variation 2: Using Carbon Monoxide and a Silane	485
25.4.2.1.5.3	Variation 3: Via Dialkylhydrazones	486
25.4.2.1.5.4	Variation 4: Via Acetals	489
25.4.3	Product Subclass 3: 2-Aminoaldehydes	492
25.4.3.1	Synthesis of Product Subclass 3	493
25.4.3.1.1	Method 1: α -Amination of Aldehydes	493
25.4.3.1.2	Method 2: Oxidative C—C Bond Cleavage of Glycols	495
25.4.3.1.3	Method 3: Addition of Formyl Anion Equivalents to Aldimines and Their Derivatives	496
25.4.3.1.3.1	Variation 1: Via Thiazoles	496
25.4.3.1.3.2	Variation 2: Via Thioacetals	501
25.5	Product Class 5: Ynals	
	B. Witulski and C. Alayrac	
25.5	Product Class 5: Ynals	507
25.5.1	Synthesis of Product Class 5	508
25.5.1.1	Method 1: Substitution Reactions with Alk-1-ynes	508
25.5.1.1.1	Variation 1: Direct Formylation	508
25.5.1.1.2	Variation 2: Two-Step Protocol via Formation of an Acetal	508
25.5.1.1.3	Variation 3: Two-Step Protocol via Formation of an Alcohol	510
25.5.1.2	Method 2: Functionalization of 3,3-Diethoxypropane and Subsequent Acidic Treatment	511
25.5.1.3	Method 3: Oxidation of Propargyl Alcohols	512
25.5.1.3.1	Variation 1: With Chromium(VI) Oxide	512
25.5.1.3.2	Variation 2: With Dess–Martin Periodinane	512

25.5.1.3.3	Variation 3: Swern–Moffatt Reaction	513
25.5.1.3.4	Variation 4: With Titanium(IV) Chloride–Triethylamine	513
25.5.1.4	Method 4: Bromination–Dehydrobromination of Enals	514
25.5.1.5	Method 5: Fritsch–Buttenberg–Wiechell Rearrangement of 1,1-Dibromoalkenes and Subsequent Formylation	515
25.5.1.6	Method 6: Unmasking of Carbonyl Derivatives	515
25.5.1.6.1	Variation 1: Cleavage of Acetals	515
25.5.1.6.2	Variation 2: Synthesis of But-2-ynedial	516
25.5.1.6.3	Variation 3: Deprotection of Tosylhydrazones, Oximes, or Semicarbazones with Chlorotrimethylsilane–Dimethyl Sulfoxide	517
25.5.1.7	Method 7: Vacuum Pyrolysis	518

25.6 Product Class 6: Arenecarbaldehydes

25.6.1 Synthesis by Oxidative Cleavage of Carbon–Carbon Bonds

K. Ditrich

25.6.1	Synthesis by Oxidative Cleavage of Carbon–Carbon Bonds	523
25.6.1.1	Method 1: Cleavage of Arene-Substituted Alkenes	523
25.6.1.1.1	Variation 1: Ozonolysis	523
25.6.1.1.2	Variation 2: Osmium-Catalyzed Cleavage	524
25.6.1.1.3	Variation 3: Cleavage by Permanganate and Periodate	526
25.6.1.2	Method 2: Cleavage of Arylacetic Acids	527
25.6.1.3	Method 3: Cleavage of α -Aryl-Substituted α -Hydroxycarboxylic Acids	528
25.6.1.4	Method 4: Cleavage of α -Aryl-Substituted α -Aminocarboxylic Acids	529

25.6.2 Synthesis by Oxidation

K. Ditrich

25.6.2	Synthesis by Oxidation	531
25.6.2.1	Method 1: Oxidation of Methylarenes	531
25.6.2.1.1	Variation 1: Aerobic Oxidation	531
25.6.2.1.2	Variation 2: Oxidation with Cerium Compounds	532
25.6.2.1.3	Variation 3: Electrochemical Oxidation	533
25.6.2.1.4	Variation 4: Oxidation by Halogenation	534
25.6.2.1.5	Variation 5: Oxidation by Hypervalent Iodine Compounds	535
25.6.2.1.6	Variation 6: Additional Procedures	535
25.6.2.2	Method 2: Oxidation of Arylmethanols	537
25.6.2.2.1	Variation 1: Oxidation with Oxygen or Hydrogen Peroxide	537
25.6.2.2.2	Variation 2: Oxidation with Sodium Hypochlorite	538
25.6.2.2.3	Variation 3: Oxidation with Cerium Compounds	539
25.6.2.2.4	Variation 4: Oxidation with Hypervalent Iodine Compounds	539
25.6.2.2.5	Variation 5: Oxidation with Chromium Compounds	541
25.6.2.2.6	Variation 6: Oxidation with Manganese Compounds	543
25.6.2.2.7	Variation 7: Oxidation with Perruthenates	543

25.6.2.2.8	Variation 8: Oxidation with Sulfoxides (Swern and Pfitzner–Moffat Oxidations)	545
25.6.2.2.9	Variation 9: Oxidation with <i>N</i> -Oxoammonium Salts	547
25.6.2.2.10	Variation 10: Additional Procedures	548
25.6.2.3	Method 3: Oxidation of Benzylic Ethers Including Silyl Ethers	551
25.6.2.4	Method 4: Oxidation of Benzylic Halides	552
25.6.2.4.1	Variation 1: Kornblum Oxidation	552
25.6.2.4.2	Variation 2: Sommelet Reaction	554
25.6.2.4.3	Variation 3: Additional Procedures	554
25.6.2.5	Method 5: Oxidation of Benzylic Nitrogen Compounds	557
25.6.2.5.1	Variation 1: C=N Bond Migration in Schiff Bases	557
25.6.2.5.2	Variation 2: Oxidation of Benzylic Nitro Compounds (The Nef Reaction)	558
25.6.2.5.3	Variation 3: Additional Procedures	559
25.6.3	Synthesis by Reduction	
	K. Ditrich	
25.6.3	Synthesis by Reduction	563
25.6.3.1	Method 1: Reduction of Arenecarboxylic Acids	563
25.6.3.2	Method 2: Reduction of Arenecarboxylic Acid Chlorides	564
25.6.3.2.1	Variation 1: Reduction by Hydrogenation (Rosenmund Reduction)	564
25.6.3.2.2	Variation 2: Reduction by Metal Hydrides	566
25.6.3.3	Method 3: Reduction of Arenecarboxylic Acid Anhydrides	567
25.6.3.4	Method 4: Reduction of Arenecarboxylic Acid Esters	568
25.6.3.5	Method 5: Reduction of Carboxylic Acid Amides and Hydrazides	570
25.6.3.6	Method 6: Reduction of Arenecarbonitriles	571
25.6.3.6.1	Variation 1: Reduction by Hydrogenation	571
25.6.3.6.2	Variation 2: Hydride Reductions	573
25.6.4	Synthesis by Hydrolysis of Aldehyde Derivatives	
	K. Ditrich	
25.6.4	Synthesis by Hydrolysis of Aldehyde Derivatives	575
25.6.4.1	Method 1: Hydrolysis of α,α -Dihalo Compounds	575
25.6.4.2	Method 2: Hydrolysis of <i>O,O</i> -Acetals	577
25.6.4.3	Method 3: Hydrolysis of <i>S,S</i> -Acetals	578
25.6.4.4	Method 4: Hydrolysis of Oximes	580
25.6.4.5	Method 5: Hydrolysis of Hydrazones and Semicarbazones	581
25.6.5	Synthesis by Formylation of Arylmetal Reagents	
	A. Schall and O. Reiser	
25.6.5	Synthesis by Formylation of Arylmetal Reagents	585
25.6.5.1	Formylation of Aryllithium Reagents	585
25.6.5.1.1	Method 1: Formylation of Aryllithium Reagents Generated by Metalation of Arenes	585

25.6.5.1.1.1	Variation 1: <i>ortho</i> -Lithiation Followed by Formylation with Dimethylformamide or Related Reagents	586
25.6.5.1.1.2	Variation 2: <i>ortho</i> -Lithiation Followed by Formylation with Pentacarbonyliron(0)	592
25.6.5.1.1.3	Variation 3: Metalation of Arenes Using the Lochmann–Schlosser Base Followed by Formylation with Dimethylformamide	593
25.6.5.1.2	Method 2: Formylation of Aryllithium Reagents Generated by Lithium–Halogen Exchange	593
25.6.5.2	Formylation of Arylmagnesium Compounds	596
25.6.5.2.1	Method 1: Formylation of Arylmagnesium Compounds Generated by Reductive Magnesiation or Magnesium–Halogen Exchange	596
25.6.5.2.2	Method 2: Formylation of Arylmagnesium Reagents Generated by Addition of Magnesium Thiolates or Amides to Benzyne	601
25.6.6	Synthesis by Formylation of Arene–Hydrogen Bonds	
	A. Schall and O. Reiser	
25.6.6	Synthesis by Formylation of Arene–Hydrogen Bonds	605
25.6.6.1	Method 1: Formylation with Formic Acid	606
25.6.6.2	Method 2: Intramolecular Formylation with Formic Esters: Lewis Acid Mediated Formylation of Phenols by Fries Rearrangement of Aryl Formates	606
25.6.6.3	Method 3: Formylation with Formyl Fluoride	608
25.6.6.4	Method 4: The Vilsmeier–Haack Reaction	609
25.6.6.4.1	Variation 1: Using Dimethylformamide and Pyrophosphoryl Chloride	618
25.6.6.4.2	Variation 2: Formylation in Solvent-Free Conditions Using Microwaves	619
25.6.6.4.3	Variation 3: Vilsmeier–Haack Formylation on Solid Support	620
25.6.6.4.4	Variation 4: Formylation with Polymer-Bound Vilsmeier–Haack Reagent	620
25.6.6.4.5	Variation 5: Vilsmeier–Haack Formylation in a Fluorous/Organic Amphiphilic Ether Solvent	621
25.6.6.5	Method 5: Lewis Acid Mediated Formylation of Aromatic Compounds with Other Formamides	622
25.6.6.5.1	Variation 1: Lewis Acid Catalyzed Formylation of Aromatic Compounds with Triformamide	623
25.6.6.5.2	Variation 2: Formylation of Aromatic Compounds with Tris(diformylamino)methane	626
25.6.6.6	Method 6: Formylation of Aromatic Compounds with Tris(dichloromethyl)amine	628
25.6.6.7	Method 7: Formylation of Aromatic Compounds with Hexamethylenetetramine	630
25.6.6.8	Method 8: Gross Formylation with Dichloromethyl Methyl Ether	632
25.6.6.9	Method 9: Formylation with Triethyl Orthoformate	636
25.6.6.10	Method 10: The Gattermann Reaction	636
25.6.6.10.1	Variation 1: In Situ Generation of Hydrogen Cyanide from Zinc(II) Cyanide	639
25.6.6.10.2	Variation 2: In Situ Generation of Hydrogen Cyanide from 1,3,5-Triazine (Kreutzberger Modification)	640

25.6.6.11	Method 11: The Gattermann–Koch Reaction	642
25.6.6.12	Method 12: Formylation of Arenes with Formaldehyde	643
25.6.6.12.1	Variation 1: Synthesis of Aromatic Aldehydes by Oxidative Hydroxy-methylation with Formaldehyde and 2,3-Dichloro-5,6-dicyanobenzo-1,4-quinone	645
25.6.6.13	Method 13: The Reimer–Tiemann Reaction	645
25.6.7	Synthesis by Carbonylation of Arylpalladium Intermediates	
	A. Schall and O. Reiser	
25.6.7	Synthesis by Carbonylation of Arylpalladium Intermediates	655
25.6.7.1	Method 1: Reductive Carbonylation of Haloarenes and Related Compounds Using Carbon Monoxide	655
25.6.7.2	Method 2: Reductive Carbonylation of Iodoarenes Using Acetic Formic Anhydride as a Carbon Monoxide Source	663
25.6.8	Synthesis by C–C Bond Formation	
	M. Oestreich	
25.6.8	Synthesis by C–C Bond Formation	667
25.6.8.1	Electrophilic Aromatic Substitution of Unprotected Arenecarbaldehydes	668
25.6.8.1.1	Method 1: Aminomethylation (Mannich Reaction)	668
25.6.8.1.2	Method 2: Chloromethylation	670
25.6.8.1.3	Method 3: Friedel–Crafts Acylation	670
25.6.8.2	Directed <i>ortho</i> -Metalation of In Situ Formed α -Amino Alkoxides Derived from Unprotected Arenecarbaldehydes	671
25.6.8.3	<i>ortho</i> -Claisen Rearrangement of (Allyloxy)arenecarbaldehydes	672
25.6.8.4	Transition-Metal-Catalyzed Cross-Coupling Reactions of Electrophilic or Nucleophilic Arenecarbaldehydes	673
25.6.8.4.1	Method 1: sp^2 – sp Cross-Coupling Reactions of Electrophilic Arenecarbaldehydes (Sonogashira Coupling)	673
25.6.8.4.2	Method 2: sp^2 – sp^2 Cross-Coupling Reactions of Electrophilic or Nucleophilic Arenecarbaldehydes	675
25.6.8.4.2.1	Variation 1: Classic Suzuki–Miyaura Coupling Reactions Using Electrophilic Arenecarbaldehydes	675
25.6.8.4.2.2	Variation 2: Ligand-Free Palladium Catalysis and “Transition-Metal-Free” Suzuki–Miyaura-Type Cross Coupling Using Electrophilic Arenecarbaldehydes	677
25.6.8.4.2.3	Variation 3: Nickel(0)-Catalyzed Suzuki–Miyaura Cross-Coupling Reactions Using Electrophilic Arenecarbaldehydes	677
25.6.8.4.2.4	Variation 4: Suzuki–Miyaura-Type Cross-Coupling Reactions Using Dihydroxyborylated Arenecarbaldehydes	678
25.6.8.4.2.5	Variation 5: Stille-Type Cross-Coupling Reactions Using Electrophilic Arenecarbaldehydes	679

25.6.8.4.2.6	Variation 6: Stille-Type Cross-Coupling Reactions Using Trialkylstannylated Arenecarbaldehydes	680
25.6.8.4.2.7	Variation 7: Negishi-Type Cross-Coupling Reactions Using Electrophilic Arenecarbaldehydes	681
25.6.8.4.2.8	Variation 8: Hiyama-Type Cross-Coupling Reactions Using Electrophilic Arenecarbaldehydes	681
25.6.8.5	Palladium-Catalyzed Arylation of Alkenes Using Electrophilic Arenecarbaldehydes (Heck Reaction)	682
25.6.8.6	Transition-Metal-Catalyzed Cyanation of Haloarenecarbaldehydes	683
25.6.8.7	Transition-Metal-Catalyzed Homocoupling of 4-Halobenzaldehydes (Ullmann-Type Reactions) or Dihydroxyborylated Arenecarbaldehydes	683
25.6.9	Synthesis by C—X Bond Formation	
	T. Berkenbusch	
25.6.9	Synthesis by C—X Bond Formation	689
25.6.9.1	Synthesis by Electrophilic Aromatic Substitution: Hydrogen–Heteroatom Exchange	690
25.6.9.1.1	Halogenation of Arenecarbaldehydes	690
25.6.9.1.1.1	Method 1: Fluorination	690
25.6.9.1.1.2	Method 2: Chlorination	691
25.6.9.1.1.3	Method 3: Bromination	692
25.6.9.1.1.4	Method 4: Iodination	693
25.6.9.1.2	Nitration of Arenecarbaldehydes	694
25.6.9.2	Synthesis by Nucleophilic Aromatic Substitution: Heteroatom–Heteroatom Exchange	695
25.6.9.2.1	Halogen–Heteroatom Exchange Reactions	695
25.6.9.2.1.1	Method 1: Halogen–Nitrogen Exchange	696
25.6.9.2.1.1.1	Variation 1: Halogen–Nitrogen Exchange in the Absence of a Transition Metal	696
25.6.9.2.1.1.2	Variation 2: Palladium-Mediated Halogen–Nitrogen Exchange	698
25.6.9.2.1.2	Method 2: Halogen–Phosphorus Exchange	699
25.6.9.2.1.3	Method 3: Halogen–Oxygen Exchange	700
25.6.9.2.1.3.1	Variation 1: Halogen–Oxygen Exchange in the Absence of a Transition Metal	700
25.6.9.2.1.3.2	Variation 2: Copper-Mediated Halogen–Oxygen Exchange	701
25.6.9.2.1.3.3	Variation 3: Palladium- and Nickel-Mediated Halogen–Oxygen Exchange	702
25.6.9.2.1.4	Method 4: Halogen–Sulfur Exchange	703
25.6.9.2.1.4.1	Variation 1: Halogen–Sulfur Exchange in the Absence of a Transition Metal	703
25.6.9.2.1.4.2	Variation 2: Copper-Mediated Halogen–Sulfur Exchange	704
25.6.9.2.1.5	Method 5: Halogen–Fluorine Exchange	705
25.6.9.2.2	Diazonium–Heteroatom Exchange Reactions	705
25.6.9.3	Functionalization of <i>ortho</i> -Lithiated α -Amino Alkoxides Derived from Arenecarbaldehydes	707

25.7	Product Class 7: Polyenals	
	I. Escher and F. Glorius	
<hr/>		
25.7	Product Class 7: Polyenals	711
25.7.1	Synthesis of Product Class 7	711
25.7.1.1	Method 1: Oxidation of Alcohols	711
25.7.1.2	Method 2: Ring-Opening Reactions of Heterocycles	712
25.7.1.2.1	Variation 1: Addition of α -Oxocarbenes to Furans	713
25.7.1.2.2	Variation 2: Addition of Organolithium Reagents to Pyrylium Salts	714
25.7.1.2.3	Variation 3: Addition of Amines or Hydroxide Ion to Pyridinium Salts	715
25.7.1.3	Method 3: Reduction of Carboxylic Acid Derivatives	716
25.7.1.4	Method 4: Synthesis by Elimination	717
25.7.1.5	Method 5: Formylation of Dienes	719
25.7.1.6	Method 6: Addition of Enolates and Derivatives to Carbonyl Compounds	721
25.7.1.6.1	Variation 1: Addition of Enolates and Silyl Enol Ethers to Carbonyl Compounds	721
25.7.1.6.2	Variation 2: Addition of Metalated Vinyl Ethers to Carbonyl Compounds	723
25.7.1.7	Method 7: Wittig and Horner–Wadsworth–Emmons Reactions	724
25.7.1.8	Method 8: Cross-Coupling Reaction of Enals and Polyenals	726
25.7.1.9	Methods 9: Additional Methods	728
<hr/>		
25.8	Product Class 8: α,β-Unsaturated Aldehydes	
	I. Escher and F. Glorius	
<hr/>		
25.8	Product Class 8: α,β-Unsaturated Aldehydes	733
25.8.1	Product Subclass 1: Nonheteroatom-Substituted α,β-Unsaturated Aldehydes	733
25.8.1.1	Synthesis of Product Subclass 1	733
25.8.1.1.1	Method 1: Oxidative Cleavage of Alkenes	733
25.8.1.1.2	Method 2: Oxidation of Allylic Alcohols	734
25.8.1.1.3	Method 3: Oxidation of Allylic Methyl Groups	736
25.8.1.1.4	Method 4: Unsaturation of Saturated Aldehydes	736
25.8.1.1.4.1	Variation 1: Unsaturation of Silyl Enol Ethers with Lead(IV) Acetate	736
25.8.1.1.4.2	Variation 2: Unsaturation of Alkenyl Allyl Carbonates or Methyl Enol Ethers by Palladium Catalysis	737
25.8.1.1.4.3	Variation 3: Conversion of Saturated Primary Alcohols or Aldehydes into α,β -Unsaturated Aldehydes	738
25.8.1.1.5	Method 5: Synthesis by Reduction	739
25.8.1.1.6	Method 6: Synthesis by Elimination	741
25.8.1.1.7	Method 7: Synthesis by Hydrolysis of Acetals or Imines	742
25.8.1.1.8	Method 8: One-Carbon-Atom Extension	742
25.8.1.1.8.1	Variation 1: By Formylation of Alkenes	743
25.8.1.1.8.2	Variation 2: One-Carbon-Atom Extension of Alkenyl Halides Using Organometallic Reagents	743
25.8.1.1.8.3	Variation 3: Formation of α,β -Unsaturated Aldehydes by Rearrangement of β -Hydroxy Alcohols	744

25.8.1.1.9	Method 9:	Cross Metathesis of Terminal Alkenes with Acrolein	745
25.8.1.1.10	Method 10:	Aldol Condensations	747
25.8.1.1.11	Method 11:	Cross Aldolization of Aldehydes with Vinyl Acetate	748
25.8.1.1.12	Method 12:	Addition of Organometallic Reagents to Carbonyl Compounds	749
25.8.1.1.12.1	Variation 1:	Addition of Vinyllithium Reagents to Carbonyl Compounds ..	749
25.8.1.1.12.2	Variation 2:	Wittig Reaction	750
25.8.1.1.12.3	Variation 3:	Combined Alcohol Oxidation and Wittig Reaction	751
25.8.1.1.12.4	Variation 4:	Peterson Alkenation	751
25.8.1.1.13	Method 13:	Double Bond Migration	752
25.8.1.1.13.1	Variation 1:	Isomerization of β,γ - to α,β -Unsaturated Aldehydes	752
25.8.1.1.13.2	Variation 2:	Opening of Vinyl Epoxides	753
25.8.1.1.13.3	Variation 3:	Isomerization of Alkynols by Meyer–Schuster–Rupe Reactions	753
25.8.1.1.14	Method 14:	Three-Carbon-Atom Elongation	755
25.8.1.1.14.1	Variation 1:	Heck Reaction	755
25.8.1.1.14.2	Variation 2:	Vinylogous–Vilsmeier Formylation	756
25.8.1.1.15	Method 15:	Diels–Alder Reactions	757
25.8.1.1.16	Method 16:	Modification of α,β -Unsaturated Aldehydes	757
25.8.1.1.16.1	Variation 1:	Substitution of an Alkoxy or Siloxy Group by Nucleophiles ...	757
25.8.1.1.16.2	Variation 2:	Cross-Coupling Reactions	758
25.8.1.1.17	Methods 17:	Additional Methods	759
25.8.1.1.17.1	Variation 1:	Formylalkenation	760
25.8.1.1.17.2	Variation 2:	Two-Carbon-Atom Homologation with α,α -Disilylated Aldimines	760
25.8.1.1.17.3	Variation 3:	Kharasch Addition	761
25.8.1.1.17.4	Variation 4:	Four-Carbon-Atom Extension of Grignard Reagents	762
25.8.2	Product Subclass 2: Heteroatom-Substituted α,β-Unsaturated Aldehydes		763
25.8.2.1	Synthesis of Product Subclass 2		763
25.8.2.1.1	Method 1:	Addition of Organometallic Reagents to Carbonyl Compounds	763
25.8.2.1.2	Method 2:	Cyclopropanation with Halogenated Carbenes, Followed by Ring Opening of the Halogenated Cyclopropanes	764
25.8.2.1.3	Method 3:	Reactions of 1,3-Dicarbonyl Compounds with Nitrogen Nucleophiles	765
25.8.2.1.4	Method 4:	Formylation Reactions	765
25.8.2.1.4.1	Variation 1:	Vilsmeier–Haack–Arnold Formylation	765
25.8.2.1.4.2	Variation 2:	Formylation of Electron-Rich Double Bonds	767
25.8.2.1.4.3	Variation 3:	Sulfanylformylation of Alkynes	768
25.8.2.1.5	Method 5:	α -Halogenation, Selenation, or Methoxylation of α,β -Unsaturated Aldehydes	768
25.8.2.1.6	Method 6:	Substitution of the Halogen Atom of α -Halogenated α,β -Unsaturated Aldehydes	770
25.8.2.1.7	Methods 7:	Additional Methods	770
25.8.2.1.7.1	Variation 1:	Addition to Acetylene Aldehydes	770

25.9	Product Class 9: 3-Heteroatom-Substituted Aldehydes	
	A. Lindenschmidt	
25.9	Product Class 9: 3-Heteroatom-Substituted Aldehydes	779
25.9.1	Product Subclass 1: 3-Silicon-Substituted Aldehydes	779
25.9.1.1	Synthesis of Product Subclass 1	779
25.9.2	Product Subclass 2: 3-Tin-Substituted Aldehydes	780
25.9.2.1	Synthesis of Product Subclass 2	780
25.9.3	Product Subclass 3: 3-Boron-Substituted Aldehydes	781
25.9.3.1	Synthesis of Product Subclass 3	781
25.9.4	Product Subclass 4: 3-Halogen-Substituted Aldehydes	782
25.9.4.1	Synthesis of Product Subclass 4	782
25.9.5	Product Subclass 5: 3-Oxygen-Substituted Aldehydes	782
25.9.5.1	Synthesis of Product Subclass 5	782
25.9.5.1.1	Method 1: Oxidative Cleavage of Homoallylic Alcohols	782
25.9.5.1.1.1	Variation 1: By Ozonolysis	783
25.9.5.1.1.2	Variation 2: By Dihydroxylation/Diol Cleavage	784
25.9.5.1.2	Method 2: Wacker Oxidation of Homoallylic Alcohols	785
25.9.5.1.3	Method 3: Hydroboration of Allylic or Propargylic Alcohols	786
25.9.5.1.4	Method 4: Ruthenium-Catalyzed Anti-Markovnikov Hydration of Terminal Alkynes	787
25.9.5.1.5	Method 5: Ring Opening of Epoxides and 1,3-Dithianes	788
25.9.5.1.6	Method 6: Synthesis from 4,5-Dihydroisoxazoles	790
25.9.5.1.7	Method 7: Hydroformylation of Enol Ethers	791
25.9.5.1.8	Method 8: 1,4-Addition of Oxygen Nucleophiles to α,β -Unsaturated Aldehydes	792
25.9.6	Product Subclass 6: 3-Sulfur-Substituted Aldehydes	792
25.9.6.1	Synthesis of Product Subclass 6	792
25.9.7	Product Subclass 7: 3-Nitrogen-Substituted Aldehydes	793
25.9.7.1	Synthesis of Product Subclass 7	793
25.9.7.1.1	Method 1: 1,4-Addition of Nitrogen Nucleophiles to α,β -Unsaturated Aldehydes	793
25.9.7.1.2	Method 2: Oxidative Cleavage of Homoallylic Amines	794
25.9.7.1.3	Method 3: Oxidation of Allylic or Propargylic Amines	795
25.9.7.1.4	Method 4: Ring Opening of Aziridines or Cyclic Sulfamidates	796
25.9.7.1.5	Method 5: Synthesis by Substitution	797
25.9.8	Product Subclass 8: 3-Phosphorus-Substituted Aldehydes	797
25.9.8.1	Synthesis of Product Subclass 8	797

Keyword Index	803
Author Index	841
Abbreviations	897