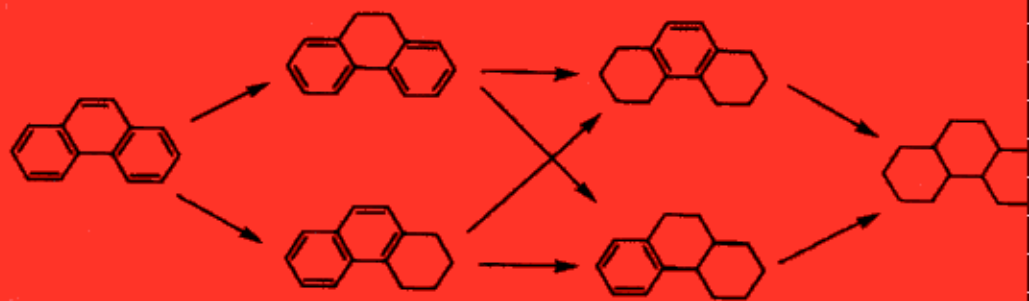


Handbook of  
Heterogeneous  
Catalytic  
Hydrogenation  
for  
Organic Synthesis



SHIGEO NISHIMURA

## CONTENTS

---

<b>Preface</b>	<b>xi</b>
<b>1 Hydrogenation Catalysts</b>	<b>1</b>
1.1 Nickel Catalysts	2
1.1.1 Reduced Nickel	3
1.1.2 Nickel from Nickel Formate	5
1.1.3 Raney Nickel	7
1.1.4 Urushibara Nickel	19
1.1.5 Nickel Boride	20
1.2 Cobalt Catalysts	23
1.2.1 Reduced Cobalt	23
1.2.2 Raney Cobalt	24
1.2.3 Cobalt Boride	25
1.2.4 Urushibara Cobalt	26
1.3 Copper Catalysts	26
1.4 Iron Catalysts	28
1.5 Platinum Group Metal Catalysts	29
1.5.1 Platinum	30
1.5.2 Palladium	34
1.5.3 Ruthenium	38
1.5.4 Rhodium	40
1.5.5 Osmium	41
1.5.6 Iridium	42
1.6 Rhenium Catalysts	42
1.7 The Oxide and Sulfide Catalysts of Transition Metals Other than Rhenium	43
<b>2 Reactors and Reaction Conditions</b>	<b>52</b>
2.1 Reactors	52
2.2 Reaction Conditions	53
2.2.1 Inhibitors and Poisons	53
2.2.2 Temperature and Hydrogen Pressure	59

<b>3</b>	<b>Hydrogenation of Alkenes</b>	<b>64</b>
3.1	Isolated Double Bonds: General Aspects	65
3.2	Hydrogenation and Isomerization	68
3.3	Alkyl-Substituted Ethylenes	72
3.4	Selective Hydrogenation of Isolated Double Bonds	77
3.5	Fatty Acid Esters and Glyceride Oils	84
3.6	Conjugated Double Bonds	92
3.6.1	Aryl-Substituted Ethylenes	92
3.6.2	$\alpha,\beta$ -Unsaturated Acids and Esters	93
3.6.3	Conjugated Dienes	94
3.7	Stereochemistry of the Hydrogenation of Carbon–Carbon Double Bonds	100
3.7.1	<i>Syn</i> and Apparent <i>Anti</i> Addition of Hydrogen	100
3.7.2	Catalyst Hindrance	105
3.7.3	Effects of Polar Groups	111
3.8	Selective Hydrogenations in the Presence of Other Functional Groups	119
3.8.1	Isolated Double Bonds in the Presence of a Carbonyl Group	119
3.8.2	Double Bonds Conjugated with a Carbonyl Group	122
3.8.3	Stereochemistry of the Hydrogenation of $\Delta^{1,9}$ -2-Octalone and Related Systems	129
3.8.4	An Olefin Moiety in the Presence of Terminal Alkyne Function	136
3.8.5	$\beta$ -Alkoxy- $\alpha,\beta$ -Unsaturated Ketones (Vinylogous Esters)	137
<b>4</b>	<b>Hydrogenation of Alkynes</b>	<b>148</b>
4.1	Hydrogenation over Palladium Catalysts	149
4.2	Hydrogenation over Nickel Catalysts	160
4.3	Hydrogenation over Iron Catalysts	165
<b>5</b>	<b>Hydrogenation of Aldehydes and Ketones</b>	<b>170</b>
5.1	Aldehydes	170
5.2	Hydrogenation of Unsaturated Aldehydes to Unsaturated Alcohols	178
5.3	Ketones	185
5.3.1	Aliphatic and Alicyclic Ketones	186
5.3.2	Aromatic Ketones	190
5.3.3	Hydrogenation Accompanied by Hydrogenolysis and Cyclization	193
5.3.4	Amino Ketones	197
5.3.5	Unsaturated Ketones	198
5.4	Stereochemistry of the Hydrogenation of Ketones	200
5.4.1	Hydrogenation of Cyclohexanones to Axial Alcohols	200

5.4.2	Hydrogenation of Cyclohexanones to Equatorial Alcohols	205
5.4.3	Effects of a Polar Substituent and Heteroatoms in the Ring	207
5.4.4	Alkylcyclopentanones	208
5.4.5	Hindered Ketones	209
5.4.6	Hydrogenation of Fructose	212
5.4.7	Enantioselective Hydrogenations	212
5.5	Mechanistic Aspects of the Hydrogenation of Ketones	218
<b>6</b>	<b>Preparation of Amines by Reductive Alkylation</b>	<b>226</b>
6.1	Reductive Alkylation of Ammonia with Carbonyl Compounds	226
6.2	Reductive Alkylation of Primary Amines with Carbonyl Compounds	236
6.3	Preparation of Tertiary Amines	241
6.4	Reductive Alkylation of Amine Precursors	246
6.5	Alkylation of Amines with Alcohols	247
6.6	Synthesis of Optically Active $\alpha$ -Amino Acids from $\alpha$ -Oxo Acids by Asymmetric Transamination	248
6.7	Asymmetric Synthesis of 2-Substituted Cyclohexylamines	250
<b>7</b>	<b>Hydrogenation of Nitriles</b>	<b>254</b>
7.1	General Aspects	254
7.2	Hydrogenation to Primary Amines	259
7.3	Hydrogenation of Dinitriles to Aminonitriles	265
7.4	Hydrogenation to Aldimines or Aldehydes	267
7.5	Hydrogenation to Secondary and Tertiary Amines	270
7.6	Hydrogenation Accompanied by Side Reactions	273
7.6.1	Aminonitriles	273
7.6.2	Hydroxy- and Alkoxy nitriles	275
7.6.3	Hydrogenation Accompanied by Cyclization	277
<b>8</b>	<b>Hydrogenation of Imines, Oximes, and Related Compounds</b>	<b>286</b>
8.1	Imines	286
8.1.1	<i>N</i> -Unsubstituted Imines	286
8.1.2	Aliphatic <i>N</i> -Substituted Imines	287
8.1.3	Aromatic <i>N</i> -Substituted Imines	288
8.2	Oximes	290
8.2.1	Hydrogenation to Amines	291
8.2.2	Hydrogenation to Hydroxylamines	301
8.2.3	Hydrogenation Accompanied by Cyclization	302
8.3	Hydrazones and Azines	305
8.3.1	Hydrazones	305
8.3.2	Azines	310

<b>9 Hydrogenation of Nitro, Nitroso, and Related Compounds</b>	<b>315</b>
9.1 Hydrogenation of Nitro Compounds: General Aspects	315
9.2 Aliphatic Nitro Compounds	315
9.2.1 Hydrogenation Kinetics	315
9.2.2 Hydrogenation to Amines	316
9.2.3 Hydrogenation to Nitroso or Hydroxyimino and Hydroxyamino Compounds	322
9.2.4 Conjugated Nitroalkenes	327
9.2.5 Hydrogenation Accompanied by Cyclization	330
9.3 Aromatic Nitro Compounds	332
9.3.1 Hydrogenation to Amines	332
9.3.2 Halonitrobenzenes	342
9.3.3 Hydrogenation of Dinitrobenzenes to Aminonitrobenzenes	347
9.3.4 Selective Hydrogenations in the Presence of Other Unsaturated Functions	350
9.3.5 Hydrogenation Accompanied by Condensation or Cyclization	353
9.3.6 Hydrogenation to Hydroxylamines	359
9.3.7 Hydrogenation to Hydrazobenzenes	362
9.4 Nitroso Compounds	363
9.5 <i>N</i> -Oxides	369
9.6 Other Nitrogen Functions Leading to the Formation of Amino Groups	371
9.6.1 Azo Compounds	371
9.6.2 Diazo Compounds	375
9.6.3 Azides	377
<b>10 Hydrogenation of Carboxylic Acids, Esters, and Related Compounds</b>	<b>387</b>
10.1 Carboxylic Acids	387
10.1.1 Hydrogenation to Alcohols	387
10.1.2 Hydrogenation to Aldehydes	391
10.2 Esters, Lactones, and Acid Anhydrides	392
10.2.1 Esters	392
10.2.2 Hydrogenation of Unsaturated Esters to Unsaturated Alcohols	398
10.2.3 Hydrogenation of Esters to Ethers	399
10.2.4 Lactones	399
10.2.5 Acid Anhydrides	402
10.3 Acid Amides, Lactams, and Imides	406
<b>11 Hydrogenation of Aromatic Compounds</b>	<b>414</b>
11.1 Aromatic Hydrocarbons	414

11.1.1	Hydrogenation of Benzene to Cyclohexene	419
11.1.2	Hydrogenation of Polyphenyl Compounds to Cyclohexylphenyl Derivatives	421
11.1.3	Stereochemistry of Hydrogenation	423
11.2	Phenols and Phenyl Ethers	427
11.2.1	Phenols	427
11.2.2	Hydrogenation to Cyclohexanones	436
11.2.3	Phenyl Ethers	441
11.3	Aromatic Compounds Containing Benzyl–Oxygen Linkages	447
11.4	Carboxylic Acids and Esters	454
11.5	Arylamines	459
11.6	Naphthalene and Its Derivatives	469
11.7	Anthracene, Phenathrene, and Related Compounds	477
11.8	Other Polynuclear Compounds	482
<b>12</b>	<b>Hydrogenation of Heterocyclic Aromatic Compounds</b>	<b>497</b>
12.1	<i>N</i> -Heterocycles	497
12.1.1	Pyrroles	497
12.1.2	Indoles and Related Compounds	500
12.1.3	Pyridines	504
12.1.4	Quinolines, Isoquinolines, and Related Compounds	518
12.1.5	Polynuclear Compounds Containing a Bridgehead Nitrogen	532
12.1.6	Polynuclear Compounds with More than One Nitrogen Ring	534
12.1.7	Compounds with More than One Nitrogen Atom in the Same Ring	536
12.2	<i>O</i> -Heterocycles	547
12.2.1	Furans and Related Compounds	547
12.2.2	Pyrans, Pyrones, and Related Compounds	554
12.3	<i>S</i> -Heterocycles	562
<b>13</b>	<b>Hydrogenolysis</b>	<b>572</b>
13.1	Hydrogenolysis of Carbon–Oxygen Bonds	572
13.1.1	Alcohols and Ethers	572
13.1.2	Epoxy Compounds	575
13.1.3	Benzyl–Oxygen Functions	583
13.1.4	Stereochemistry of the Hydrogenolysis of Benzyl–Oxygen Compounds	594
13.1.5	Vinyl–Oxygen Compounds	598
13.2	Hydrogenolysis of Carbon–Nitrogen Bonds	601
13.3	Hydrogenolysis of Organic Sulfur Compounds	607
13.3.1	Thiols	610

13.3.2	Thioethers	613
13.3.3	Hemithioacetals	614
13.3.4	Dithioacetals	616
13.3.5	Thiophenes	617
13.3.6	Thiol Esters and Thioamides	618
13.3.7	Disulfides	618
13.3.8	Hydrogenolysis over Metal Sulfide Catalysts	619
13.3.9	Sulfones, Sulfonic Acids, and Their Derivatives	620
13.3.10	Stereochemistry of the Desulfurization with Raney Nickel	622
13.4	Hydrogenolysis of Carbon–Halogen Bonds	623
13.4.1	R–X Bonds at Saturated Carbons	623
13.4.2	Activated Alkyl and Cycloalkyl Halides	629
13.4.3	Allyl and Vinyl Halides	631
13.4.4	Benzyl and Aryl Halides	633
13.4.5	Halothiazoles	637
13.4.6	Hydrogenolysis of Acid Chlorides to Aldehydes (the Rosenmund Reduction)	638
13.5	Hydrogenolysis of Carbon–Carbon Bonds	640
13.5.1	Cyclopropanes	640
13.5.2	Cyclobutanes	647
13.5.3	Open-Chain Carbon–Carbon Bonds	647
13.6	Miscellaneous Hydrogenolyses	651
13.6.1	Nitrogen–Oxygen and Nitrogen–Nitrogen Bonds	651
13.6.2	Oxygen–Oxygen Bonds	653
	<b>General Bibliography</b>	<b>664</b>
	<b>Author Index</b>	<b>665</b>
	<b>Subject Index</b>	<b>679</b>