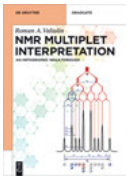
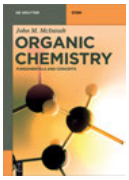
Roman A. Valiulin

Organic Chemistry: 100 Must-Know Mechanisms

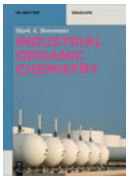
Also of Interest



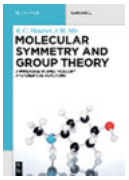
NMR Multiplet Interpretation.
An Infographic Walk-Through
Valiulin, 2019
ISBN 978-3-11-060835-9, e-ISBN 978-3-11-060840-3



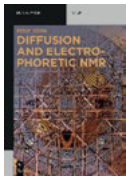
Organic Chemistry.
Fundamentals and Concepts
McIntosh, 2018
ISBN 978-3-11-056512-6, e-ISBN 978-3-11-056514-0



Industrial Organic Chemistry.
Benvenuto, 2017
ISBN 978-3-11-049446-4, e-ISBN 978-3-11-049447-1



Molecular Symmetry and Group Theory.
Approaches in Spectroscopy and Chemical Reactions
Maurya, Mir, 2019
ISBN 978-3-11-063496-9, e-ISBN 978-3-11-063503-4



Diffusion and Electrophoretic NMR.
Stilbs, 2019
ISBN 978-3-11-055152-5, e-ISBN 978-3-11-055153-2

Roman A. Valiulin

Organic Chemistry: 100 Must-Know Mechanisms

DE GRUYTER

Author
Dr. Roman A. Valiulin

ISBN 978-3-11-060830-4
e-ISBN (PDF) 978-3-11-060837-3
e-ISBN (EPUB) 978-3-11-060851-9

Library of Congress Control Number: 2020931119

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

© 2020 Walter de Gruyter GmbH, Berlin/Boston
Cover image: Roman A. Valiulin (graphics), bestbrk / iStock / Getty Images Plus (background)
Typesetting: Integra Software Services Pvt. Ltd.
Printing and binding: CPI books GmbH, Leck

www.degruyter.com

Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.

— Marie Curie

Preface and Overview

Pedagogical Principles. At first, every body of knowledge that is new to us seems to have boundless complexity and creates the initial impression of incomprehensibility and even fear. Organic chemistry provides an excellent example of this phenomenon. The discipline is replete with complex and initially abstract concepts, as a result the information may seem overwhelming, particularly for the young chemist. But as with most new subjects, consistent study and practice reveals patterns, commonalities, rules, and an apparent logic. Eventually, an "architecture" becomes more apparent as we grow to become more experienced chemists. To develop this intuition, it requires close study, repetition, and breadth of exposure. A significant element of that learning is intrinsic and simply requires time and immersion. However, to help with the development of this intuition, an organic chemist would also be wise to focus on mechanisms for organic reactions as a foundation or anchoring point. This, in combination with deep study, can help organize knowledge into skill and expertise. An understanding of reaction mechanisms provides a solid foundation for the field and a scaffold for further study and life-long learning. Mechanisms are highly useful because they can logically explain how a chemical bond in a molecule was formed or broken and help to rationalize the formation of the final synthetic target or an undesired side-product. Moreover, as we parse an increasing number of mechanisms, we begin to see the similarities and an invisible conceptual "thread" then forms in our mind's eye that was not previously apparent. It helps to organize thinking and brings sense to the otherwise foreign concepts such as reactive intermediates, transition states, charges, radicals, and mechanistic arrows.

The Approach. To help galvanize – and perhaps catalyze – the organic chemist's inductive ability and to provide a "go-to" reference for closer study, this book strives to present an abridged summary of some of the most important mechanisms. In today's terms, these are 100 MUST-KNOW Mechanisms. The author draws upon scientific knowledge developed through undergraduate and graduate years, including post-doctoral research and study focused on organic synthesis. With a keen awareness of the incremental learning process, the book curates and presents mechanisms by category, starting with the fundamental and basic mechanisms (e.g., *nucleophilic substitution* or *elimination*), and mechanisms associated with the most well-known named reactions (e.g., the ***Diels–Alder*** *reaction* or the ***Mitsunobu*** *reaction*). Additionally, the collection is complemented with historically important mechanisms (e.g., the *diazotization* or the *haloform reaction*). Finally, it includes some mechanisms dear to the author's heart, which he deems elegant or simply "cool" (e.g., the ***Paternò–Büchi*** *cycloaddition* or the *alkyne zipper reaction*).

Organization. The mechanisms are organized alphabetically by chapter for ease of reference, and numbered from 1 to 100. The dedicated student will consistently proceed through every single mechanism, giving each one time to study, practice with, memorize, and ponder. At the same time, the book can be used as a quick visual

https://doi.org/10.1515/9783110608373-202

reference or as a starting point for further research and reading. The 100 mechanisms are selected for being classic and famous, core or fundamental, and useful in practice. Of course, a good degree of personal intuition is involved in the selection and it is definitely not a dogmatic ordering or a comprehensive anthology. The book is intended to be a visual guide as distinguished from a traditional text book. The presentation of each mechanism constitutes a complete InfoGraphic (or "MechanoGraphic") and provides distilled information focusing on key concepts, rules, acronyms, and terminology. It heavily focuses on the basic core – the starting amount of information, the extract – that a good organic chemist can commit to memory and understanding. Starting initially as a daily micro-blog post with a "hash tag" (#100MustKnowMechanisms) that gained a lot of support from students and chemists around the world, the book is really intended to bring together an array of mechanisms, organize them, provide additional historical context, and enable a conceptual space where the reader can focus on learning them as well as serve as a desk-reference or a "flip-book".

The book is color-coded: each key reaction is enclosed in a dark blue frame; each key mechanism (the center piece of the book) is presented in a red frame; other reactions and mechanisms related to the core 100 mechanisms covered in this book are usually summarized in grey frames. The book also collects a few useful rules, facts, and concepts that are presented in green frames. The reader may find several star diagrams, representing synthetic diversity, for example, throughout the book as well. Relevant comments and clarifications can be found in footnotes.

Sources. The underlying information stays very close to information usually covered in classic or key organic chemistry text books [1]. More specialized literature may be necessary in some cases (for organometallic or photochemical transformations, for example) [2]. The reader is also encouraged to familiarize themselves with some other supporting bibliography [3]. Where appropriate, it also references texts that the author trusts and cites for further in-depth study if the reader so chooses. Since this book strives to be an abridged visual illustration, students are encouraged to use other, more comprehensive books on the subject, especially those related to the *named reactions* in organic chemistry [4]. Additionally, open on-line sources, when thoughtfully selected, can also be very useful [5]. Such sources may be mentioned here when the information was deemed accurate, thorough, and supported by the references. This is further supplemented by the author's aggregate knowledge and education gained through college, graduate school, and post-doctoral academic research. The author also found the encyclopedia of organic reagents [6] to be an extremely useful "go-to" starting point in his personal experience and professional career, especially when embracing a new chemistry topic or using a new reagent. Moreover, each *MechanoGraphic* is supported by reference to the likely first original publication where the related reaction or mechanism was first mentioned (see the time-scale after each mechanism). Finally, several key and fundamental reviews; publications on recently elucidated mechanisms; and other research articles are referenced, as needed. The author uses his best judgement in each case. However, even though the

provided information was carefully checked, and presented in agreement with standard and accepted chemistry rules, this does not guarantee that it is free of all errors. A further caveat, the variety of text and scholarly references does not imply a comprehensive and chronological review of the literature and history – it is not a global historic review of mechanisms from 1800–2020. Mechanisms and our understanding of them can also change as this book is being prepared and the corresponding literature revised. Thus, the reader should supplement the use of the book with primary source reading and deeper study through a comprehensive textbook prepared by a cohort of experienced professors and experts. Here, the most common and known pathways, those that do not violate basic standard chemistry rules and that are frequently referenced in the classic and contemporary literature, are summarized visually.

A Few Things to Keep in Mind. It is also important that the reader remain flexible and mindful that mechanisms are represented based on our current understanding, taking into consideration basic chemistry rules, valency, electron pushing rules, charge preservation, Lewis dot structures, etc. They may not be the most "cutting-edge" or up-to-date (e.g., cross-coupling reactions that may not be well-understood). They may also be substrate-dependent and each reaction may undergo a slightly different pathway. Thus, the reader should not treat the book as a dogmatic guide, and should keep an open mind for new data, creativity, and view the book as part of a continuous debate in the subject.

Background Knowledge. To fully benefit from the book, the reader should have basic knowledge of organic chemistry. Figures are presented with an assumption that the reader understands common terms and symbols. Thus, basic concepts are not introduced or explained. Undergraduate students, graduate students, scientists, teachers, and professors in the discipline should be able to utilize the book. The book can also serve as a good condensed "refresher" for the experienced organic chemist who wants to "zero-in" on the most basic and fundamental core mechanisms as judged by the author.

The Inspiration and Further Reading. The author heavily draws upon his personal experience as a student of chemistry and later an academic researcher. Never having taken a formal course on mechanisms in organic chemistry, he approached the material initially through memorization as opposed to derivation. The first impression was fear and a sense of being overwhelmed. However, after many years of experience, more obvious patterns, trends, rules, and dependencies appear to have crystallized providing an inductive ability to navigate and identify the mechanisms behind reactions. This personal experience has definitely shaped the teaching philosophy of the book, and is further enhanced by the efficient way in which information can be conveyed through visuals and space. Moreover, as most individuals have a predisposition for visual learning – this book is more intuitively aligned with the way that we seem to learn the fastest. It strives to be a focused collection of the most useful, basic, and fundamental mechanisms. Started initially as a micro-blog post, the discussion, engagement, and interest it sparked indicated a clear need for a more-carefully prepared,

organized, and curated presentation in a format that could be placed in a physical library and easily internalized. The author hopes the book serves as a good starting point for the developing chemist who may need the most guidance and encouragement. No doubt it may stimulate constructive discussion, but nevertheless this will ultimately encourage and challenge everyone to learn, to search for a different answer, to think critically, and grow as a chemist and stay sharp as a scientist. Finally, knowledge is a fractal-like concept, the closer we look the more detail we see and learn. Here, we strive to reach a reasonable asymptote of precision and comprehensiveness given the purpose of the book. Further core reading [1], reference of primary and secondary sources [2–4], and on-line sources [5 and 6] as well as actual experimentation and practice will help paint the complete picture and prepare the organic chemist to be a well-rounded and informed scientist.

Contents

Preface and Overview —— VII

List of Acronyms and Abbreviations —— 6

1 Electrophilic Addition Mechanism —— 10

2 Nucleophilic Substitution Mechanism —— 12

3 Aromatic Electrophilic Substitution Mechanism —— 14

4 Aromatic Nucleophilic Substitution Mechanism —— 16

5 Aromatic Radical Nucleophilic Substitution Mechanism —— 18

6 Elimination Mechanism —— 22

7 Acyloin Condensation —— 26

8 Alkyne Zipper Reaction —— 28

9 Arbuzov Reaction —— 30

10 Arndt–Eistert Synthesis —— 32

11 Baeyer–Villiger Oxidation —— 34

12 Barton Decarboxylation —— 36

13 Baylis–Hillman Reaction —— 38

14 Beckmann Rearrangement —— 40

15 Benzoin Condensation —— 42

16 Benzyne Mechanism —— 44

17 Bergman Cyclization —— 46

18 Birch Reduction —— 48

19 Bischler–Napieralski Cyclization —— 50

20 Brown Hydroboration —— 52

21 Buchwald–Hartwig Cross Coupling —— 54

22 Cannizzaro Reaction —— 56

23 Chan–Evans–Lam Cross Coupling —— 58

24 Chichibabin Amination —— 60

25 Claisen Condensation —— 62

26 Claisen Rearrangement —— 64

27 Cope Elimination —— 66

28 Cope Rearrangement —— 68

29 Criegee & Malaprade Oxidation —— 70

30 CuAAC —— 72

31 Curtius Rearrangement —— 74

32 Darzens Condensation —— 78

33 Dess–Martin Oxidation —— 80

34 Diazotization (Diazonium Salt) —— 82

35 Diels–Alder Cycloaddition —— 84

36 Di–π–Methane Rearrangement —— 86

37 Favorskii Rearrangement —— 88

38 Fischer Indole Synthesis —— 90

39 Friedel–Crafts Acylation & Alkylation —— 92

40 Gabriel Synthesis —— 94

41 Gewald Reaction —— 96

42 Glaser–Eglinton–Hay Coupling —— 98

43 Grignard Reaction —— 100

44 Grob Fragmentation —— 102

45 Haloform Reaction —— 104

46 Heck Cross Coupling —— 106

47 Hell–Volhard–Zelinsky Reaction —— 108

48 Hiyama Cross Coupling —— 110

49 Hofmann Elimination —— 112

50 Horner–Wadsworth–Emmons Olefination —— 114

51 Jones Oxidation —— 116

52 Kucherov Reaction —— 118

53 Kumada Cross Coupling —— 120

54 Ley–Griffith Oxidation —— 122

55 Liebeskind–Srogl Cross Coupling —— 124

56 Mannich Reaction —— 126

57 McMurry Coupling —— 128

58 Meerwein–Ponndorf–Verley Reduction —— 130

59 Michael Addition —— 132

60 Minisci Reaction —— 134

61 Mitsunobu Reaction — 136

62 Miyaura Borylation — 138

63 Mukaiyama RedOx Hydration — 140

64 Nazarov Cyclization — 142

65 Nef Reaction — 144

66 Negishi Cross Coupling — 146

67 Norrish Type I & II Reaction — 148

68 Olefin (Alkene) Metathesis — 150

69 Oppenauer Oxidation — 154

70 Ozonolysis — 156

71 Paal–Knorr Syntheses — 158

72 Paternò–Büchi Reaction — 162

73 Pauson–Khand Reaction — 164

74 Peptide (Amide) Coupling — 166

75 Pictet–Spengler Reaction — 170

76 Pinacol–Pinacolone Rearrangement — 172

77 Polonovski Reaction — 174

78 Prilezhaev Epoxidation — 176

79 Prins Reaction — 178

80 Pummerer Rearrangement — 180

81 Ramberg–Bäcklund Rearrangement — 182

82 Reformatsky Reaction —— 184

83 Robinson Annulation —— 186

84 Shapiro Reaction —— 188

85 Sonogashira Cross Coupling —— 190

86 Staudinger Reaction —— 192

87 Steglich Esterification —— 194

88 Stille Cross Coupling —— 196

89 Suzuki Cross Coupling —— 198

90 Swern Oxidation —— 200

91 Ugi Reaction —— 202

92 Ullmann Aryl–Aryl Coupling —— 204

93 Upjohn Dihydroxylation —— 206

94 Vilsmeier–Haack Reaction —— 208

95 Wacker Oxidation —— 210

96 Wagner–Meerwein Rearrangement —— 212

97 Weinreb Ketone Synthesis —— 214

98 Wittig Reaction —— 216

99 Wohl–Ziegler Reaction —— 218

100 Wolff–Kishner Reduction —— 220

Acknowledgments —— 223

Bibliography and References —— 225

List of Acronyms and Abbreviations

≡	identical to [a depiction of a chemical structure]
1°	primary [e.g., carbocation] or first generation [e.g., catalyst]
2°	secondary [e.g., carbocation] or second generation [e.g., catalyst]
3°	tertiary [e.g., carbocation] or third generation [e.g., catalyst]
Ac	acetyl
acac	acetylacetonate
Ad_E2	**bi**molecular electrophilic addition
Ad_E3	**tri**molecular electrophilic addition
ADMET	acyclic diene metathesis [polymerization]
AIBN	azo*bis*isobutyronitrile; 2,2′-azo*bis*(2-methylpropionitrile)
Alk = R	alkyl group
anti	from opposite sides (in *anti*-addition or *anti*-elimination)
APA	3-aminopropylamine; 1,3-diaminopropane
aq	aqueous [work-up]
Ar	aryl; aromatic ring
B (B^-)	general Brønsted–Lowry base (proton acceptor)
B_2pin_2	*bis*(pinacolato)diboron; 4,4,4′,4′,5,5,5′,5′-octamethyl-2,2′-bi-1,3,2-dioxaborolane
9-BBN	9-borabicyclo[3.3.1]nonane
BH (BH^+)	general Brønsted–Lowry acid (proton donor)
Bn	benzyl
Boc	*tert*-butoxycarbonyl; *t*-butoxycarbonyl
Bs	brosyl; 4-bromobenzenesulfonyl
Bu	butyl (if not specified = *n*-Bu)
CHD	1,4-cyclohexadiene
CM = XMET	[olefin] cross-metathesis
con	conrotatory
3-CR (MCR)	3-component reaction (multi-component reaction)
4-CR (MCR)	4-component reaction (multi-component reaction)
CuAAC	copper(I)-catalyzed azide-alkyne cycloaddition
CuTC	copper(I) thiophene-2-carboxylate
Cy	cyclohexyl
Cy_2BH	dicyclohexylborane
DABCO	1,4-diazabicyclo[2.2.2]octane
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DCC	*N*,*N*′-dicyclohexylcarbodiimide; 1,3-dicyclohexylcarbodiimide
DCM	dichloromethane; methylene chloride
DEAD	diethyl azodicarboxylate
DIAD	diisopropyl azodicarboxylate
DIBAL = DIBAL-H	diisobutylaluminum hydride = $(i\text{-Bu})_2AlH$
dis	disrotatory
DMAP	4-dimethylaminopyridine; 4-(dimethylamino)pyridine
DMP	Dess–Martin periodinane
DMSO	dimethyl sulfoxide
***E*-**	*entgegen* (*trans*- or opposite)
e^-	electron
E (or E^+)	electrophile

https://doi.org/10.1515/9783110608373-204

E1	**uni**molecular elimination
E1cB (E1cb)	**uni**molecular elimination conjugate base
E2	**bi**molecular elimination
EDC = EDCI	1-ethyl-3-(3′-dimethylaminopropyl)carbodiimide hydrochloride; *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride
EDCI = EDC	1-ethyl-3-(3′-dimethylaminopropyl)carbodiimide hydrochloride; *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride
EDG (= ERG)	electron donating group (same as ERG)
E_i	internal or intramolecular elimination
eq	equivalent (e.g., 2 eq = 2 equivalents; 2 moles)
ERG (= EDG)	electron releasing group (same as EDG)
Et_2BH	diethylborane
EWG	electron withdrawing group
EYM	enyne metathesis
Grubbs 1°	the Grubbs catalyst first generation
Grubbs 2°	the Grubbs catalyst second generation
H_3B•THF	borane–tetrahydrofuran complex; borane tetrahydrofuran complex
H_3B•Me_2S = BMS	borane–dimethyl sulfide complex; borane dimethyl sulfide complex
HATU	*N*-[(dimethylamino)-1*H*-1,2,3-triazolo[4,5-*b*]pyridin-1-ylmethylene]-*N*-methylmethanaminium hexafluorophosphate *N*-oxide; 1-[bis(dimethylamino)methylene]-1*H*-1,2,3-triazolo[4,5-*b*]pyridinium 3-oxide hexafluorophosphate
HBTU	*O*-benzotriazol-1-yl-*N*,*N*,*N*′,*N*′-tetramethyluronium hexafluorophosphate; 3-[bis(dimethylamino)methyliumyl]-3*H*-benzotriazol-1-oxide hexafluorophosphate
HET = ^{HET}Ar	heterocycle; heteroaromatic ring; heteroaryl
HOAt = HOAT	1-hydroxy-7-azabenzotriazole; 3-hydroxy-3*H*-1,2,3-triazolo[4,5-*b*]pyridine
HOBt = HOBT	1-hydroxybenzotriazole
HOMO	highest occupied molecular orbital
hv	light (direct irradiation) or excited state
I_i(BR)	intermediate (biradical)
I_i(RP)	intermediate (radical pair)
IBX	2-iodoxybenzoic acid; *o*-iodoxybenzoic acid
IC	internal conversion
Ipc_2BH	di*iso*pinocampheylborane
$IpcBH_2$	mono*iso*pinocampheylborane
ISC	intersystem crossing
KAPA	potassium 3-aminopropylamide
L	ligand or leaving group
(*l*)	liquid [as in liquid ammonia: NH_3 (*l*)]
LA	Lewis acid
LAPA	lithium 3-aminopropylamide
LDA	lithium diisopropylamide = $(i\text{-Pr})_2NLi$
L_mPd	palladium(0) cross coupling catalyst
L_nPd	low-coordinate palladium(0) cross coupling catalyst
LUMO	lowest occupied molecular orbital
M	metal
[M]	metal catalyst (not specified)

M^{+3} = M(III)	oxidation state (oxidation number) of an element [e.g., Cu^{+2} = Cu(II); Pd^0 = Pd(0)]
M^{3+}	charge [e.g., Ti^{3+} in $TiCl_3$ versus Ti^{+3} = Ti(III)]
***m*-CPBA** (MCPBA)	*meta*-chloroperbenzoic acid; *m*-chloroperbenzoic acid; 3-chloroperbenzoic acid
MCR	multi-component reaction
Mes	mesityl (from mesitylene = 1,3,5-trimethylbenzene)
Ms	mesyl; methanesulfony = SO_2Me
n	nonbonding [molecular] orbital
NACM	nitrile-alkyne cross-metathesis
NBS	*N*-bromosuccinimide; 1-bromo-2,5-pyrrolidinedione
***N*-HBTU**	1-[bis(dimethylamino)methylene]-1*H*-benzotriazolium hexafluorophosphate 3-oxide
NiAAC	nickel-catalyzed azide-alkyne cycloaddition
NMM	*N*-methylmorpholine; 4-methylmorpholine
NMO	*N*-methylmorpholine *N*-oxide; 4-methylmorpholine *N*-oxide
Ns	nosyl; 4-nitrobenzenesulfonyl or 2-nitrobenzenesulfonyl
Nu (or Nu^-)	nucleophile
NuH	general Brønsted–Lowry acid (proton donor, like BH)
[O]	general oxidant (e.g., $2KHSO_5 \bullet KHSO_4 \bullet K_2SO_4$)
***O*-HBTU**	*N*-[(1*H*-benzotriazol-1-yloxy)(dimethylamino)methylene]-*N*-methylmethanaminium hexafluorophosphate
p [sp, sp^2, sp^3]	p orbital
P	product [in photochemical reactions]
PCC	pyridinium chlorochromate
PDC	pyridinium dichromate
Ph	phenyl
Ph_3P = TPP	triphenylphosphine
PhthNH	phthalimide (Phth = phthaloyl)
pK_a	acidity constant = $-\log_{10}(K_a)$
Pr	propyl (if not specified = *n*-Pr)
Py	pyridine
R	reactant; starting material [in photochemical reactions]
R ($-R_1$, $-R_2$, $-R'$, $-R''$, …)	[radical] group; alkyl group; substituent; [molecular] fragment
R^*	excited reactant [in photochemical reactions]
RCAM	ring-closing alkyne metathesis
RCEYM	ring-closing enyne metathesis
RCM	ring-closing metathesis
R_L	large group (substituent)
ROM	ring-opening metathesis
ROMP	ring-opening metathesis polymerization
R_S	small group (substituent)
RuAAC	ruthenium-catalyzed azide-alkyne cycloaddition
s [sp, sp^2, sp^3]	s orbital
S_0	ground state
S_1	first [energy level] singlet excited state
S_2	second [energy level] singlet excited state
S_EAr = $S_E(Ar)$ = S_E2Ar	[**bi**molecular] aromatic electrophilic substitution = arenium ion mechanism

^{3}sens	sensitized irradiation [to the triplet excited state]
SET	single electron transfer
Sia_2BH	disiamylborane; *bis*(1,2-dimethylpropyl)borane
S_N1	**uni**molecular nucleophilic substitution
S_N2	**bi**molecular nucleophilic substitution
S_NAr = S_N2Ar	[**bi**molecular] aromatic nucleophilic substitution
$S_{RN}1$	**uni**molecular radical nucleophilic substitution
syn	from the same side (in *syn*-addition or *syn*-elimination)
T_1	first [energy level] triplet excited state
T_2	second [energy level] triplet excited state
TBAF	tetrabutylammonium (tetra-*n*-butylammonium) fluoride = *n*-Bu_4NF
Tf	triflyl; trifluoromethanesulfonyl = SO_2CF_3
TFA	trifluoroacetic acid
TFAA	trifluoroacetic anhydride
THF	tetrahydrofuran
Thx_2BH_2	thexylborane; (2-methylpentan-2-yl)borane
TLC	thin-layer chromatography
TMEDA	*N*,*N*,*N*′,*N*′-tetramethylethylenediamine; 1,2-*bis*(dimethylamino)ethane
TMS	trimethylsilyl = $SiMe_3$
TPAP	tetrapropylammonium (tetra-*n*-propylammonium) perruthenate = $(n\text{-Pr})_4NRuO_4$
TPP = Ph_3P	triphenylphosphine
Ts	tosyl; *p*-toluenesulfonyl
X (in –X)	halogen or a general leaving group (see L)
X (in =X)	variable atom; variable group (usually O or N)
XMET = CM	[olefin] cross-metathesis
***Z*-**	*zusammen* (*cis*- or same)
Z (in –Z)	variable group (often EWG)
α	alpha position (first position)
β	beta position (second position)
γ	gamma position (third position)
Δ	temperature; heat or ground state [in photochemical reactions]
δ+	partial positive charge (low electron density)
δ–	partial negative charge (high electron density)
π	involving a π–bond (for example, π–complex)
1π e^-, 2π e^-, ...	number of electrons in a π–orbital
σ	involving a σ–bond (for example, σ–complex)
σ*	[antibonding] sigma star [molecular] orbital
Φ_{ISC}	quantum yield [for intersystem crossing]

1 Electrophilic Addition Mechanism

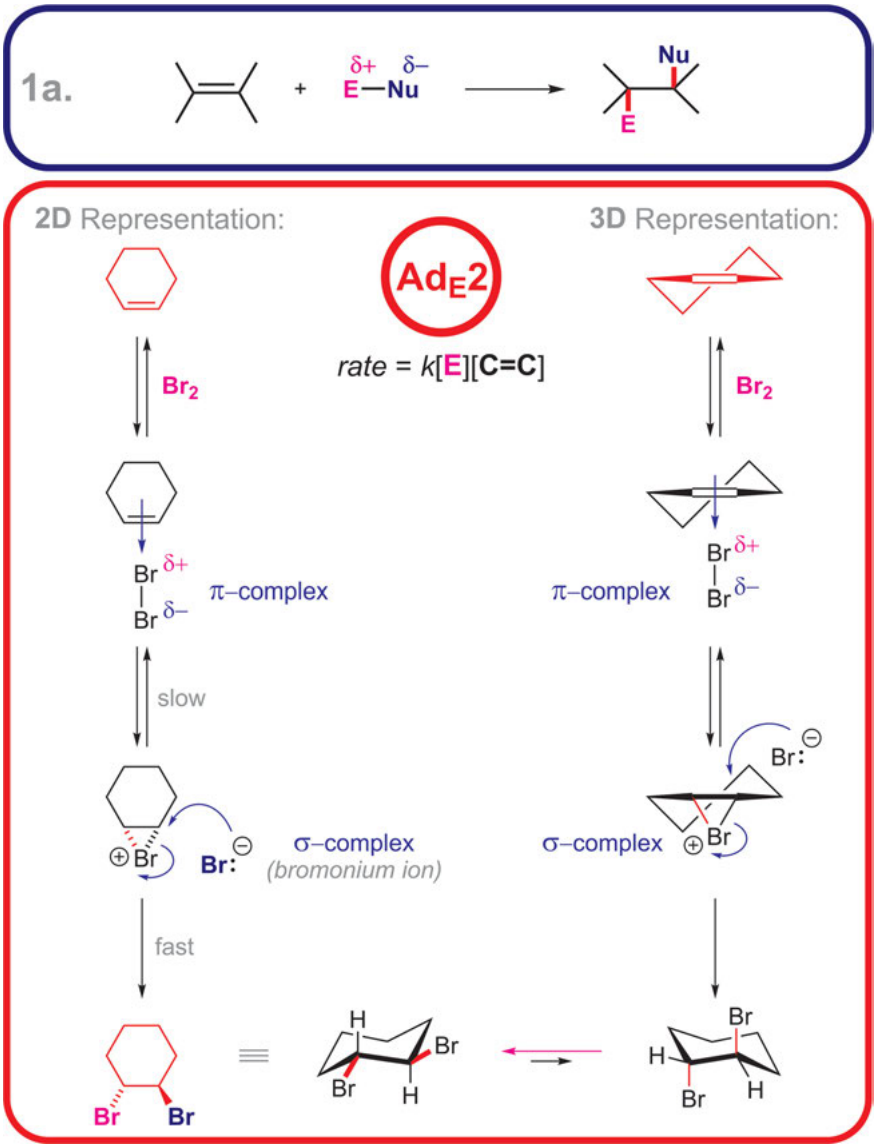


Fig. 1.1: Bimolecular electrophilic addition mechanism (**Ad$_E$2**).[1]

1 Symbol **Ad$_E$2** stands for **Ad**dition **E**lectrophilic **Bi**-molecular (**2**), that is, the rate of the reaction is ***second order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of two

https://doi.org/10.1515/9783110608373-001

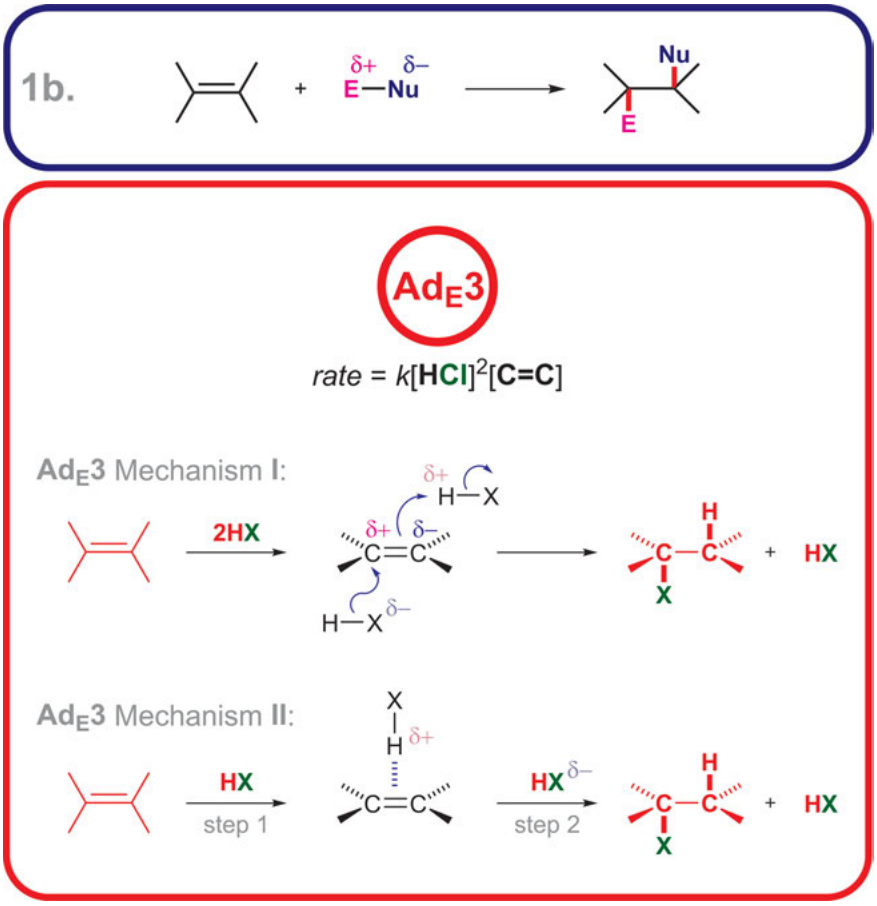


Fig. 1.2: Trimolecular electrophilic addition mechanism (**Ad$_E$3**).[2]

reactants. In the bromination of cyclohexene, it is the ***electrophile*** (**E** or **Br$_2$**) and ***alkene*** (**C=C**): *rate* = *k*[**E**]^1[**C=C**]^1.

2 Symbol **Ad$_E$3** stands for **Ad**dition **E**lectrophilic **Tri**-molecular (**3**), that is, the rate of the reaction is ***third order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of three reactants. In this less common example, it is the two ***electrophiles*** (**2HX** or **HCl** + **HCl**) and ***alkene*** (C=C): *rate* = *k*[**HCl**]^1[**HCl**]^1[**C=C**]^1 = *k*[**HCl**]^2[**C=C**]^1. In Mechanism I the collision of all three components is less probable and simultaneous. In more probable Mechanism II, a complex between the first HX and alkene is formed first (step 1), followed by step 2 (addition of the second HX).

2 Nucleophilic Substitution Mechanism

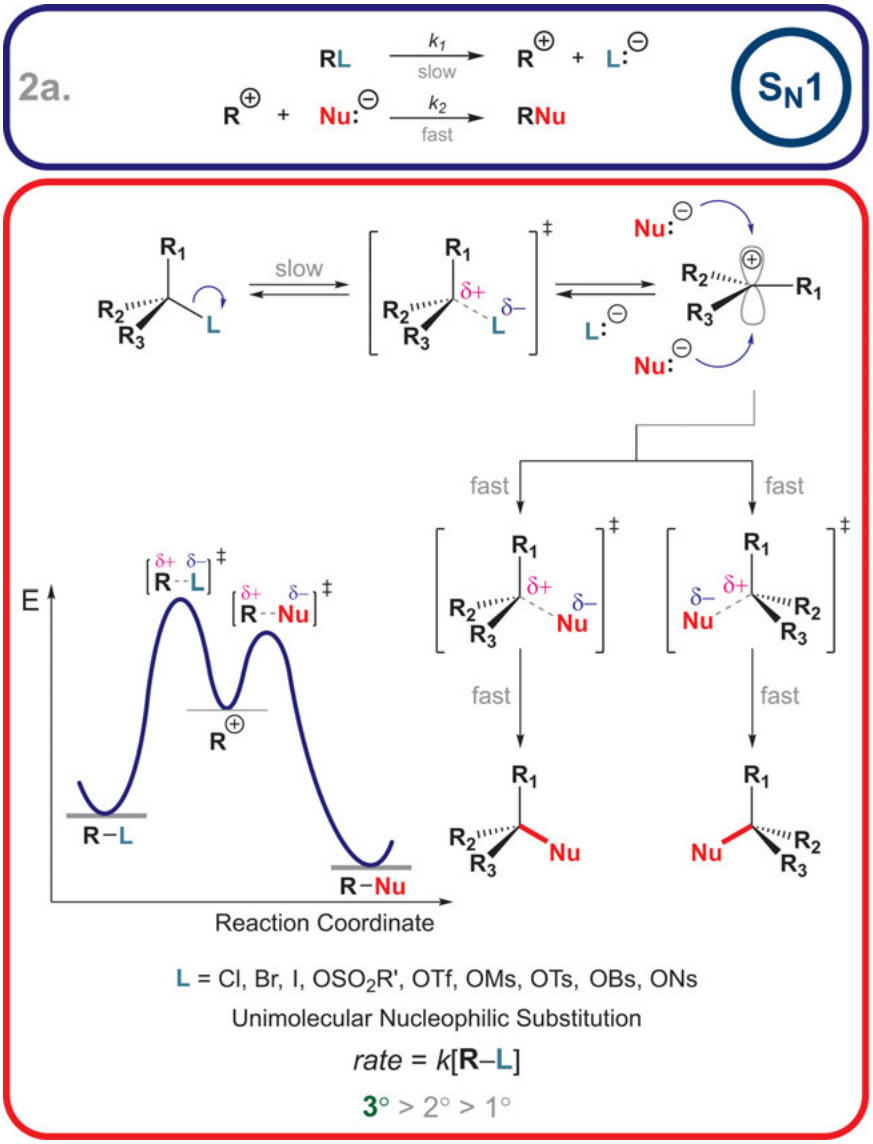


Fig. 2.1: Unimolecular nucleophilic substitution mechanism (S_N1).[3]

3 Symbol S_N1 stands for **S**ubstitution **N**ucleophilic **Uni**-molecular (**1**), that is, the rate of the reaction is ***first order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of one

https://doi.org/10.1515/9783110608373-002

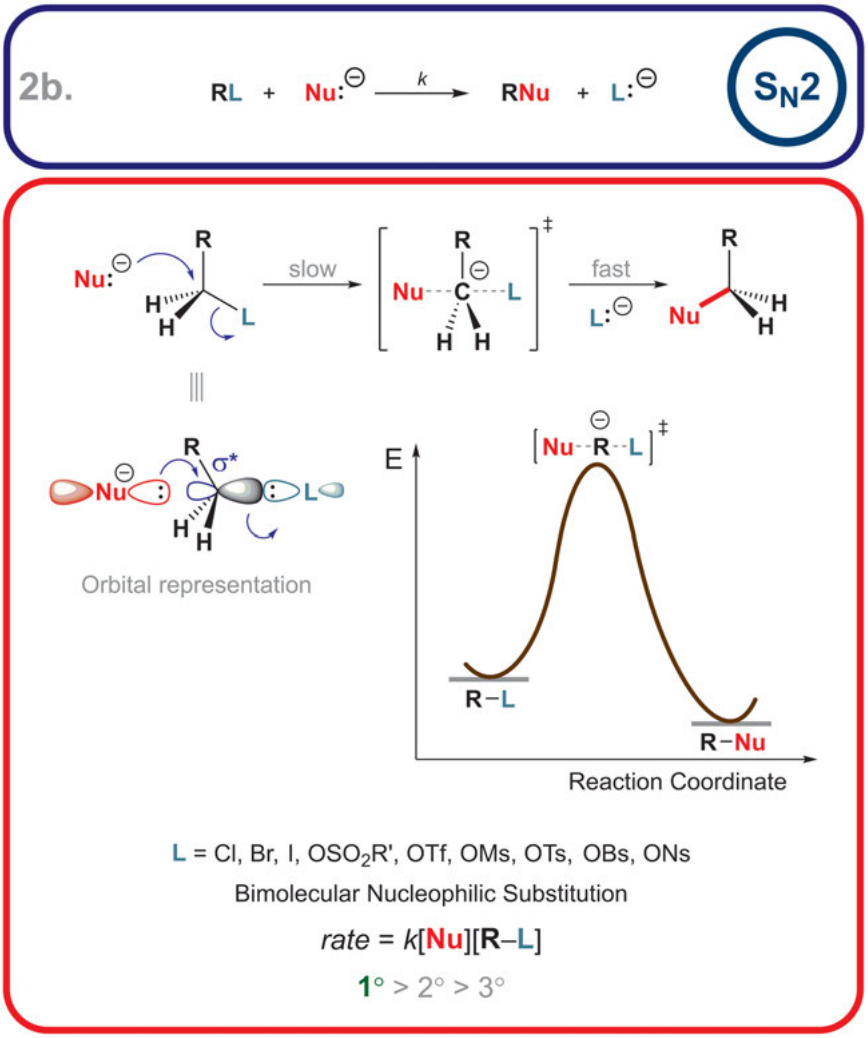


Fig. 2.2: Bimolecular nucleophilic substitution mechanism (S_N2).[4]

reactant. In this example, it is the ***starting material*** (substrate) containing a leaving group (**RL**): *rate* = *k*[**RL**]¹.

4 Symbol S_N2 stands for **S**ubstitution **N**ucleophilic **Bi**-molecular (**2**), that is, the rate of the reaction is ***second order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of two reactants. In this example, it is the ***nucleophile*** (**Nu**) and the ***starting material*** (**RL**): *rate* = *k*[**Nu**]¹[**RL**]¹.

3 Aromatic Electrophilic Substitution Mechanism

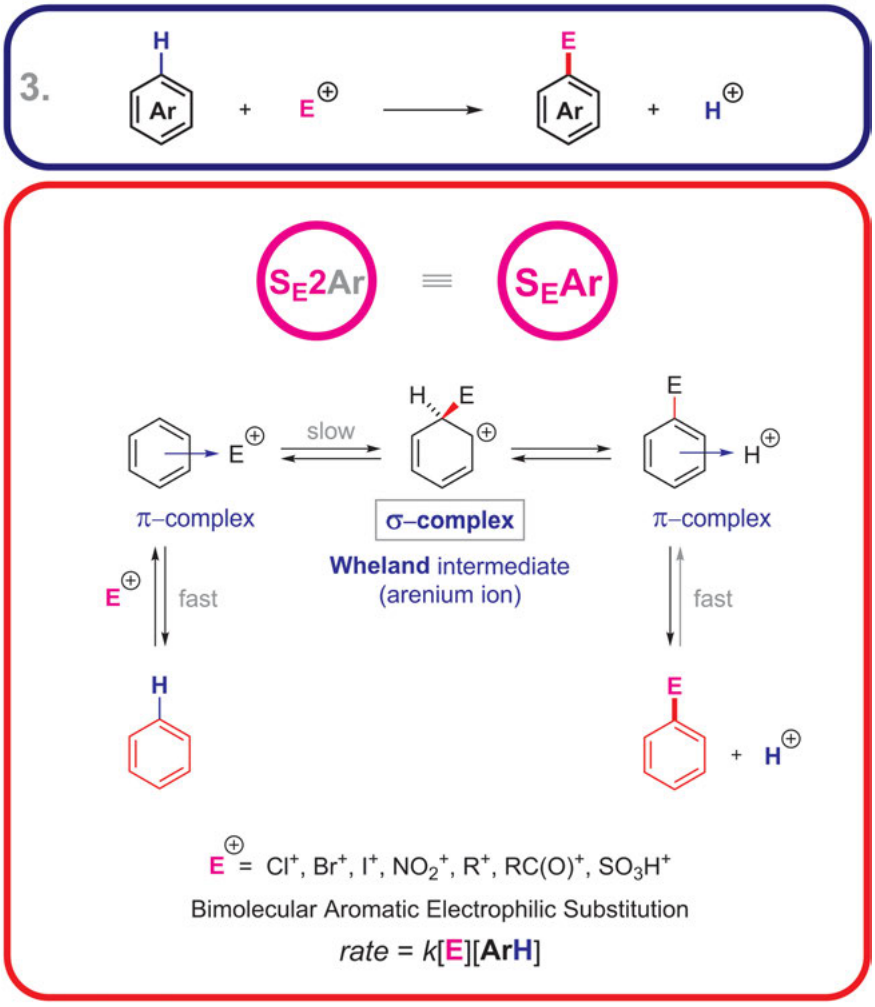


Fig. 3.1: The arenium ion mechanism (**S_EAr**).[5]

---

5 Symbol **S_EAr** or **S_E(Ar)** stands for **S**ubstitution **E**lectrophilic **Ar**enium (ion) (often confused with **Ar**omatic), that is, the ***arenium ion*** mechanism. In this example, it is a **Bi**-molecular (**2**) reaction, that is, the rate of the reaction is ***second order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of two reactants. It is the ***electrophile*** (**E**) and ***arene*** (**ArH**): $rate = k[\mathbf{E}]^1[\mathbf{ArH}]^1$. To emphasize that it is a bi-molecular mechanism, sometimes **S_E2Ar** or **S_E2(Ar)** notation is used (the use of a simple **S_E2** symbol can be confusing, since it can also apply to an Aliphatic Electrophilic Substitution).

https://doi.org/10.1515/9783110608373-003

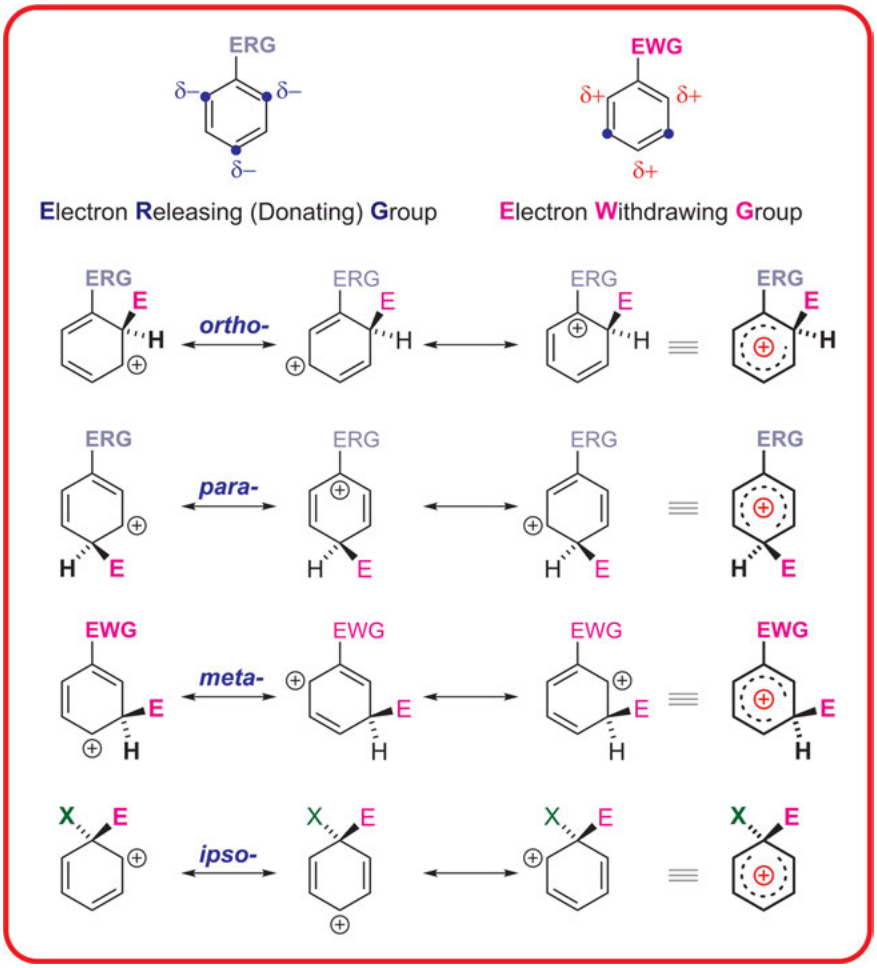


Fig. 3.2: The orientation of substitution with substrates containing EWG and ERG.[6]

6 In this book the terms Electron Releasing Group (ERG) and Electron Donating Group (EDG) are used interchangeably. Please note, ***ipso**-substitution* is provided only for the comparison with ***ortho***-, ***para***-, and ***meta***-*substitution*.

4 Aromatic Nucleophilic Substitution Mechanism

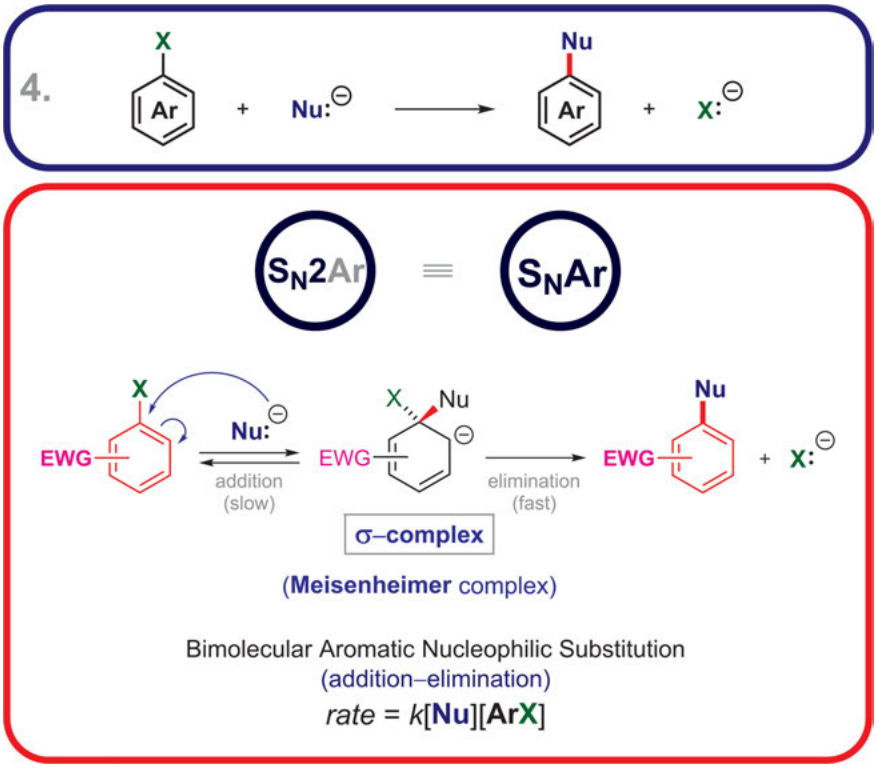


Fig. 4.1: Bimolecular aromatic nucleophilic substitution (addition-elimination) mechanism (**S_NAr**).[7]

7 Symbol **S_NAr** stands for **S**ubstitution **N**ucleophilic **Ar**omatic; it is also called the *addition-elimination* mechanism. In this example, it is a **Bi**-molecular (**2**) reaction, that is, the rate of the reaction is ***second order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of two reactants. It is the ***nucleophile*** (**Nu**) and ***arene*** (**ArX**): *rate* = k[**Nu**]^1[**ArX**]^1. To emphasize that it is a bi-molecular mechanism, sometimes **S_N2Ar** notation is used.

https://doi.org/10.1515/9783110608373-004

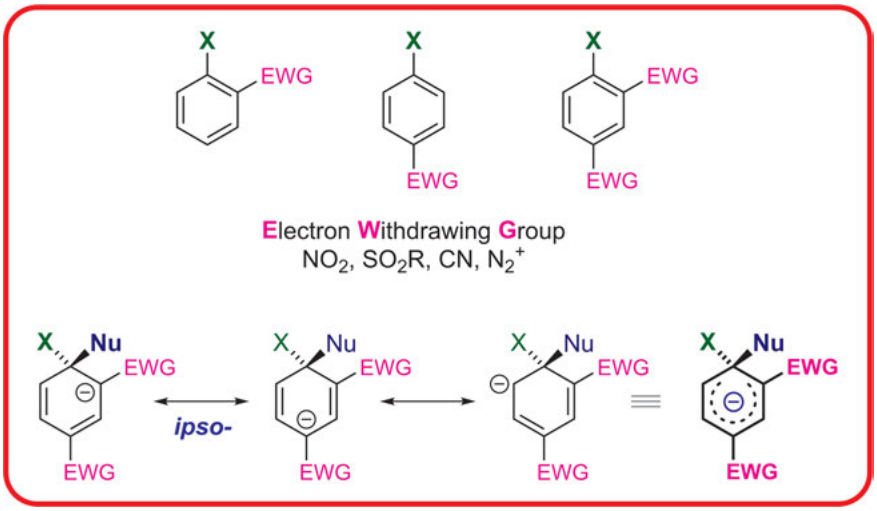


Fig. 4.2: Typical activated **S_NAr** substrates.[8]

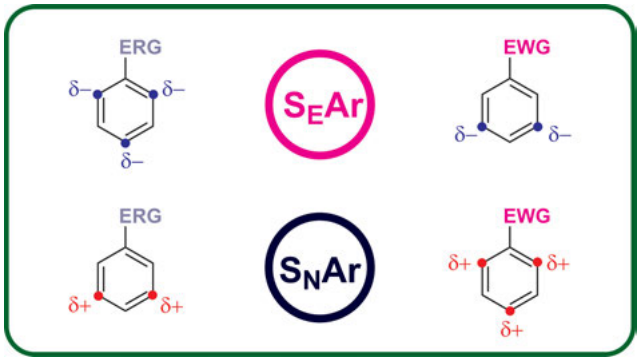


Fig. 4.3: The orientation of substitution in **S_EAr** and **S_NAr**.[9]

8 A typical **S_NAr** substrate usually contains an activating electron withdrawing group (EWG) and a leaving group (X).

9 In the **S_EAr** reaction, an EWG group orients (directs) the substitution in the *meta*-position and an ERG (EDG) directs the substitution in the *ortho*-position and/or *para*-position. However, in the **S_NAr** reaction, this trend is reversed: an EWG group orients (directs) the substitution in the *ortho*-position and/or *para*-position and ERG (EDG) directs the substitution in the *meta*-position.

5 Aromatic Radical Nucleophilic Substitution Mechanism

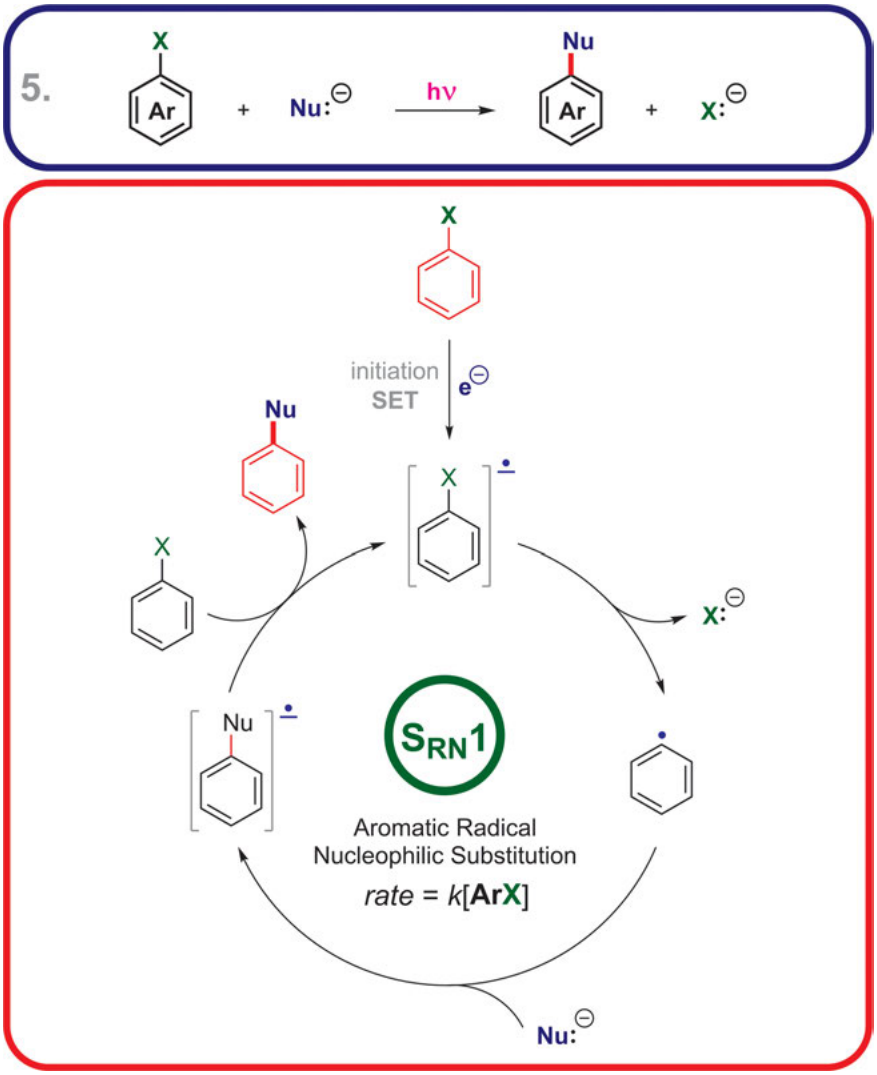


Fig. 5.1: Unimolecular aromatic radical nucleophilic substitution mechanism ($S_{RN}1$).[10]

10 Symbol $S_{RN}1$ stands for **S**ubstitution **R**adical **N**ucleophilic **Uni**-molecular (**1**), that is, the rate of the reaction is ***first order*** and the rate-determining step (the *slow* step) depends on the concentration of one reactant. In this example, it is the ***starting material*** that contains a leaving group (**ArX**): *rate* = k[**ArX**]^1.

https://doi.org/10.1515/9783110608373-005

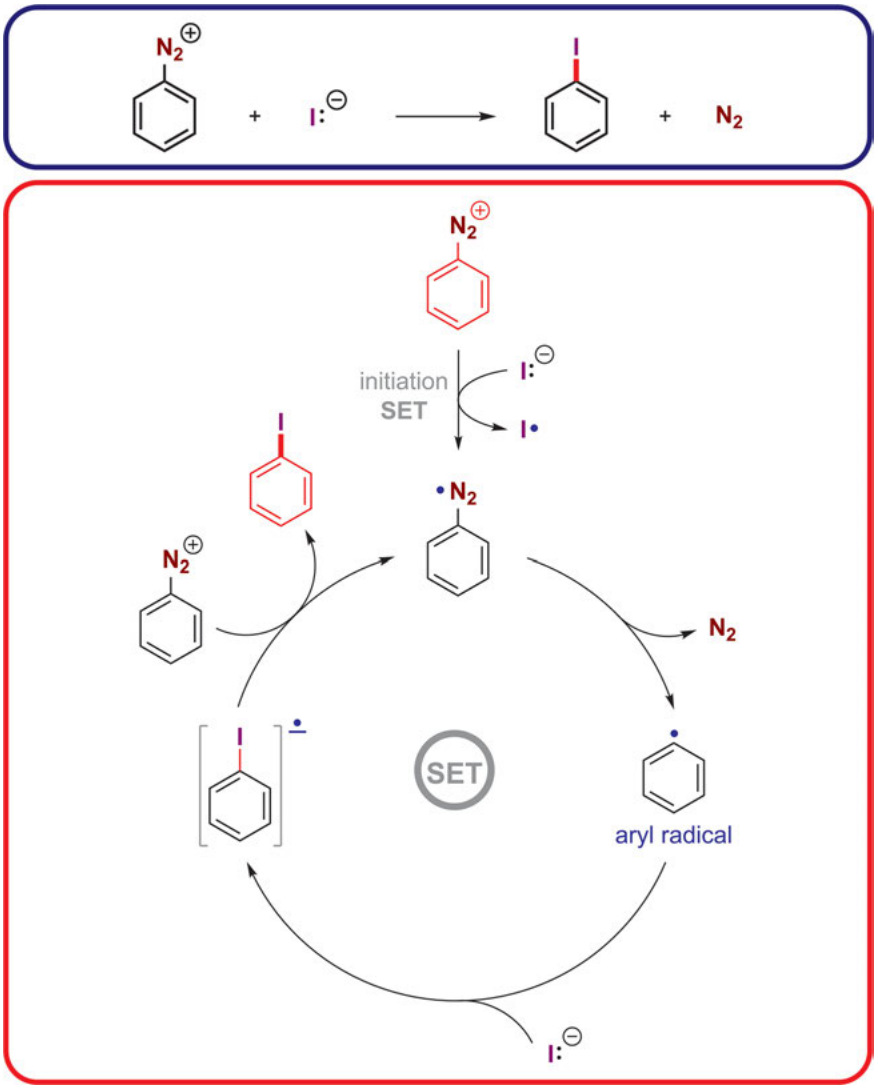


Fig. 5.2: Replacement of the diazonium group by iodide.[11]

11 The substitution of a diazonium group by iodide is an example of the **SET** (**S**ingle **E**lectron **T**ransfer) mechanism. Please note, the **$S_{RN}1$** mechanism and the **SET** mechanism are closely related and are not differentiated in this book. Jerry March [1a] distinguishes the $S_{RN}1$ mechanism (the initial attack of the aromatic substrate occurs by an electron donor) from the SET mechanism (the initial attack occurs by a nucleophile). The Sandmeyer reaction mechanism (not shown) is related [see https://doi.org/10.1002/cber.18840170219 and https://doi.org/10.1002/cber.188401702202, accessed December 5, 2019].

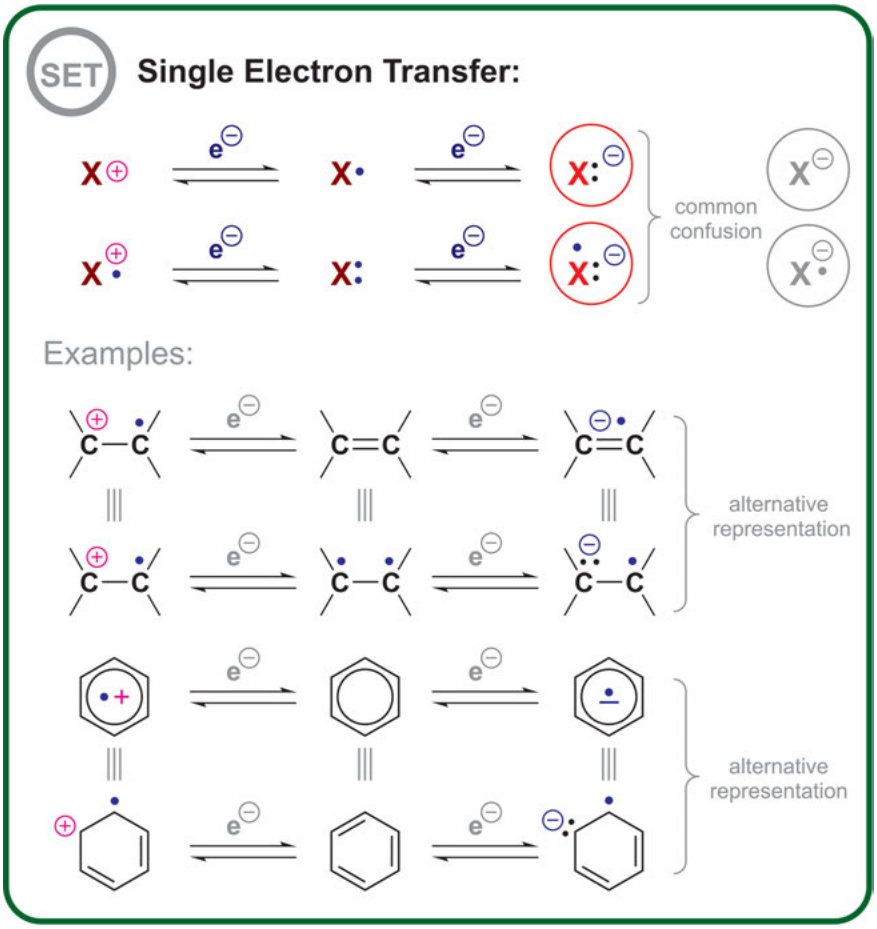


Fig. 5.3: Lewis electron dot structures of radical species involved in SET.[12]

12 This figure summarizes the Lewis (electron) dot structures of various SET processes: ***cation*** → ***radical*** → ***anion*** or ***cation-radical*** → ***di-radical*** or ***lone pair*** → ***anion-radical***, and provides several common examples. Please note, in the literature *cation-radical* is often called radical cation and *anion-radical* is called radical anion. In some instances, a *lone pair* associated with an *anion* or *anion-radical* is not represented for clarity (sometimes this simplification causes confusion).

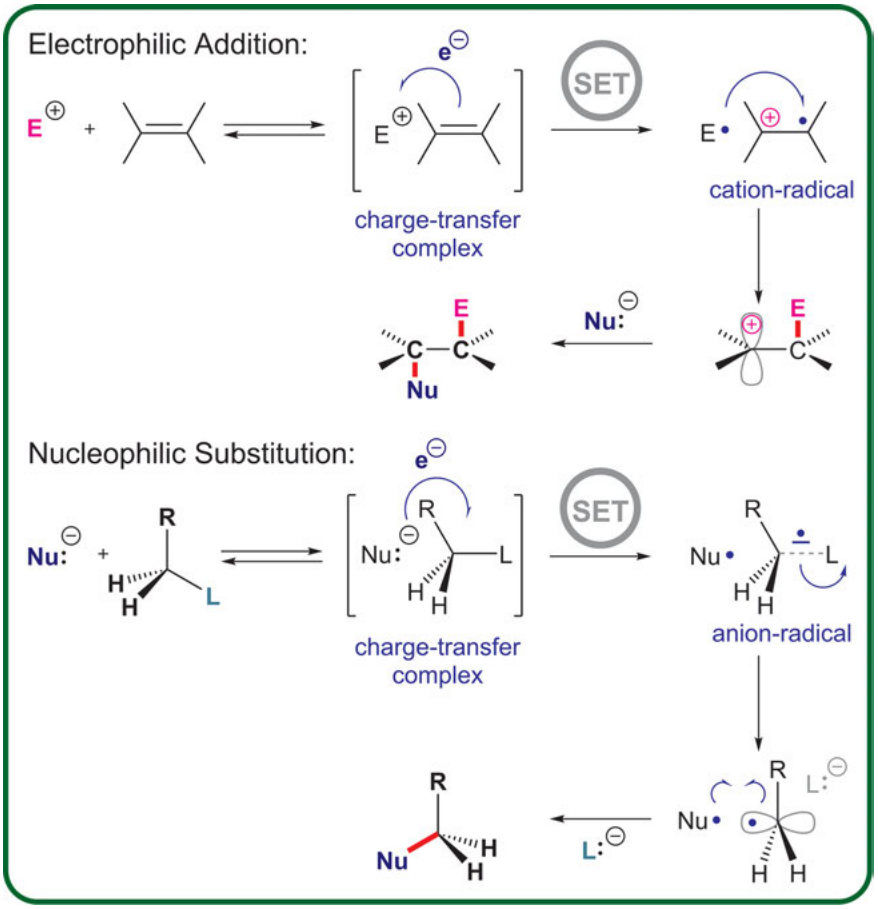


Fig. 5.4: The single electron transfer mechanism (**SET**) examples.[13]

13 An example of *Electrophilic Addition* described by the SET mechanism: a single electron transfer from an alkene to an electrophile and the formation of a *cation-radical* (radical cation). An example of *Nucleophilic Substitution* described by the SET mechanism: a single electron transfer from a nucleophile to a substrate and the formation of an *anion-radical* (radical anion) [3].

6 Elimination Mechanism

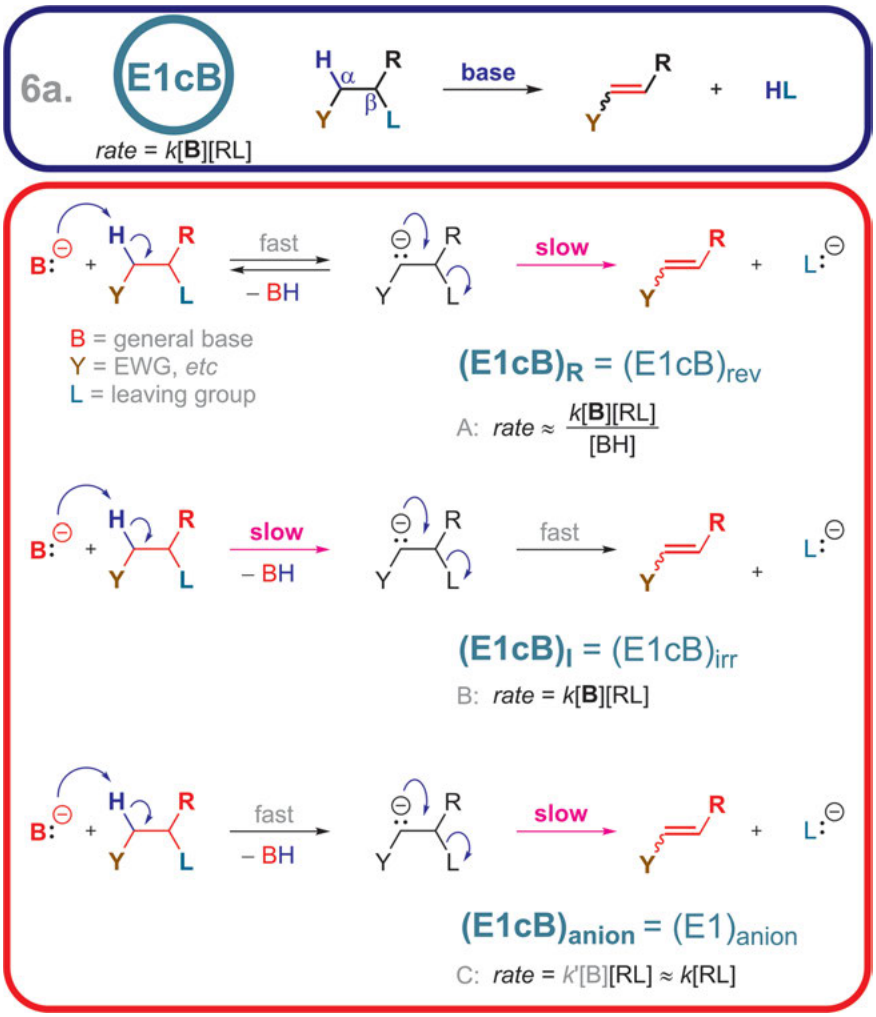


Fig. 6.1: Unimolecular β–elimination mechanism (**E1cB**).[14]

14 Symbol **E1cB** (**E1cb**) stands for **E**limination **Uni**-molecular (**1**) **c**onjugate **B**ase (**b**ase); it is also called the ***carbanion*** mechanism [McLennan DJ. The carbanion mechanism of olefin-forming elimination. *Q. Rev. Chem. Soc.* **1967**, 21 (4), 490–506]. The mechanism consists of two steps: the formation of a carbanion (step 1) and subsequent elimination (step 2). (Scenario A) Step 1 is fast and reversible (**R** or **rev**) and step 2 is rate-determining (slow): $\mathbf{(E1cB)_R} = \mathbf{(E1cB)_{rev}}$. Here, the rate of the reaction is ***second order*** and the rate-determining step depends on the concentration of two reactants, that is, the ***base*** (**B**) and ***substrate*** (**RL**): $rate \approx k[\mathbf{B}]^1[\mathbf{RL}]^1/[\mathbf{BH}]$. (Scenario B) Step 1 is slow and irreversible (**I** or **irr**) (rate-determining) and step 2 is fast: $\mathbf{(E1cB)_I} = \mathbf{(E1cB)_{irr}}$. Here, the rate of the reaction is ***sec-***

https://doi.org/10.1515/9783110608373-006

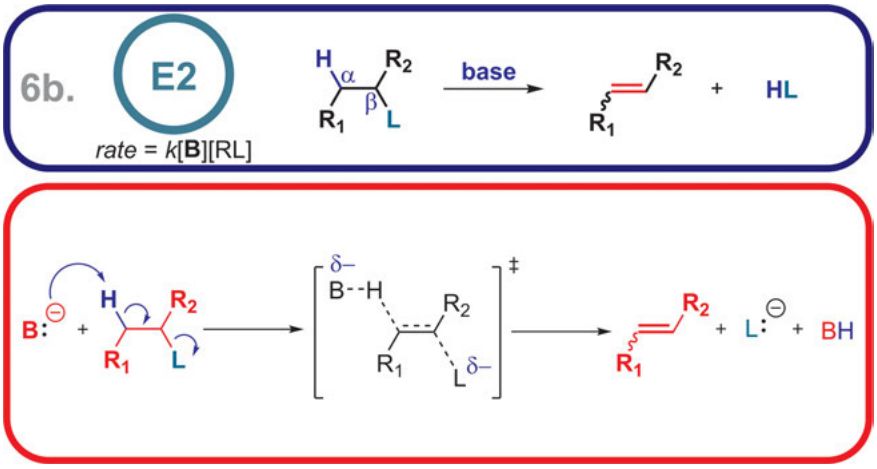


Fig. 6.2: Bimolecular β–elimination mechanism (**E2**).[15]

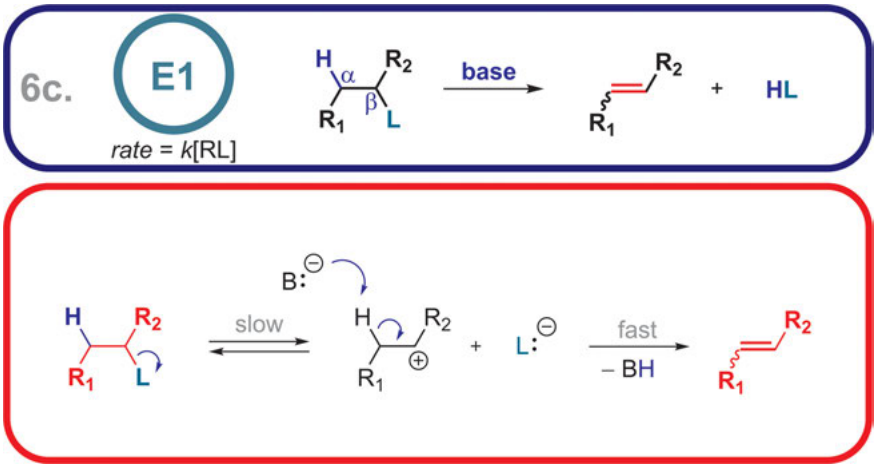


Fig. 6.3: Unimolecular β–elimination mechanism (**E1**).[16]

ond order and the rate-determining step depends on the concentration of two reactants, that is, the ***base*** (**B**) and ***substrate*** (**RL**): *rate* = *k*[**B**]^1[**RL**]^1. (Scenario C) Step 1 is fast and step 2 is rate-determining (slow): $\mathbf{(E1cB)_{anion}} = \mathbf{(E1)_{anion}}$. Here, the rate of the reaction is ***first order*** and the rate-determining step depends on the concentration of one reactant, that is, the ***substrate*** (**RL**): *rate* ≈ *k*[**RL**]^1.

15 Symbol **E2** stands for **E**limination **Bi**-molecular (**2**), that is, the rate of the reaction is ***second order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of two reactants. In this example, it is the ***base*** (**B**) and the ***substrate*** (**RL**): *rate* = *k*[**B**]^1[**RL**]^1.

16 Symbol **E1** stands for **E**limination **Uni**-molecular (**1**), that is, the rate of the reaction is ***first order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of one reactant. In this example, it is the ***substrate*** (**RL**): *rate* = *k*[**RL**]^1.

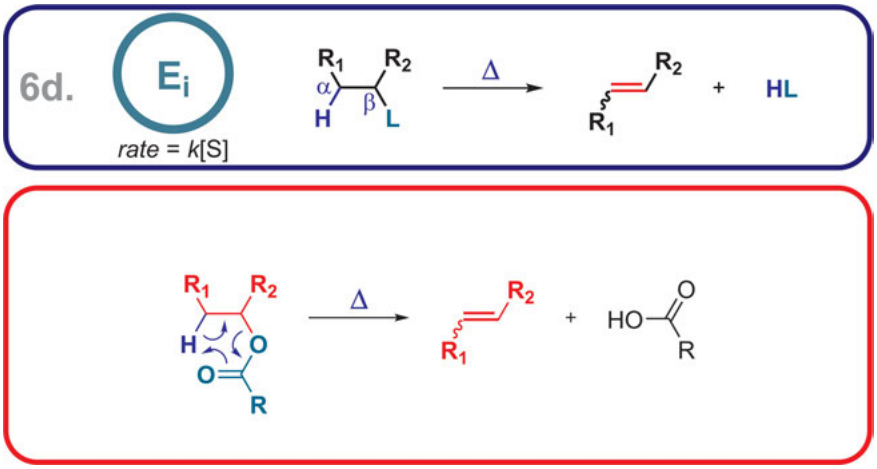


Fig. 6.4: Internal or Intramolecular β–elimination mechanism (**E**$_i$).[17]

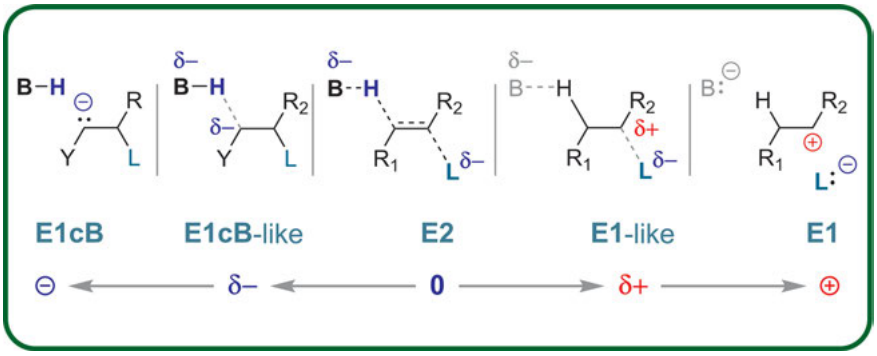


Fig. 6.5: **E1cB**, **E2**, and **E1** mechanisms.[18]

17 Symbol **E**$_i$ stands for **E**limination **I**nternal or **I**ntramolecular. The rate of the reaction is ***first order*** and the rate-determining step (i.e., the *slow* step) depends on the concentration of one reactant. In this example, it is the ***substrate*** (**S**): *rate* = *k*[**S**]^1.

18 The **E1cB** mechanism is also called the carbanion mechanism, its transition state is the most extreme case with a full negative charge. The **E2** mechanism is simultaneous and the transition state lies in the middle. A typical E2 reaction often competes with an S_N2 reaction and vice versa. The **E1** mechanism is exactly the opposite of E1cB and its transition state has a positive charge. A typical E1 reaction often competes with an S_N1 reaction and vice versa.

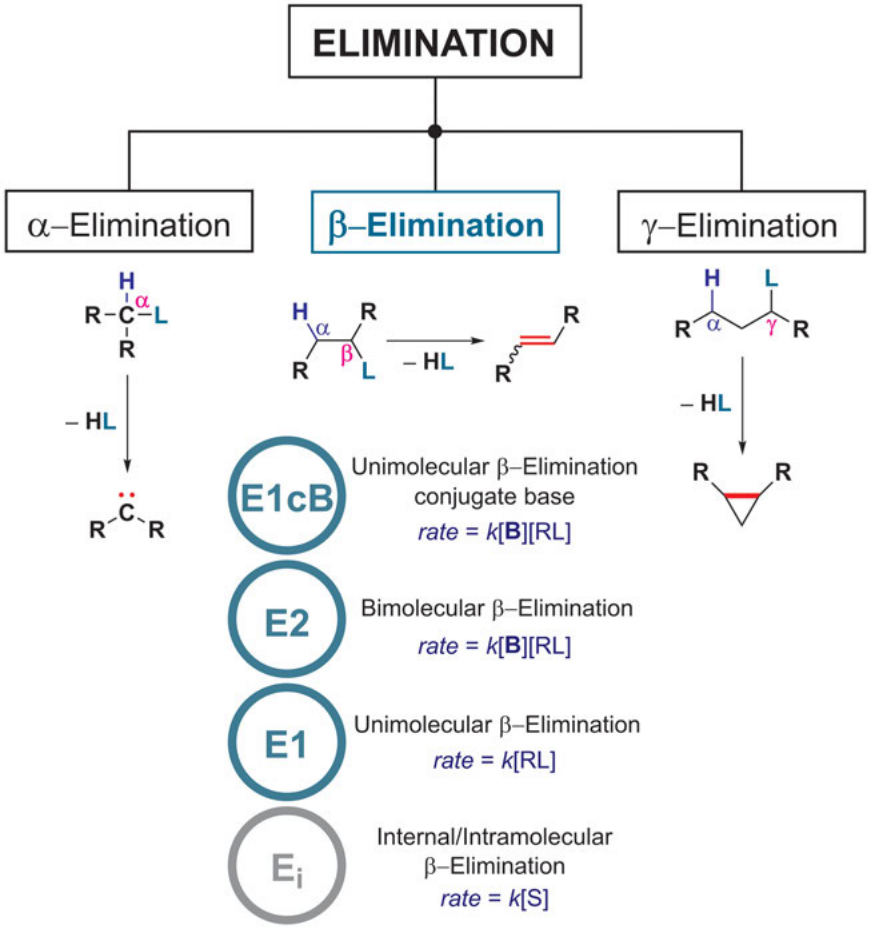


Fig. 6.6: The classification of characteristic elimination reactions.[19]

19 Only the key *β–elimination* examples are covered in this book.

7 Acyloin Condensation

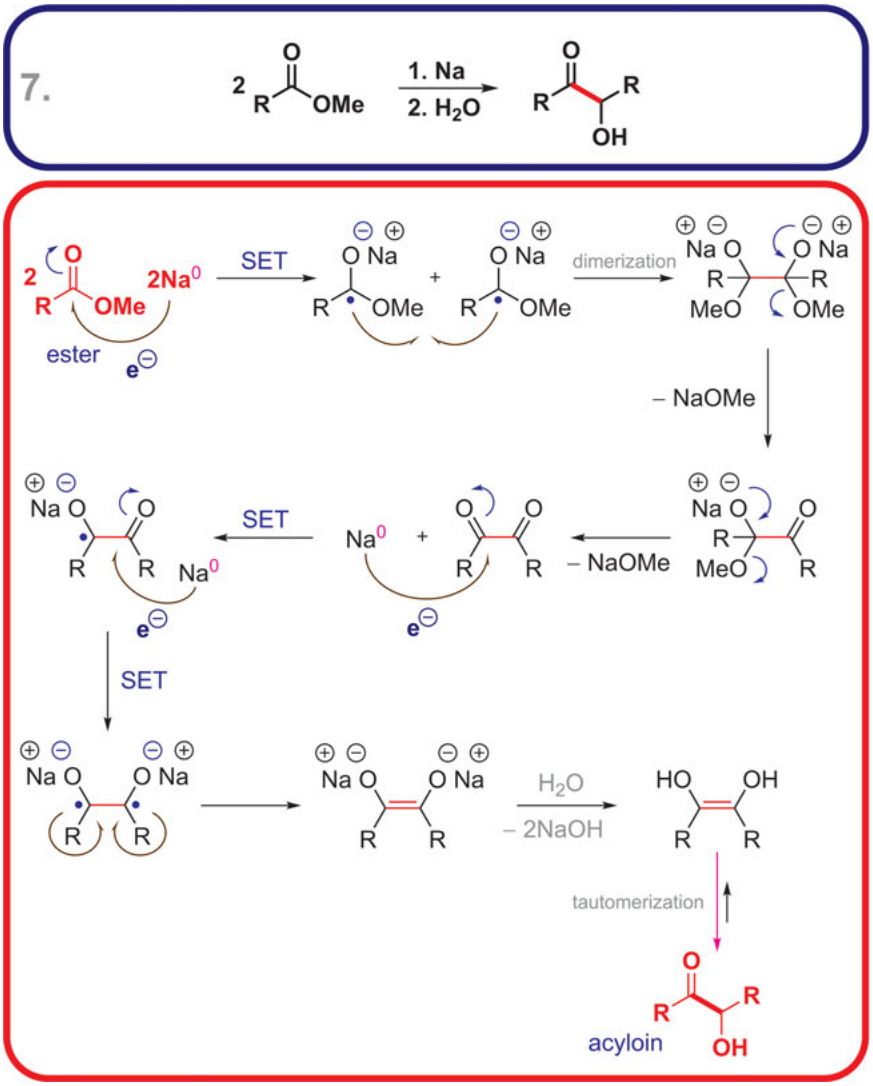


Fig. 7.1: The *acyloin condensation* mechanism.[20]

20 The reaction is also called the *acyloin ester condensation*. Please note, an *acyloin* is an α–hydroxy ketone.

https://doi.org/10.1515/9783110608373-007

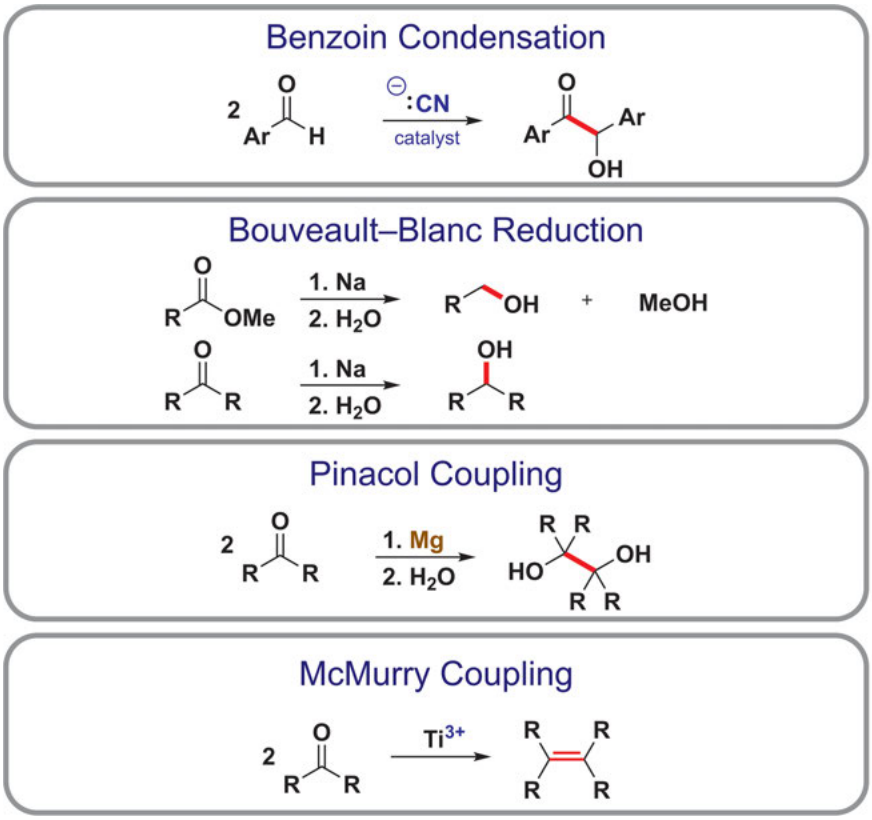


Fig. 7.2: Reactions related to the *acyloin condensation*.[21]

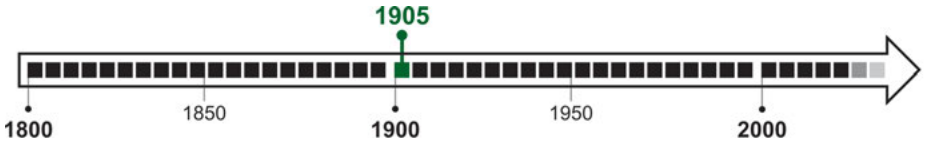


Fig. 7.3: The discovery of the *acyloin condensation*.[22]

21 Several reactions are mechanistically related to the *acyloin condensation*: the ***Bouveault–Blanc*** *reduction* [1a and 7a], the *pinacol coupling* and the ***McMurry*** *coupling* (both covered in Chapter 57). The *benzoin condensation* (covered in Chapter 15) undergoes a different mechanism, but it also yields α–hydroxy ketones containing aromatic groups *(benzoins)*.

22 The reaction was likely first described around 1905 [7b].

8 Alkyne Zipper Reaction

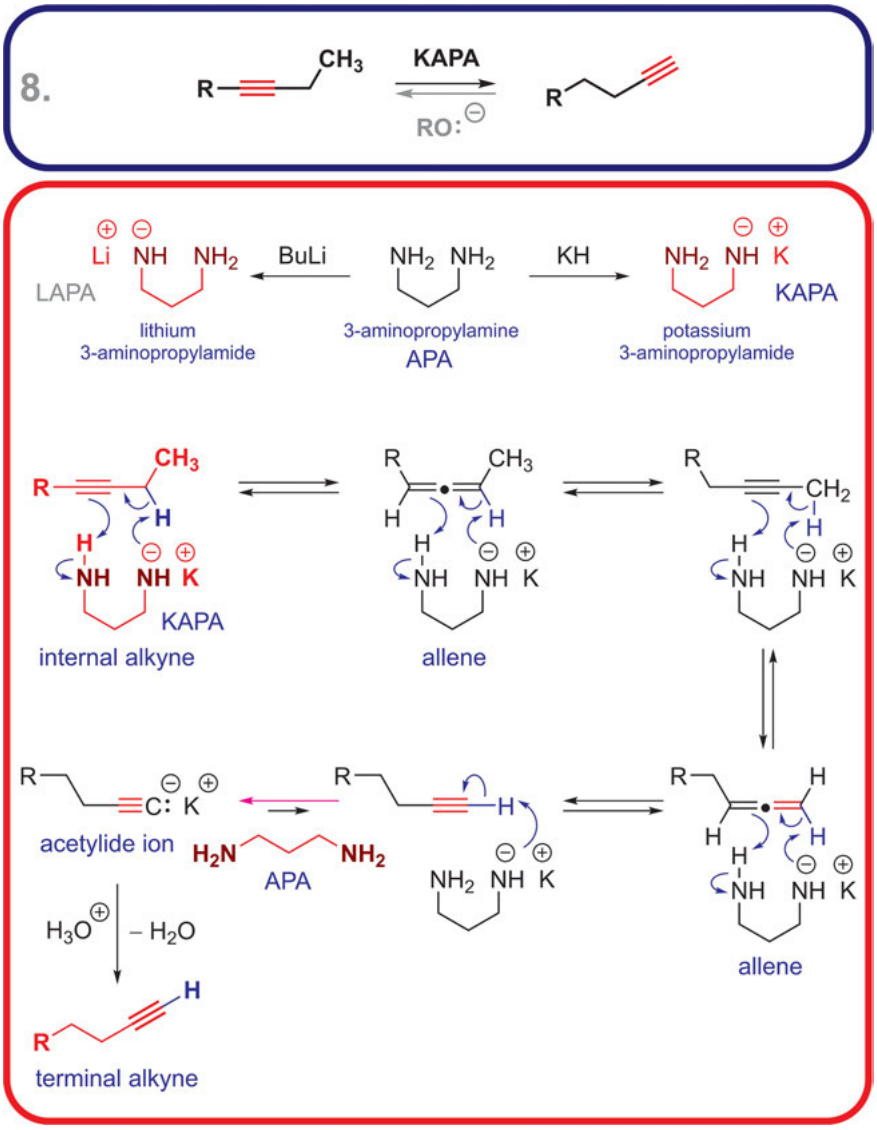


Fig. 8.1: The *alkyne zipper reaction* mechanism.[23]

23 The reaction is also called the *alkyne isomerization reaction* or the *alkyne-allene rearrangement*.

https://doi.org/10.1515/9783110608373-008

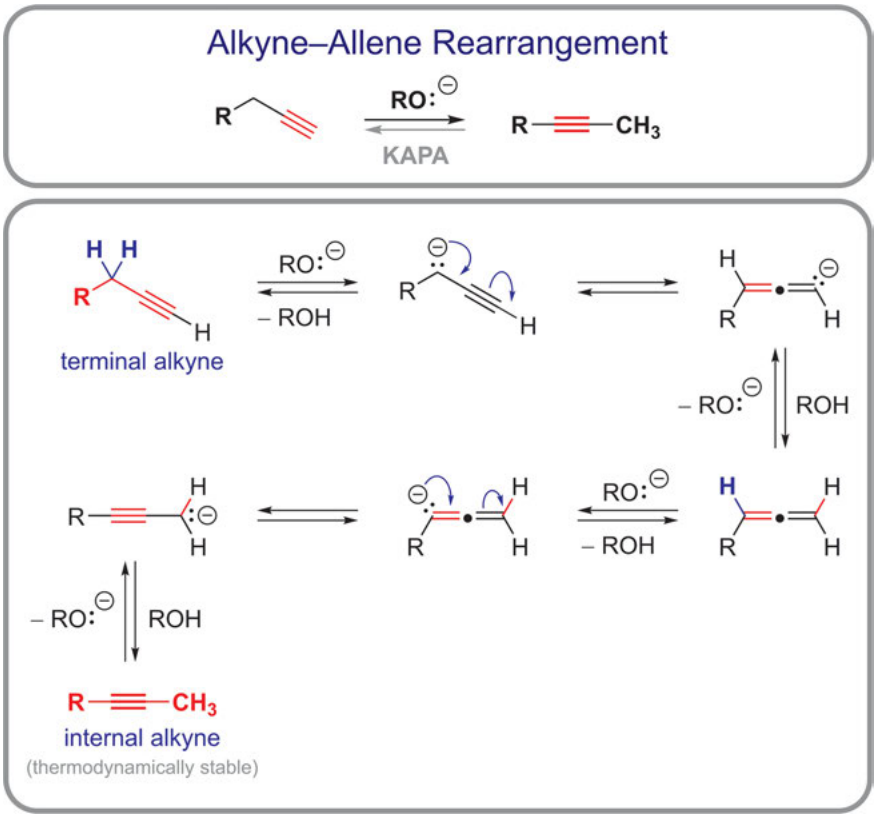


Fig. 8.2: The *alkyne-allene rearrangement* mechanism.[24]

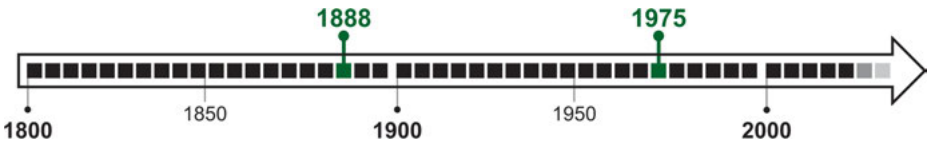


Fig. 8.3: The discovery of the *alkyne zipper reaction*.[25]

24 The *alkyne zipper reaction* with KAPA yields thermodynamically less stable *terminal alkyne*, whereas the typical *alkyne-allene rearrangement* usually produces thermodynamically more stable *internal alkyne*. Both reactions are reversible.

25 The reaction was likely first mentioned around 1888 by A. Favorsky (Favorskii) (in Russian A. E. Фаворский) [8a, 8b, 8c], the variation presented here was likely first described around 1975 [8d].

9 Arbuzov Reaction

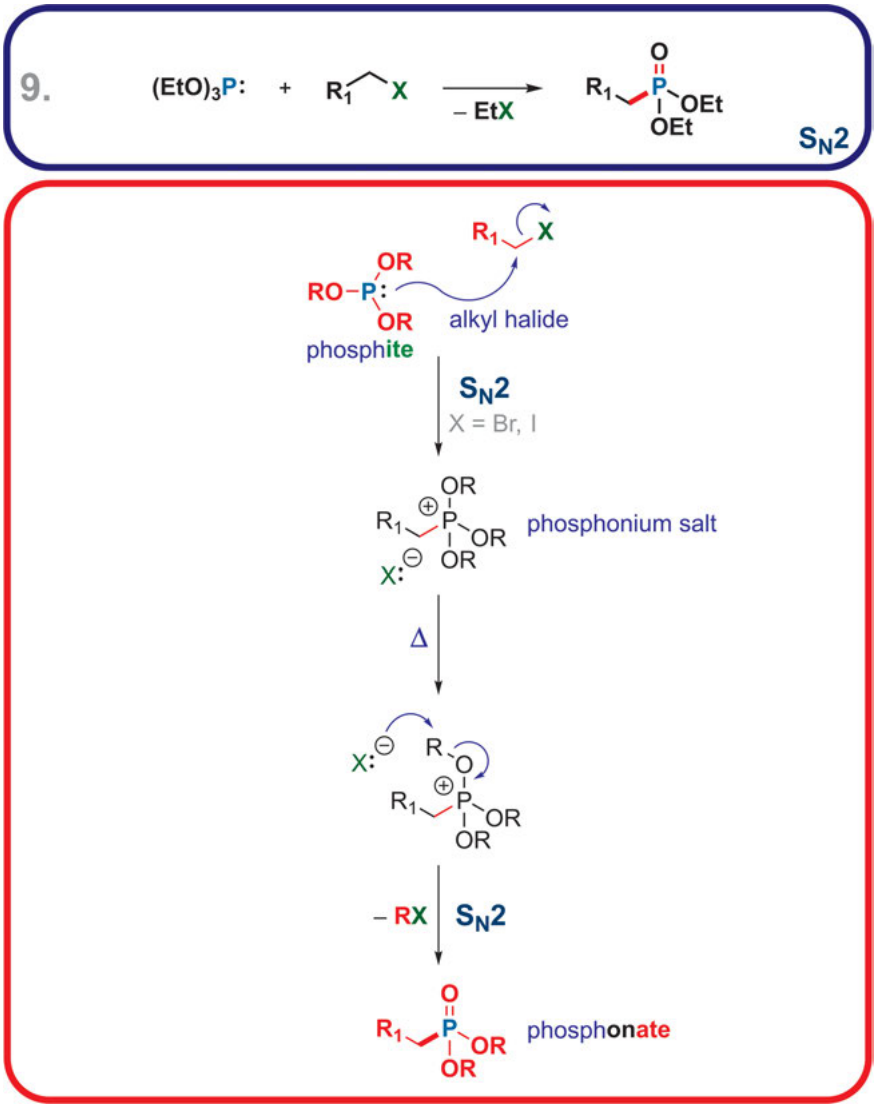


Fig. 9.1: The ***Arbuzov*** *reaction* mechanism.[26]

26 The ***Arbuzov*** *reaction* is an example of bimolecular **nucleophilic substitution** (S_N2), covered in Chapter 2. It is also referred to as the ***Michaelis–Arbuzov*** *reaction* or the ***Michaelis–Arbuzov*** *rearrangement*.

https://doi.org/10.1515/9783110608373-009

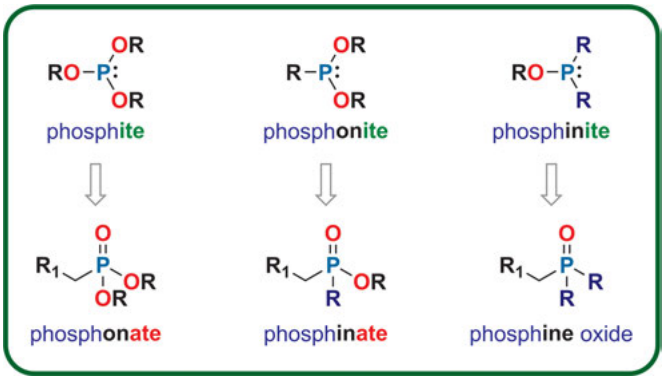


Fig. 9.2: The nomenclature of selected organophosphorus (III) and (V) compounds.[27]

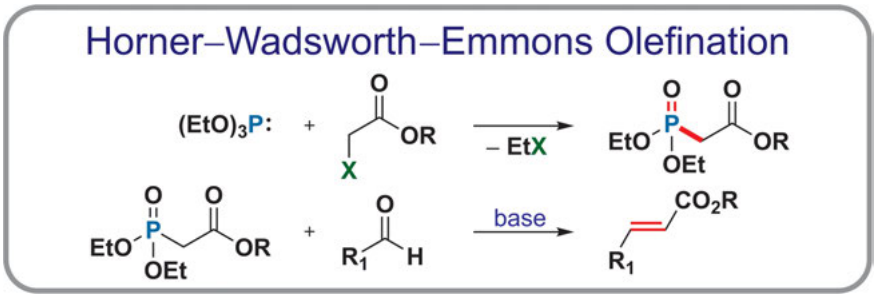


Fig. 9.3: The ***HWE*** olefination.[28]

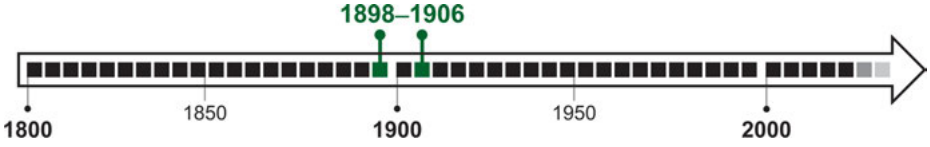


Fig. 9.4: The discovery of the ***Arbuzov*** *reaction*.[29]

---

27 A selected example of the complex organophosphorus nomenclature: the organophosphorus (III) compounds have a common suffix -***ite*** [phosph**ite**s $P(OR)_3$, phosphon**ite**s $P(OR)_2R$] and the organophosphorus (V) compounds have a common suffix -***ate*** [phosphon**ate**s $PO(OR)_2R$, phosphin**ate**s $PO(OR)R_2$] [9a].

28 The *phosphonates* produced in the ***Arbuzov*** *reaction* are essential in the ***Horner–Wadsworth–Emmons*** *(HWE) olefination* (covered in Chapter 50).

29 The reaction was likely first described around 1898 by Michaelis [9b] and around 1906 by Arbuzov [9c].

10 Arndt–Eistert Synthesis

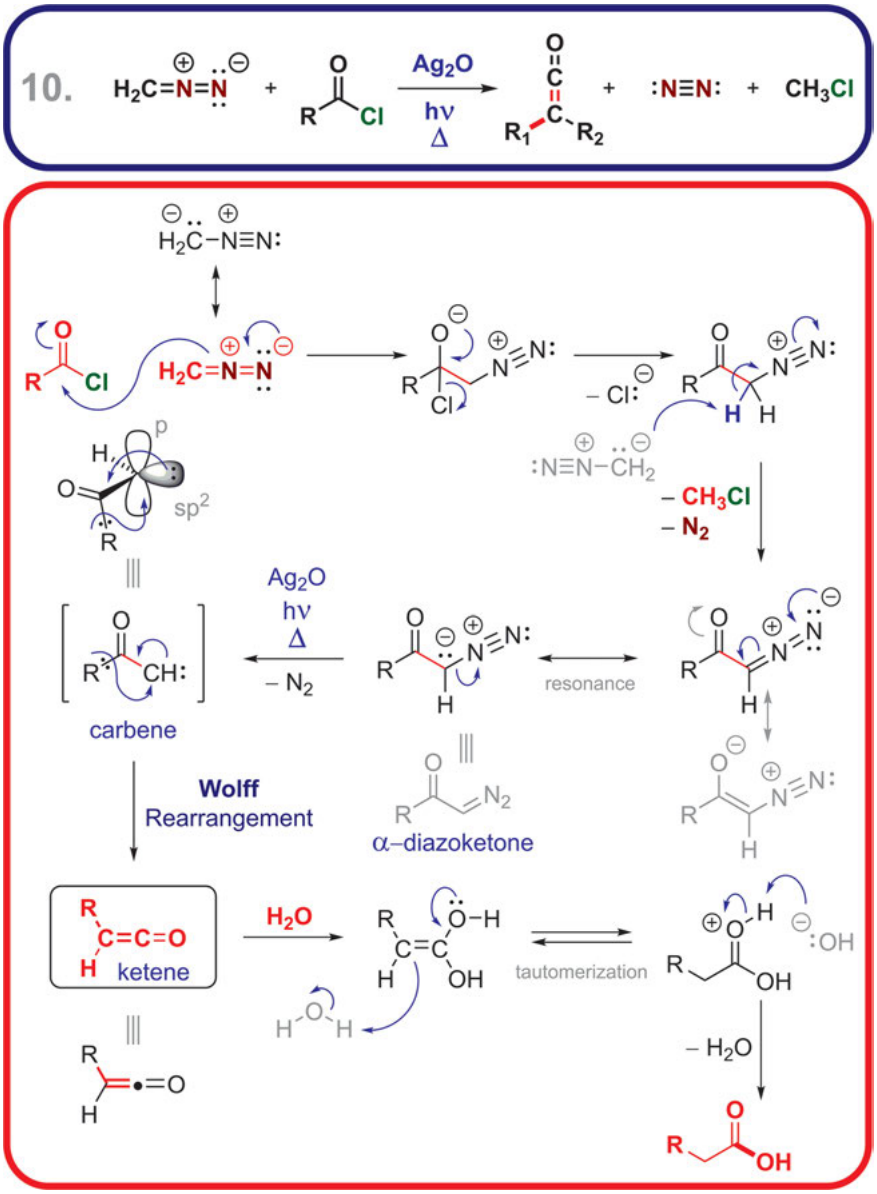


Fig. 10.1: The ***Arndt–Eistert*** *synthesis* mechanism.[30]

30 The ***Arndt–Eistert*** *synthesis* is also called the ***Arndt–Eistert*** *reaction (homologation)*. The ***Wolff*** *rearrangement* (α–diazoketone) is part of the ***Arndt–Eistert*** *synthesis* mechanism [10a].

https://doi.org/10.1515/9783110608373-010

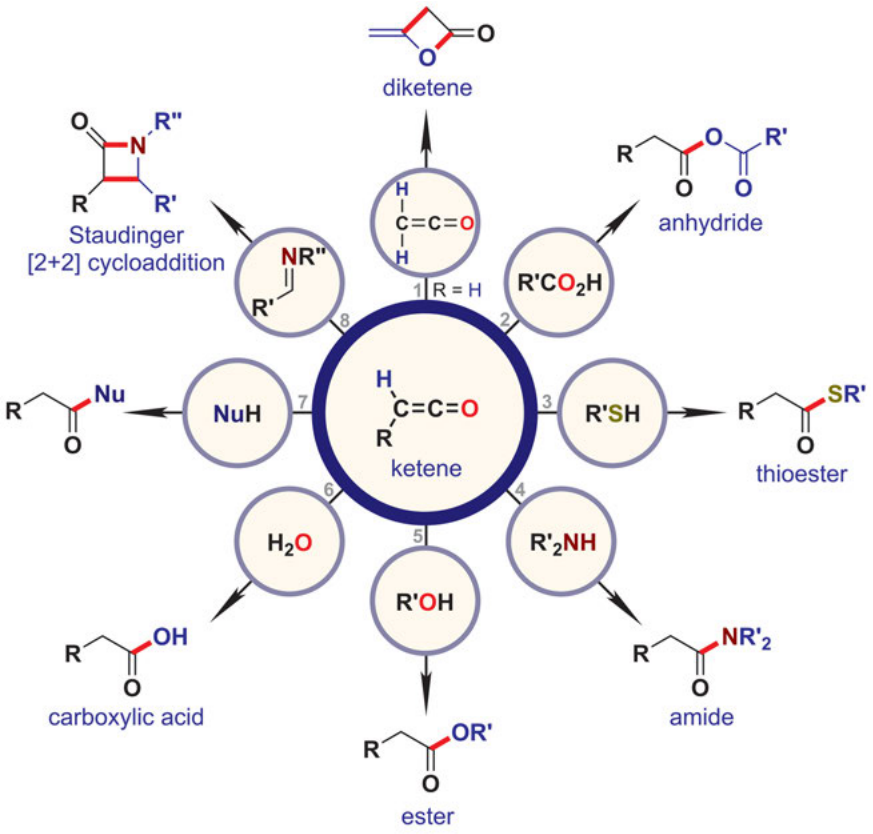


Fig. 10.2: The synthetic versatility of ketenes.[31]

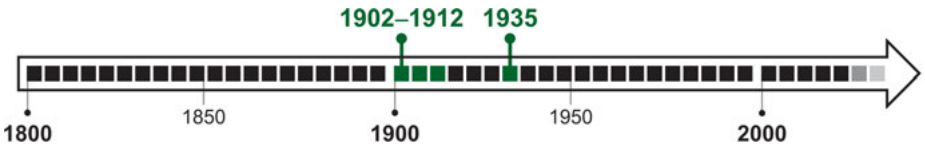


Fig. 10.3: The discovery of the ***Arndt–Eistert*** *synthesis*.[32]

31 The *ketenes* formed during the ***Arndt–Eistert*** *synthesis* can either be trapped by a variety of nucleophiles, or undergo [2+2] cycloaddition including dimerization.

32 The related reaction was likely first described by Wolff between 1902–1912 [10a, 10b] and by Arndt and Eistert around 1935 [10c].

11 Baeyer–Villiger Oxidation

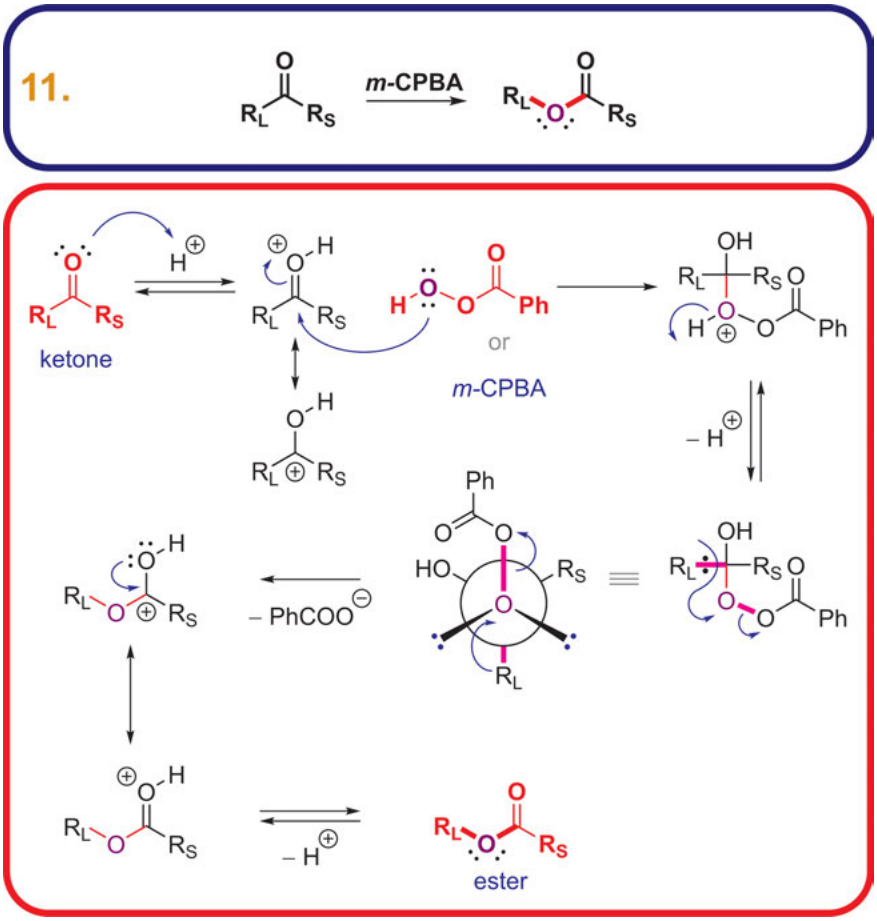


Fig. 11.1: The ***Baeyer–Villiger*** *oxidation* mechanism.[33]

33 The ***Baeyer–Villiger*** *oxidation* is also called the ***Baeyer–Villiger*** *rearrangement*.

https://doi.org/10.1515/9783110608373-011

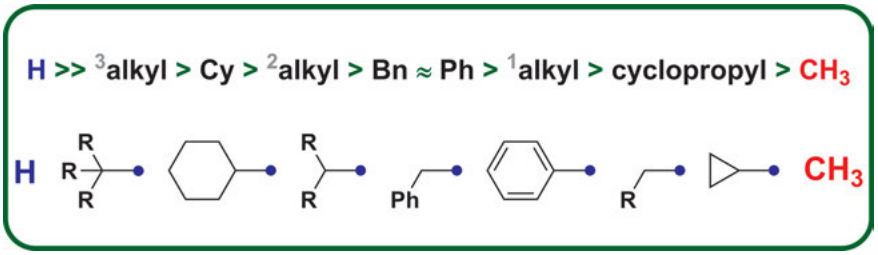


Fig. 11.2: The order of group migration in the ***Baeyer–Villiger*** *oxidation*.[34]

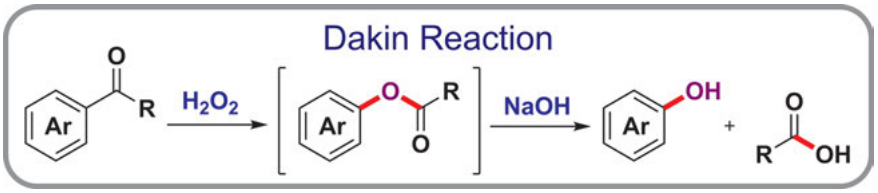


Fig. 11.3: The ***Dakin*** *reaction*.[35]

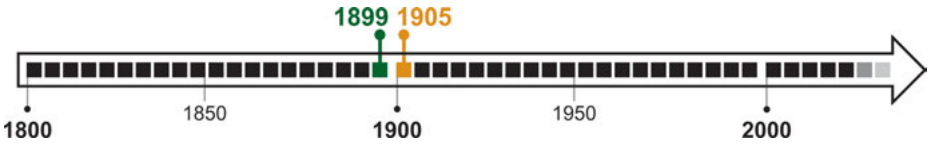


Fig. 11.4: The discovery of the ***Baeyer–Villiger*** *oxidation*.[36]

34 The order of group migration is essential for the *asymmetrical* ketones. Please note, this preference for migration is a general empirical trend and not an absolute rule [1].

35 The ***Dakin*** *reaction* (*oxidation*) is closely related to the ***Baeyer–Villiger*** *oxidation* and it usually yields *ortho*-hydroxy or *para*-hydroxy phenols (or phenols with a strong *ortho*- or *para*- ERG) [11a].

36 The reaction was likely first described around 1899 [11b]. In **1905**, Johann Friedrich Wilhelm Adolf von Baeyer received the Nobel Prize in Chemistry [11c].

12 Barton Decarboxylation

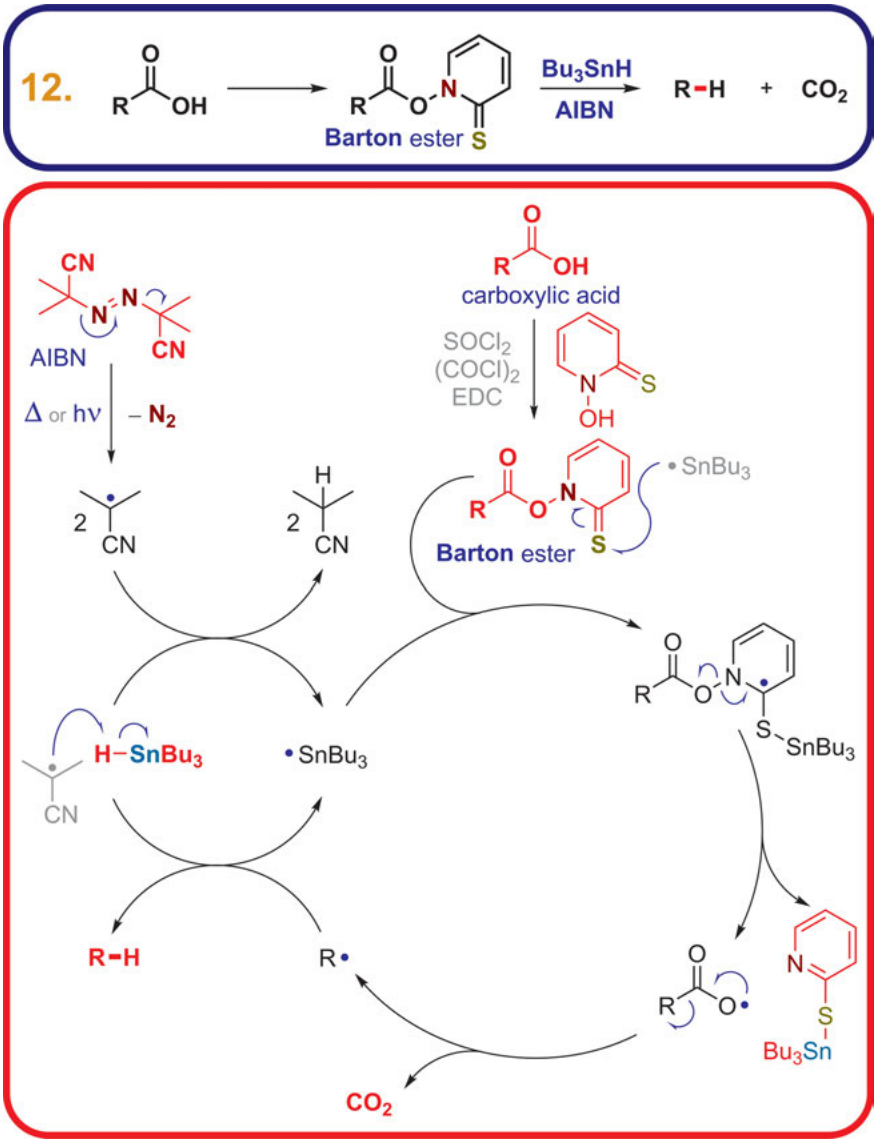


Fig. 12.1: The ***Barton*** *decarboxylation* mechanism.[37]

37 The ***Barton*** *decarboxylation* is a radical decarboxylation reaction of the ***Barton*** ester.

https://doi.org/10.1515/9783110608373-012

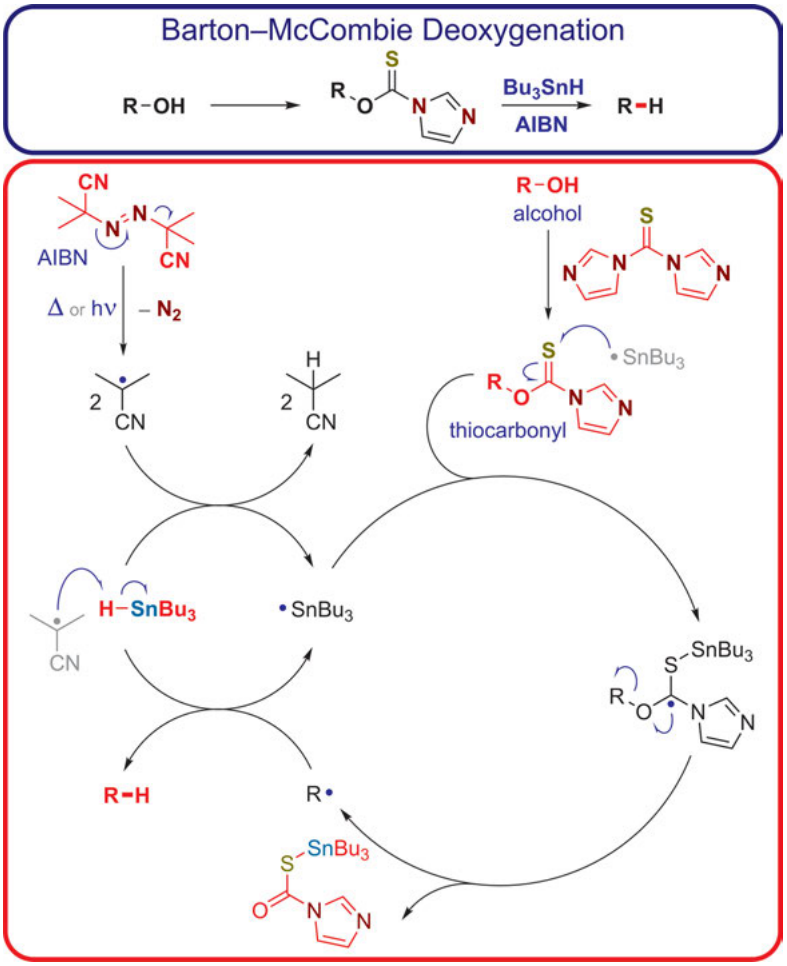


Fig. 12.2: The ***Barton–McCombie*** *deoxygenation* mechanism.[38]

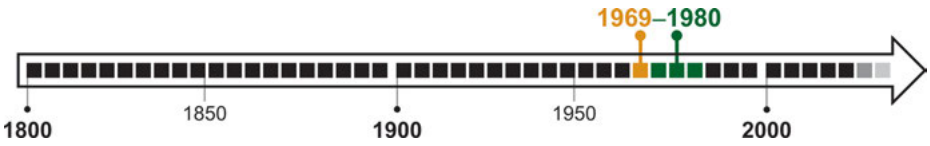


Fig. 12.3: The discovery of the ***Barton*** *decarboxylation*.[39]

38 The ***Barton–McCombie*** *deoxygenation* is a radical deoxygenation of a *thiocarbonyl*: *O*,*O*-thiocarbonate **RO**C(S)OR; *S*,*O*-dithiocarbonate = xanthate **RO**C(S)SR; or *O*-thiocarbamate **RO**C(S)NR_2.
39 The *decarboxylation* reaction was likely first described between 1980–1985 [12a, 12b] and the *deoxygenation* reaction was likely first described between 1975–1980 [12c, 12d]. In **1969**, Derek H. R. Barton (jointly with Odd Hassel) received the Nobel Prize in Chemistry [12e].

13 Baylis–Hillman Reaction

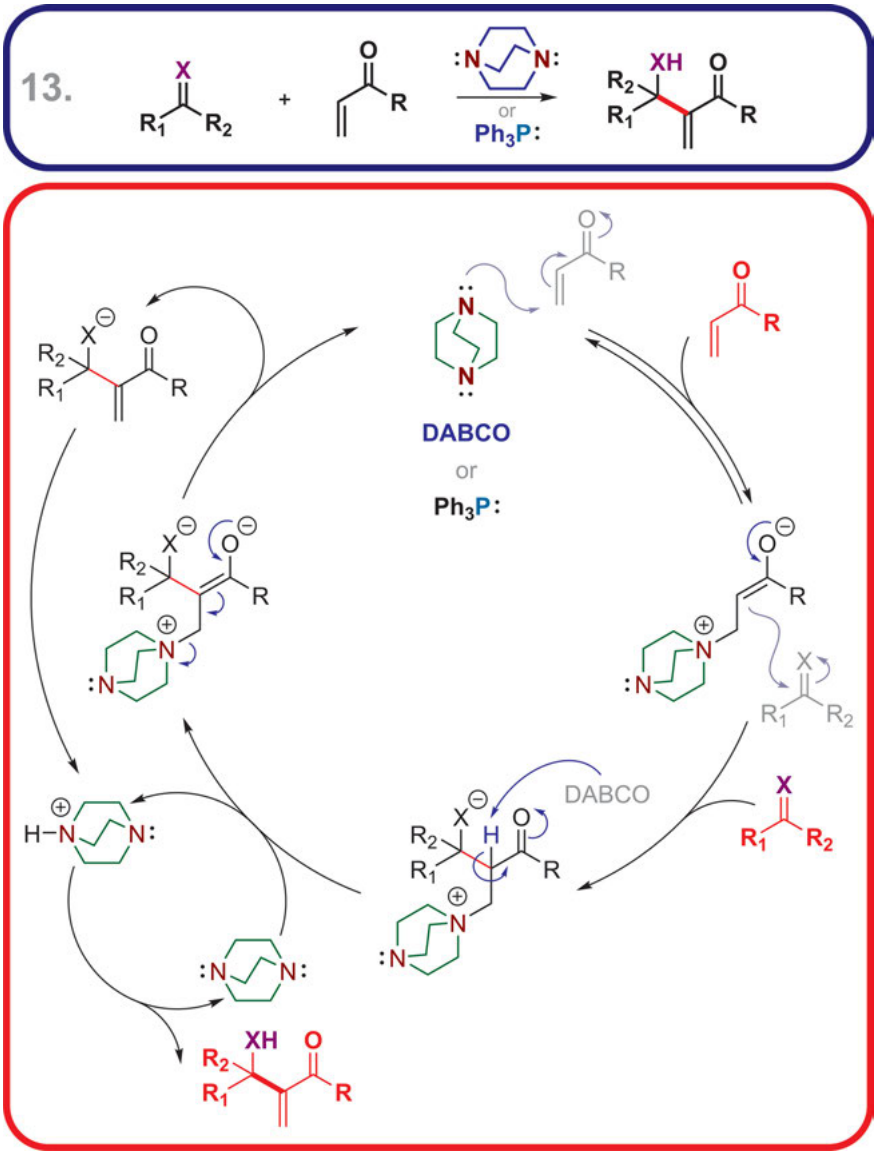


Fig. 13.1: The ***Baylis–Hillman*** *reaction* mechanism.[40]

40 The ***Baylis–Hillman*** *reaction* is also called the ***Morita–Baylis–Hillman*** *reaction*.

https://doi.org/10.1515/9783110608373-013

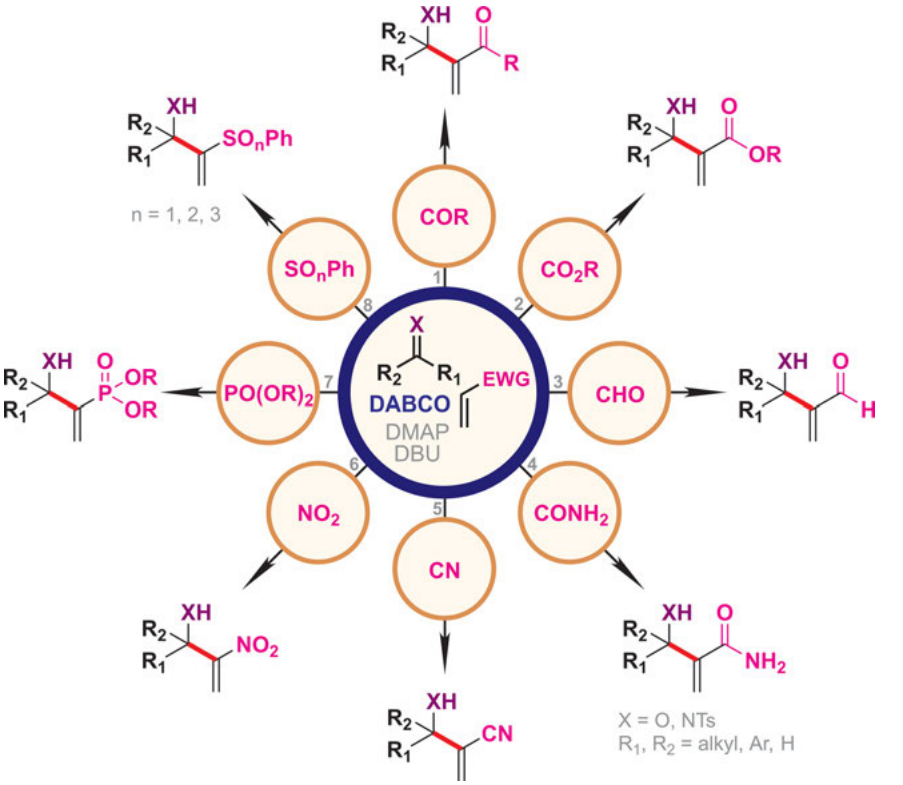


Fig. 13.2: The synthetic versatility of the ***Baylis–Hillman*** *reaction*.[41]

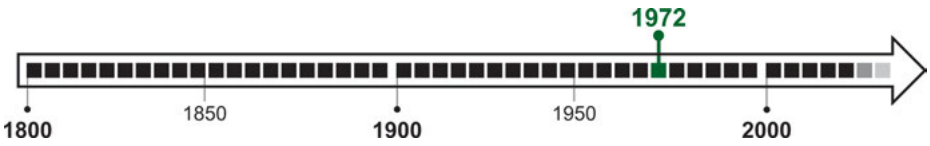


Fig. 13.3: The discovery of the ***Baylis–Hillman*** *reaction*.[42]

41 Many variations of the ***Baylis–Hillman*** *reaction* exist, depending on the nature of EWG (the *Michael* acceptor) and carbonyl compound (the electrophile). Please note, for X = NR it is called the *aza-**Baylis–Hillman** reaction*.

42 The reaction was likely first described around 1972 [13].

14 Beckmann Rearrangement

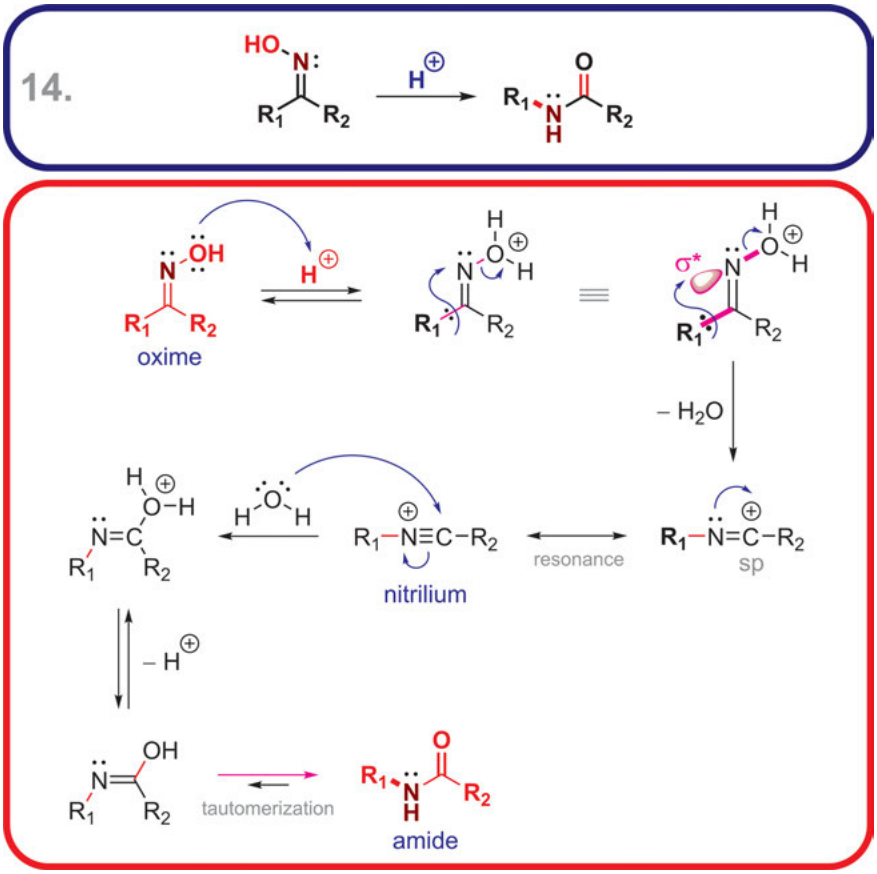


Fig. 14.1: The ***Beckmann*** *rearrangement* mechanism.[43]

43 The ***Beckmann*** *rearrangement* is seldom called the ***Beckmann*** *oxime-amide rearrangement*.

https://doi.org/10.1515/9783110608373-014

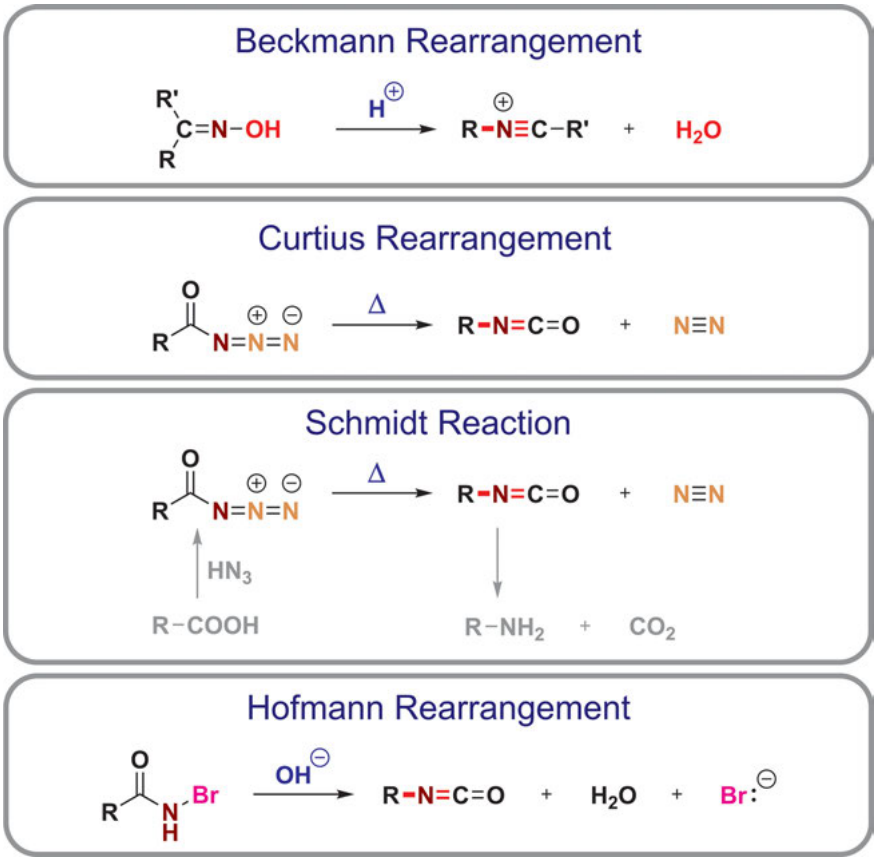


Fig. 14.2: Reactions related to the ***Beckmann*** *rearrangement*.[44]

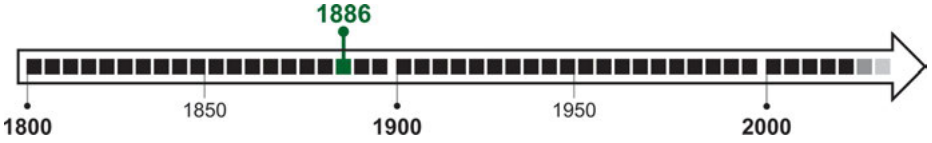


Fig. 14.3: The discovery of the ***Beckmann*** *rearrangement*.[45]

---

44 Several reactions are mechanistically related to the ***Beckmann*** *rearrangement*: the ***Curtius*** *rearrangement*, the ***Schmidt*** *reaction*, the ***Hofmann*** *rearrangement*, and the ***Lossen*** *rearrangement* (all covered in Chapter 31). The first example (the ***Beckmann*** *rearrangement*) is redrawn to emphasize the rearrangement of an *oxime* into a *nitrilium ion*. In other examples, the key step is the rearrangement of a *nitrene* (formed from a carbonyl derivative) into an *isocyanate*.

45 The reaction was likely first described around 1886 [14].

15 Benzoin Condensation

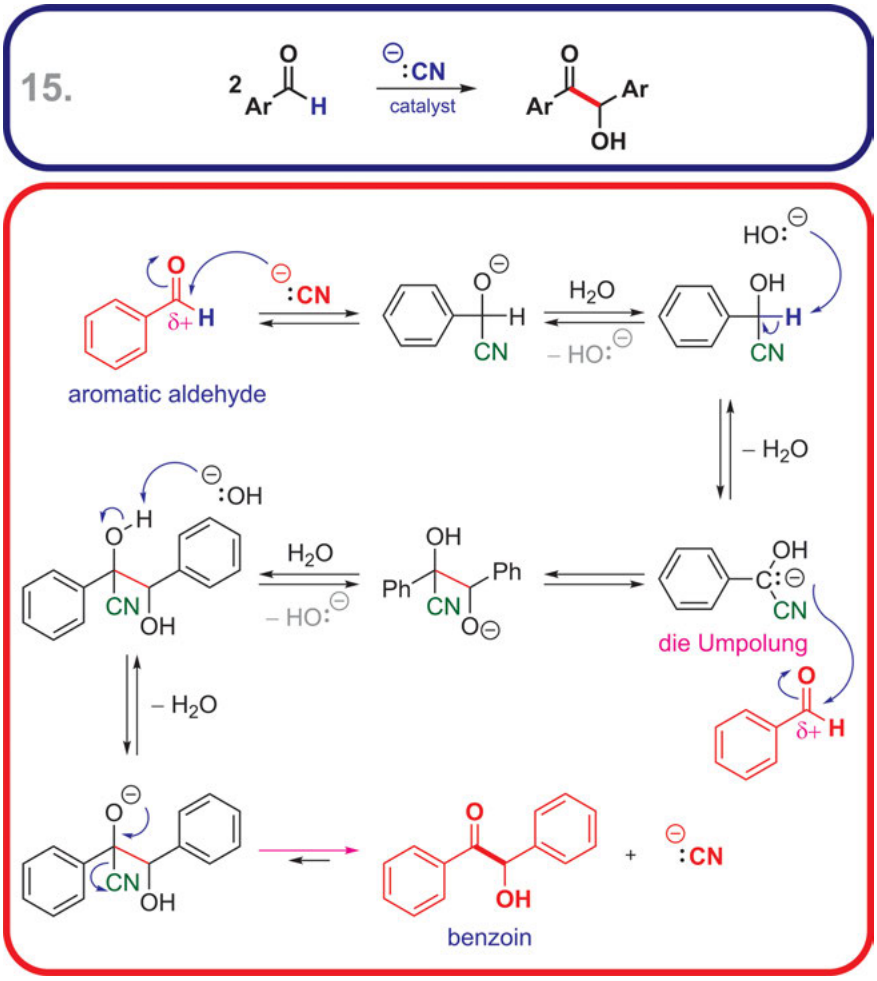


Fig. 15.1: The *benzoin condensation* mechanism.[46]

46 The *benzoin condensation* is one of the oldest reactions in organic chemistry.

https://doi.org/10.1515/9783110608373-015

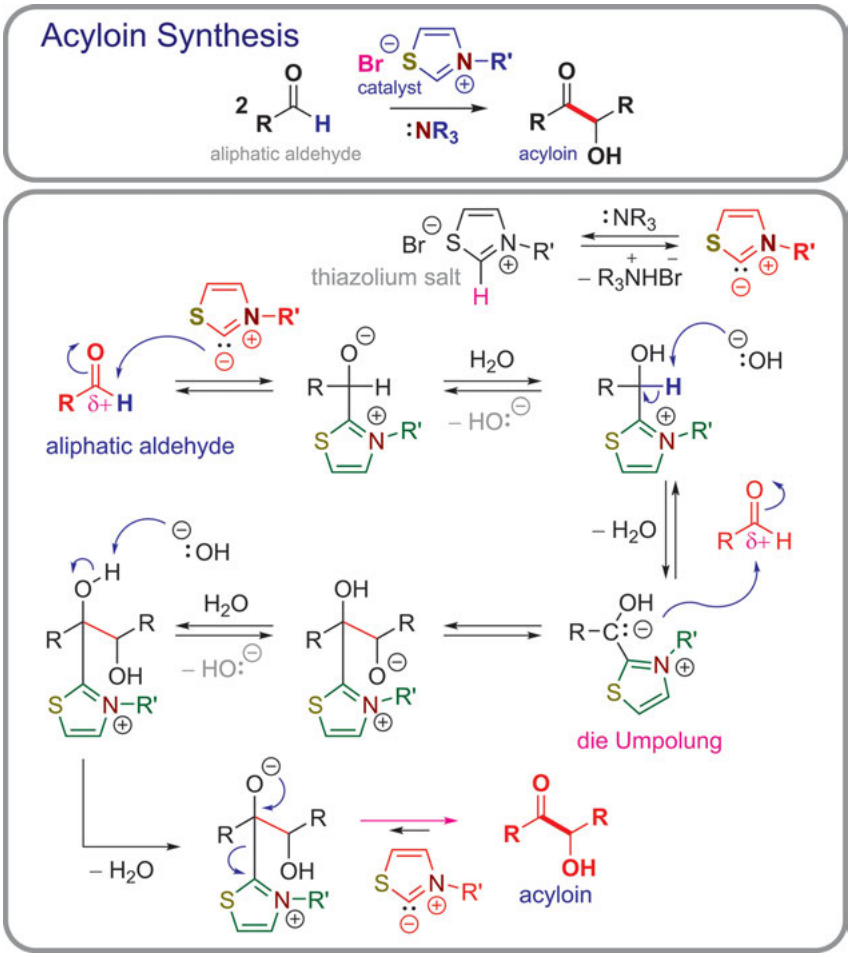


Fig. 15.2: The *acyloin synthesis* mechanism using thiazolium salts.[47]

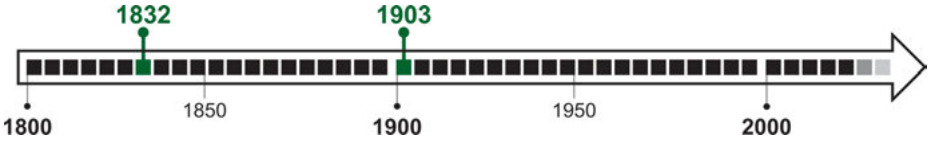


Fig. 15.3: The discovery of the *benzoin condensation*.[48]

47 The *benzoin condensation* involves two aromatic aldehydes and is catalyzed by **cyanide ion** forming aromatic α–hydroxy ketones *(benzoins)*. The *acyloin synthesis* is a condensation of two aliphatic aldehydes, it is catalyzed by **thiazolium salts** [15a, 15b] and yields aliphatic (or mixed) α–hydroxy ketones *(acyloins)*. The *acyloin synthesis* should not be confused with the *acyloin condensation* (Chapter 7).

48 The reaction was likely first described around 1832 and the mechanism in 1903 [15c, 15d].

16 Benzyne Mechanism

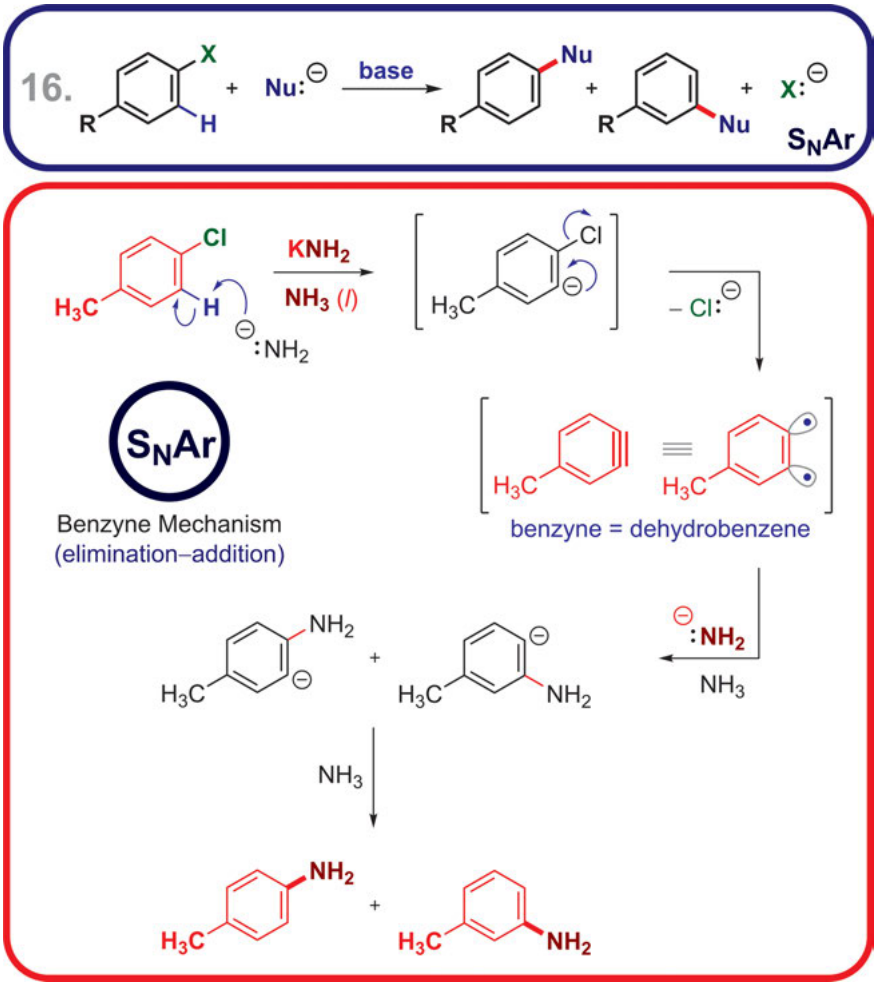


Fig. 16.1: The *benzyne (elimination-addition)* mechanism.[49]

49 The *benzyne mechanism* is one of the fundamental **aromatic nucleophilic substitution** mechanisms; it is also called the *elimination-addition* mechanism, that is, the opposite of **S_NAr** (**S_N2Ar**), or the *addition-elimination* mechanism (covered in Chapter 4).

https://doi.org/10.1515/9783110608373-016

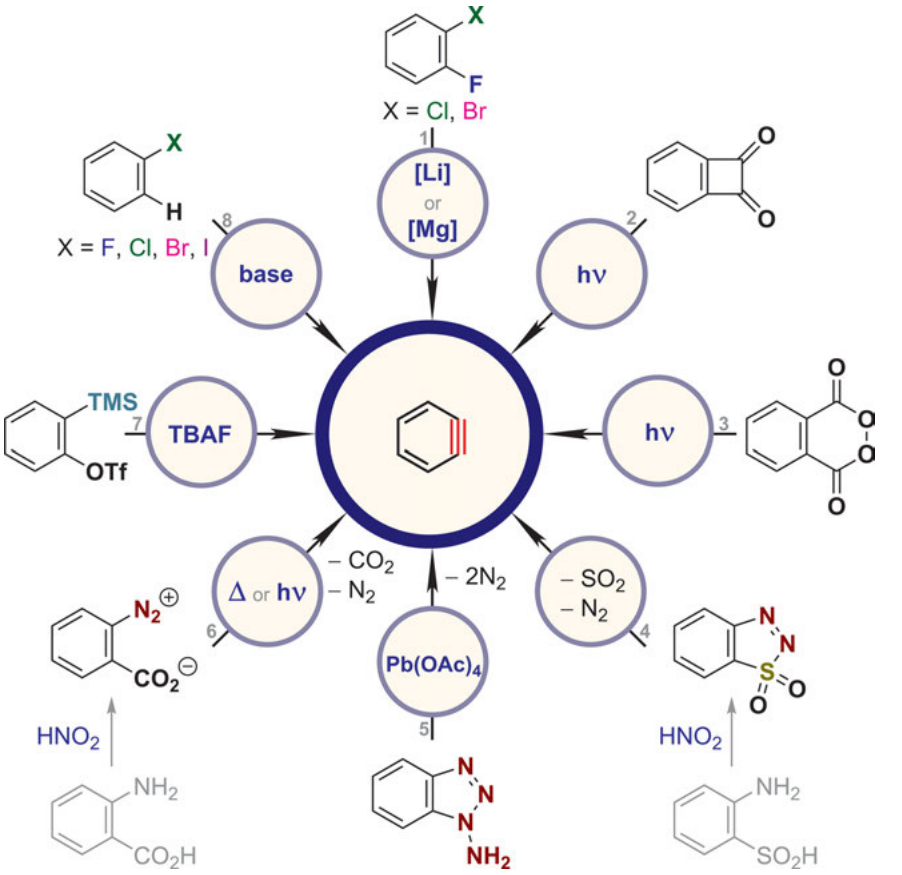


Fig. 16.2: Various synthetic methods leading to the formation of benzyne.[50]

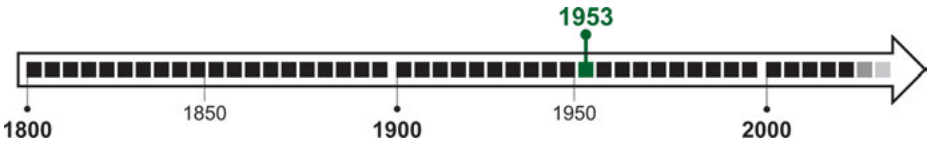


Fig. 16.3: The discovery of the *benzyne mechanism*.[51]

50 Since its first discovery, numerous methods evolved leading to the formation of the *benzyne* intermediate *(aryne)*. Please note, *benzyne (aryne)* can also be called *dehydrobenzene (dehydroarene)* [16a, 16b].

51 The mechanism in its present form was likely first proposed around 1953 [16c].

17 Bergman Cyclization

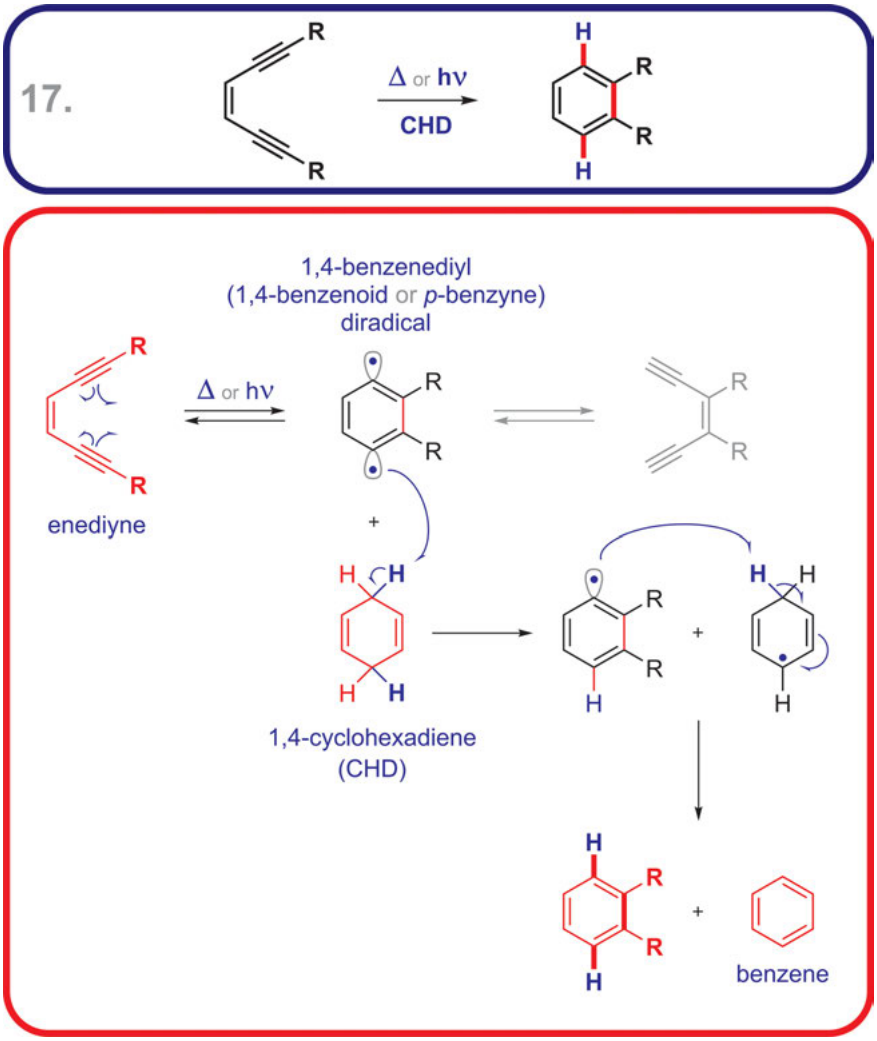


Fig. 17.1: The ***Bergman*** *cyclization* mechanism.[52]

52 The ***Bergman*** *cyclization* is also known as the ***Bergman*** *reaction (isomerization, cycloaromatization)*.

https://doi.org/10.1515/9783110608373-017

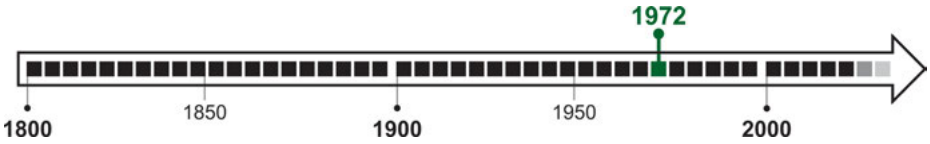


Fig. 17.2: The discovery of the ***Bergman*** *cyclization*.[53]

53 The reaction was likely first described around 1972 [17].

18 Birch Reduction

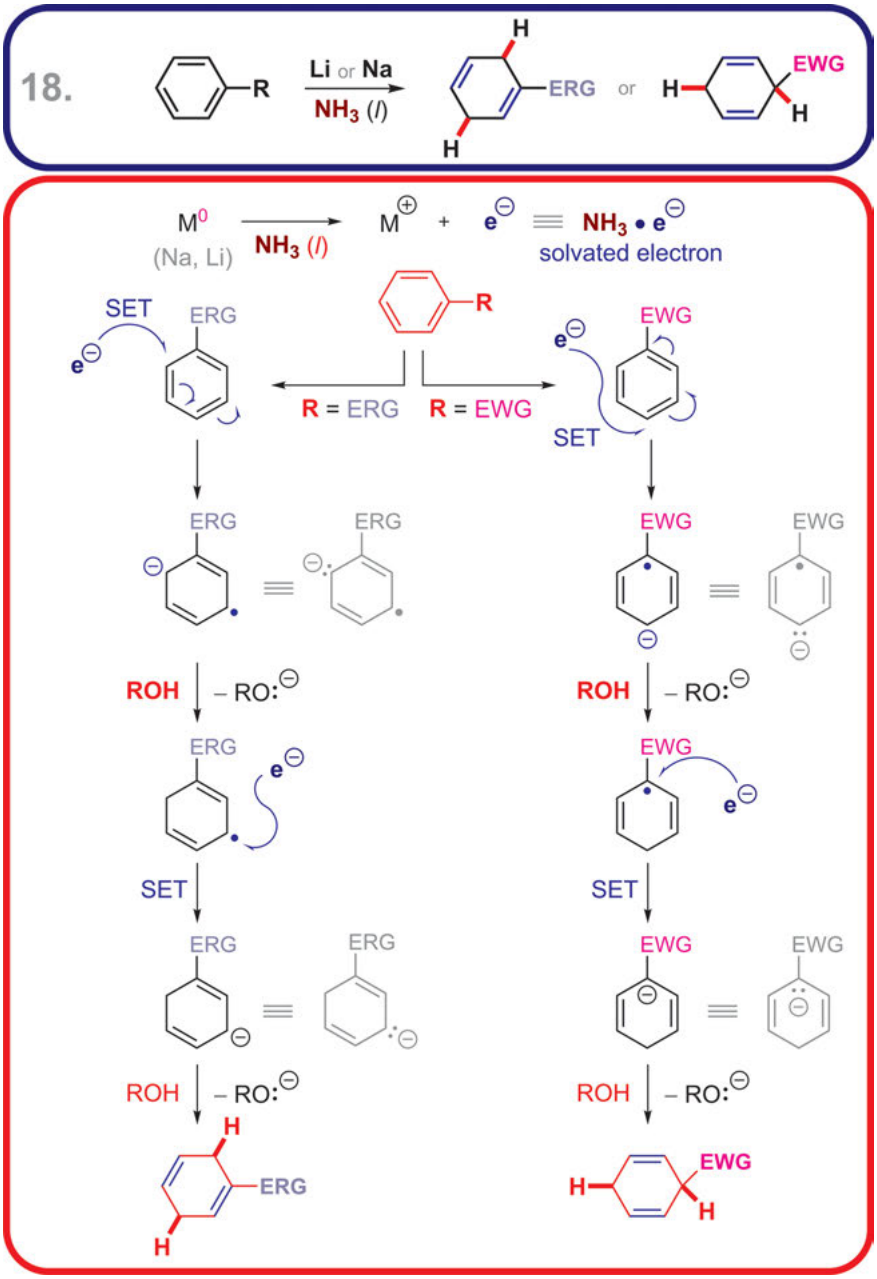


Fig. 18.1: The ***Birch*** *reduction* mechanism.[54]

https://doi.org/10.1515/9783110608373-018

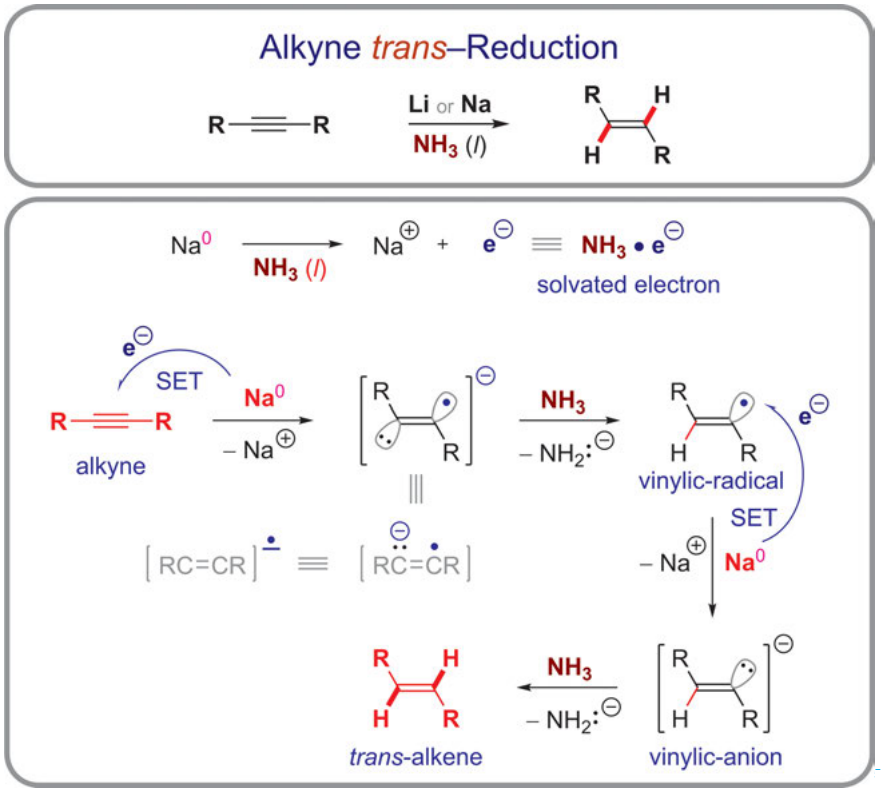


Fig. 18.2: The *alkyne trans-reduction* mechanism.[55]

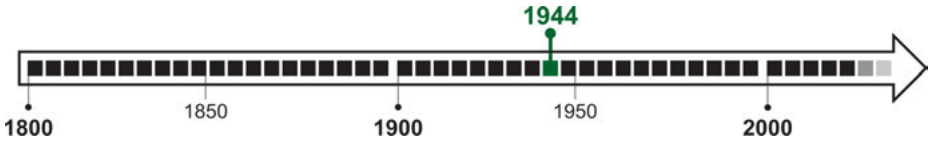


Fig. 18.3: The discovery of the ***Birch*** *reduction*.[56]

54 The first step in the ***Birch*** *reduction* mechanism is a *single electron transfer* (SET) (see Chapter 5). The regiochemistry of the formed products depends on the nature of the substitution (ERG versus EWG).
55 The *alkyne trans-reduction (alkyne metal reduction)* mechanism is much like the ***Birch*** *reduction*. Please note, under the ***Birch*** *reduction* conditions *alkynes* are reduced to ***trans****-alkenes* [18a, 18b]. Under Pd/C-catalyzed conditions, the ***cis****-alkene* is usually the major product.
56 The reaction was likely first described around 1944 [18c].

19 Bischler–Napieralski Cyclization

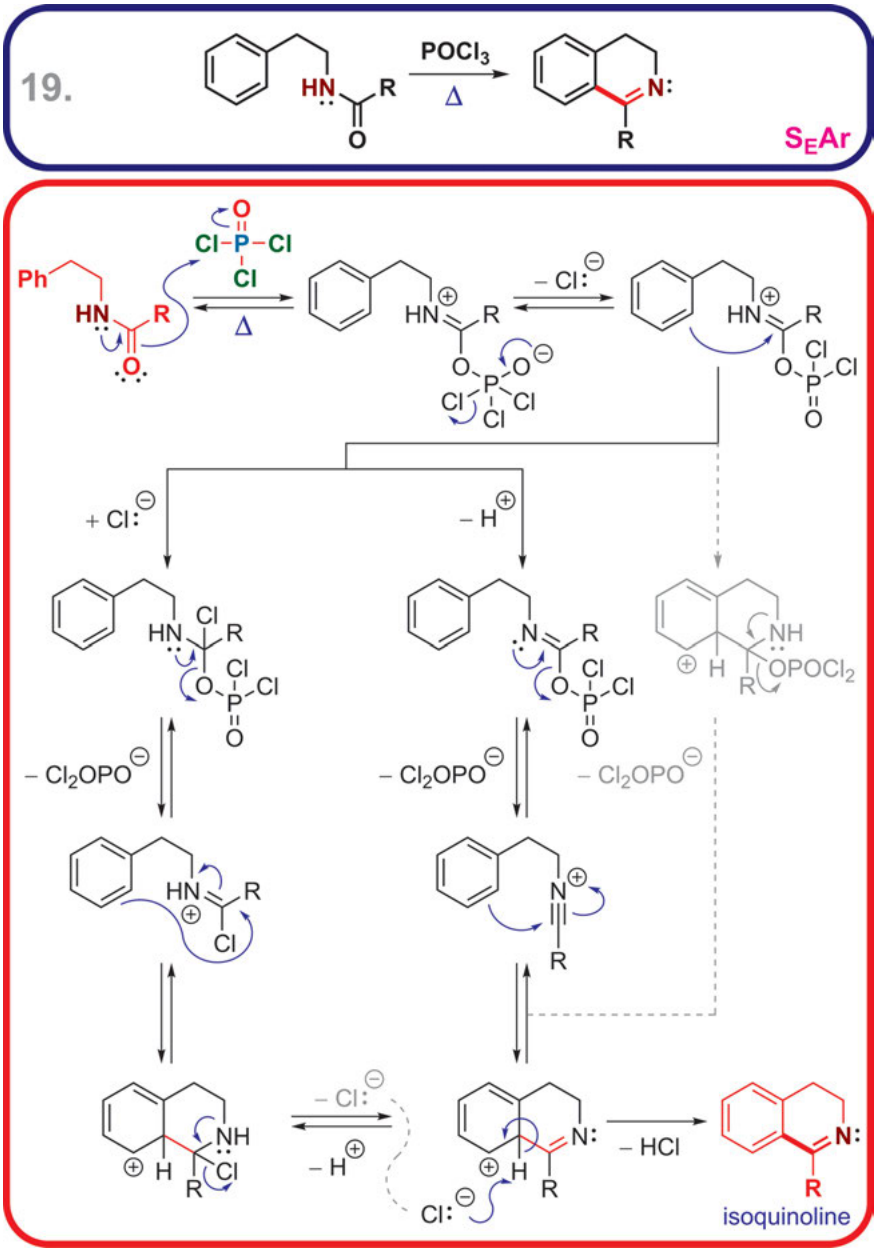


Fig. 19.1: The ***Bischler–Napieralski*** *cyclization* mechanism.[57]

https://doi.org/10.1515/9783110608373-019

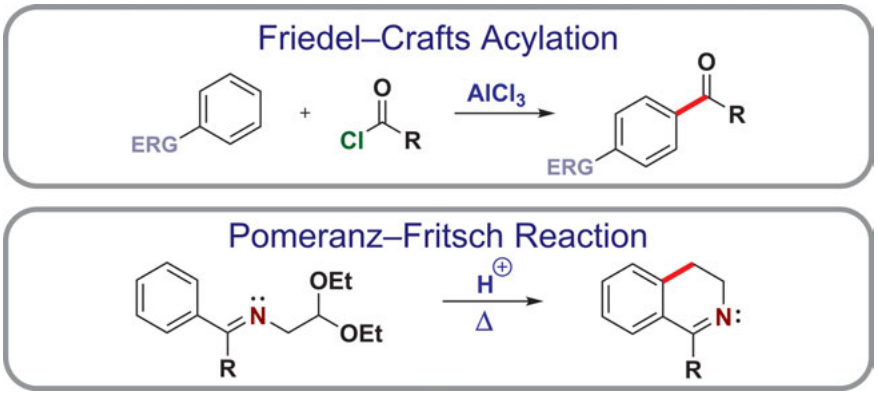


Fig. 19.2: Reactions related to the ***Bischler–Napieralski*** *cyclization*.[58]

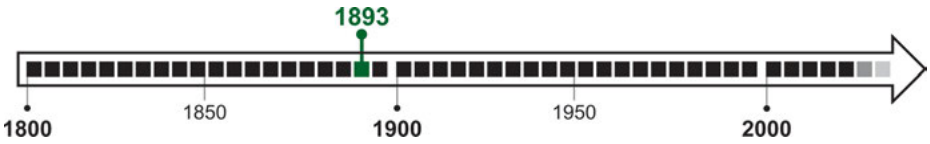


Fig. 19.3: The discovery of the ***Bischler–Napieralski*** *cyclization*.[59]

57 The ***Bischler–Napieralski*** *cyclization* also called the ***Bischler–Napieralski*** *reaction*. It is a classic example of **aromatic electrophilic substitution** (the ***arenium ion*** mechanism or $\mathbf{S_EAr}$, Chapter 3).
58 Several named reactions are related to the ***Bischler–Napieralski*** *cyclization*: the ***Friedel–Crafts*** *acylation* and *alkylation* (covered in Chapter 39), and the closely related ***Pomeranz–Fritsch*** *reaction*, which is an alternative way to make *isoquinolines* [19a, 19b].
59 The reaction was likely first described around 1893 [19c].

20 Brown Hydroboration

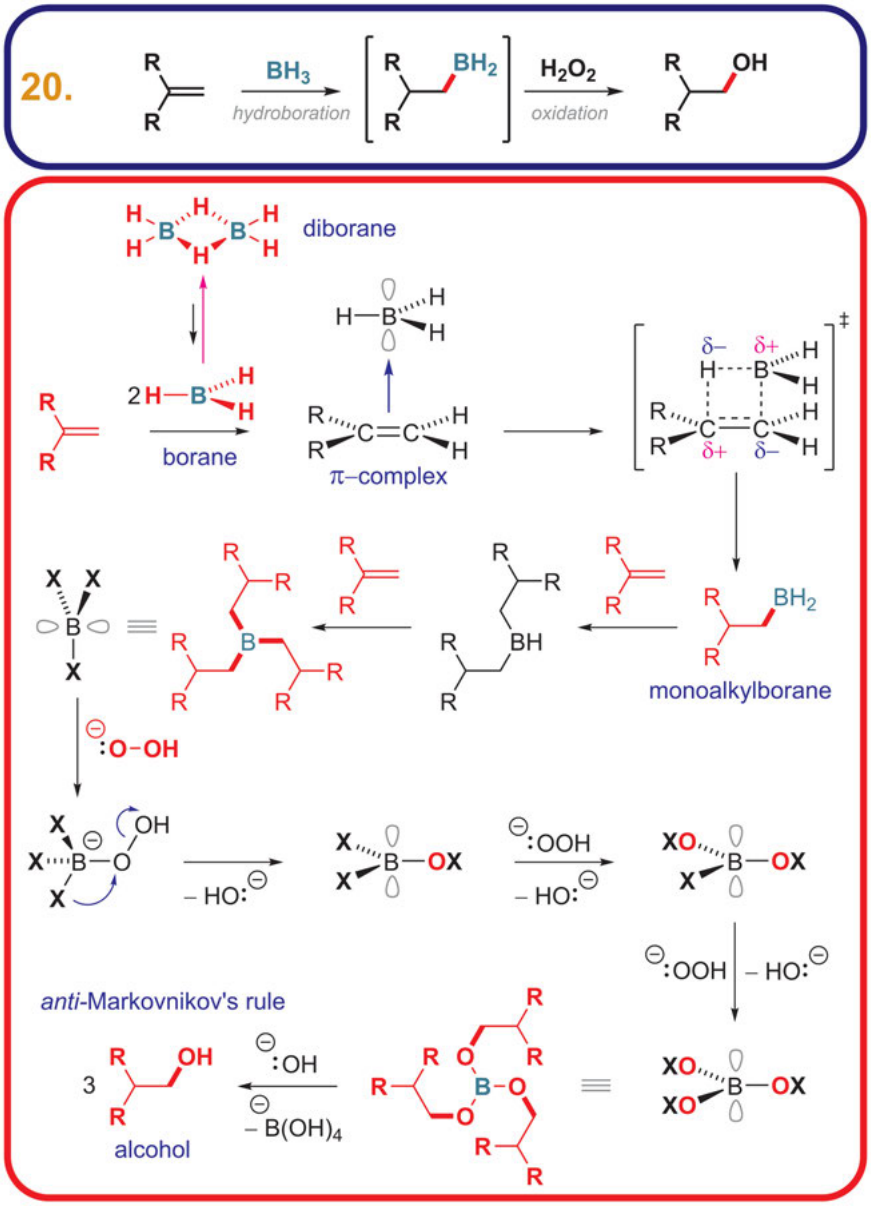


Fig. 20.1: The ***Brown*** *hydroboration* mechanism.[60]

https://doi.org/10.1515/9783110608373-020

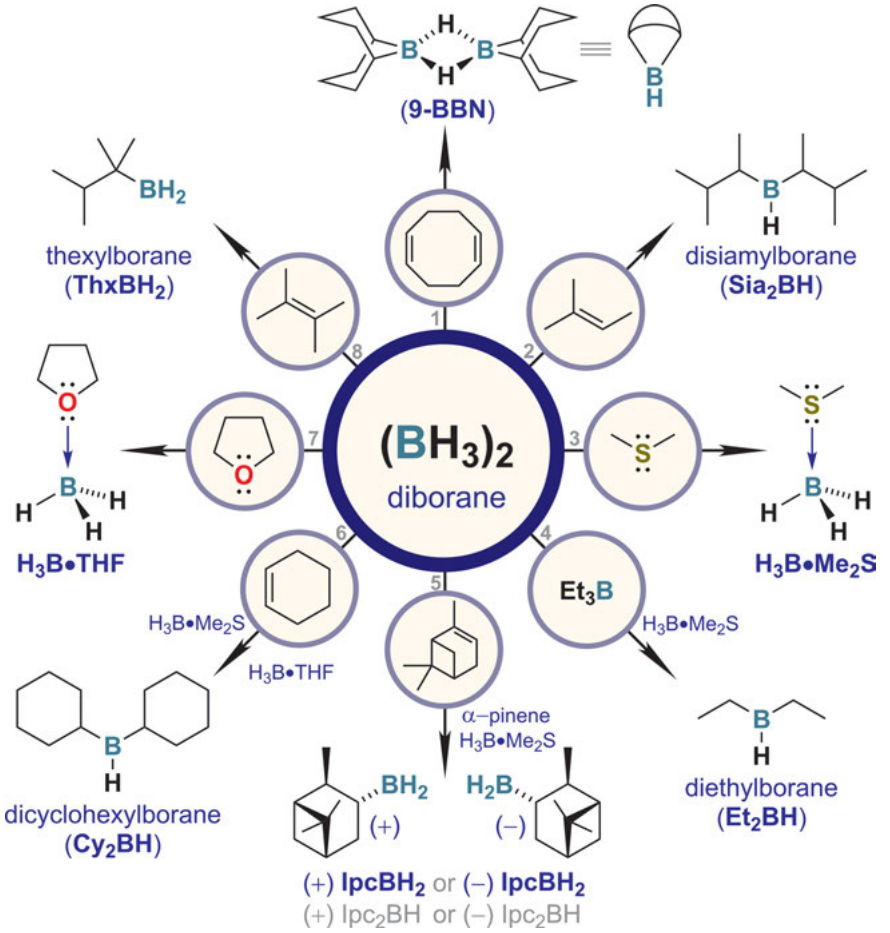


Fig. 20.2: Various borane derivatives formed from diborane.[61]

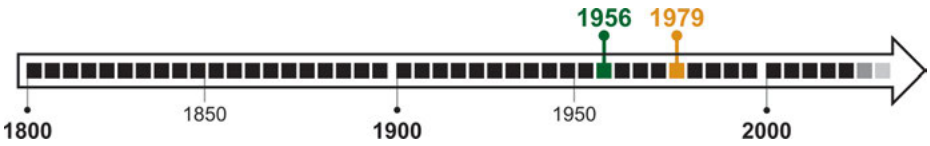


Fig. 20.3: The discovery of the ***Brown*** *hydroboration*.[62]

60 The ***Brown*** *hydroboration* is also known as the *hydroboration-oxidation*. The mechanism is believed to be concerted and ***anti-Markovnikov's*** product is usually formed. Compare to Chapter 52.

61 There are numerous examples of the borane complexes (BH_3•X); the monoalkylborane (RBH_2); and dialkylborane (R_2BH) reagents, which can be prepared from the *diborane* (B_2H_6) via the *hydroboration reaction*: 9-BBN reagent is one of the most important among them [20a].

62 The reaction was likely described around 1956 [20b]. In **1979**, Herbert C. Brown (jointly with Georg Wittig) received the Nobel Prize in Chemistry for the development of boron chemistry [20c].

21 Buchwald–Hartwig Cross Coupling

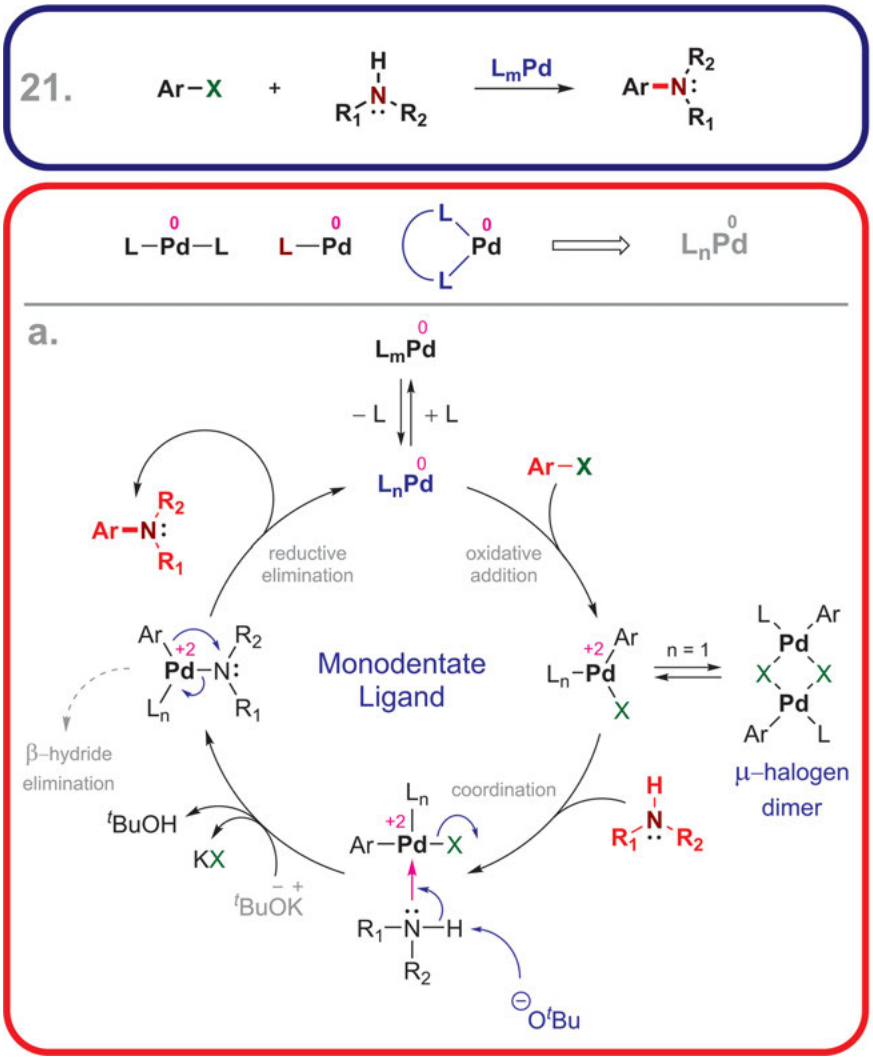


Fig. 21.1: The ***Buchwald–Hartwig*** *cross coupling* mechanism (monodentate ligand).[63]

63 The ***Buchwald–Hartwig*** *cross coupling (amination)* is a type of ***Pd****-catalyzed cross coupling* reaction (C–N bond formation using *aryl halides* and *amines*). The mechanism varies and is usually substrate and ligand dependent. For teaching purposes, a simplified and general example is shown, which may take place in the presence of a *monodentate ligand*.

https://doi.org/10.1515/9783110608373-021

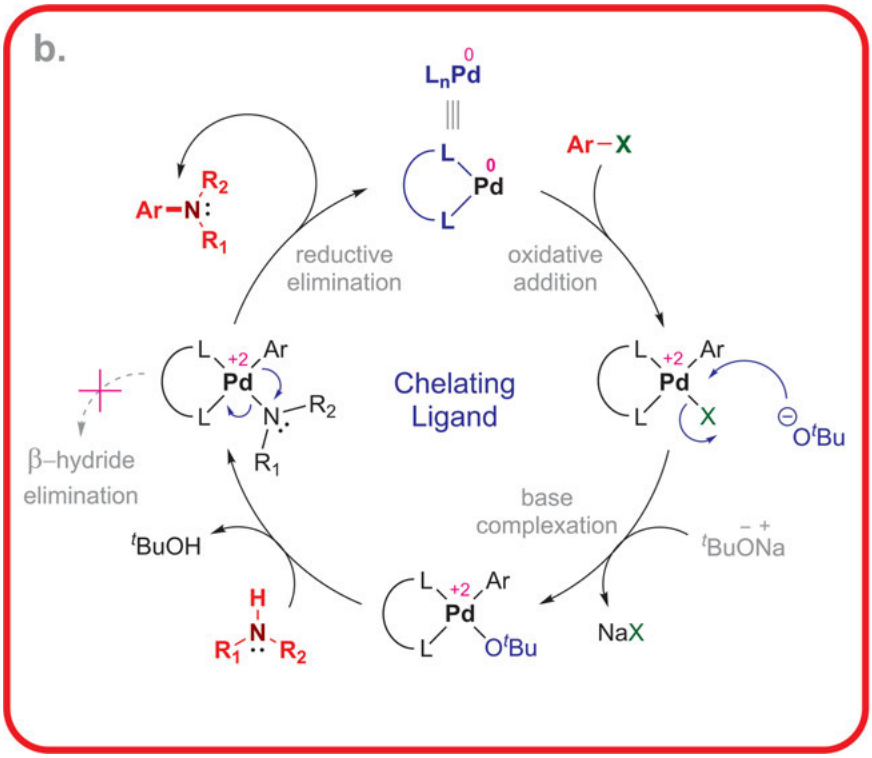


Fig. 21.2: The ***Buchwald–Hartwig*** *cross coupling* mechanism (chelating ligand).[64]

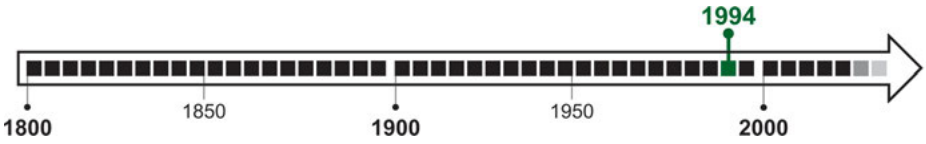


Fig. 21.3: The discovery of the ***Buchwald–Hartwig*** *cross coupling*.[65]

64 For teaching purposes, a simplified and general example is shown, which may take place in the presence of a *chelating ligand*.

65 The reaction was likely first described around 1994 [21].

22 Cannizzaro Reaction

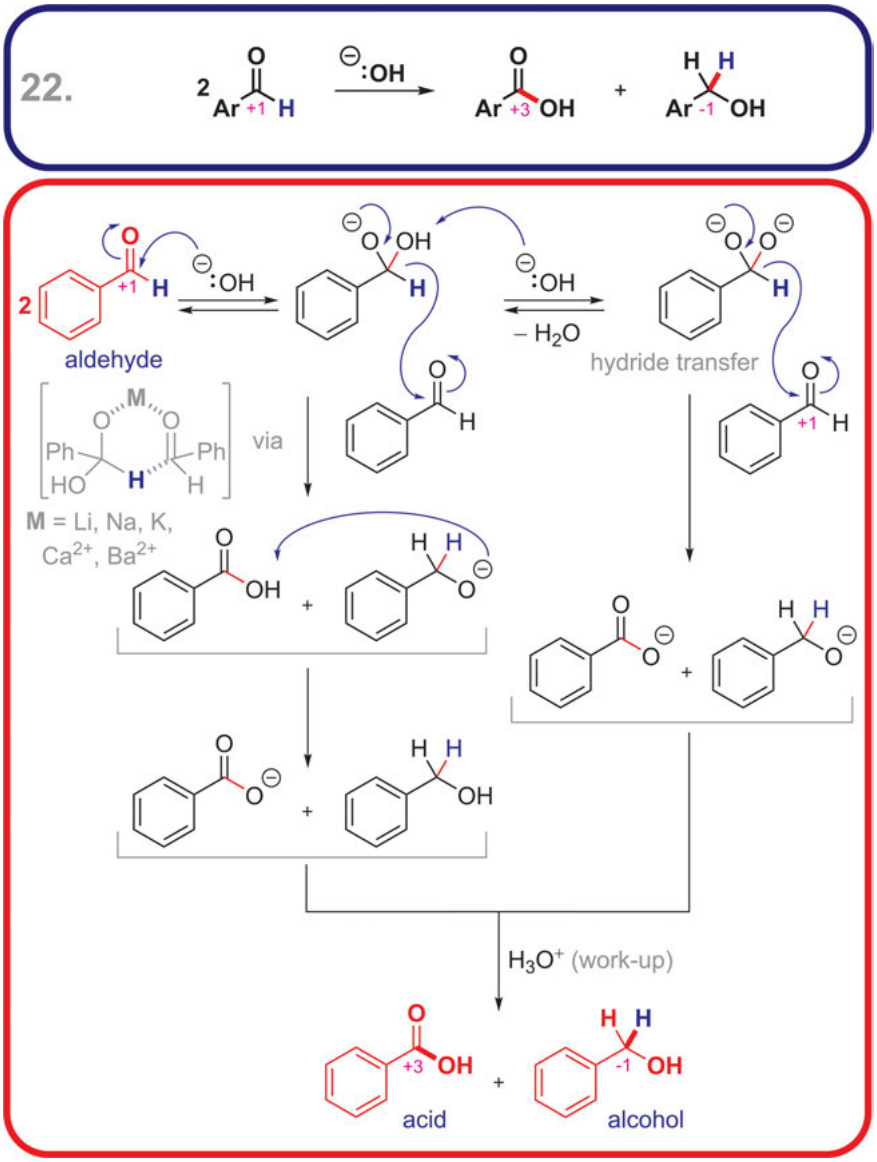


Fig. 22.1: The ***Cannizzaro*** *reaction* mechanism.[66]

66 The ***Cannizzaro*** *reaction* is seldom called the ***Cannizzaro*** *disproportionation (RedOx) reaction*. It is one of the oldest reactions in organic chemistry.

https://doi.org/10.1515/9783110608373-022

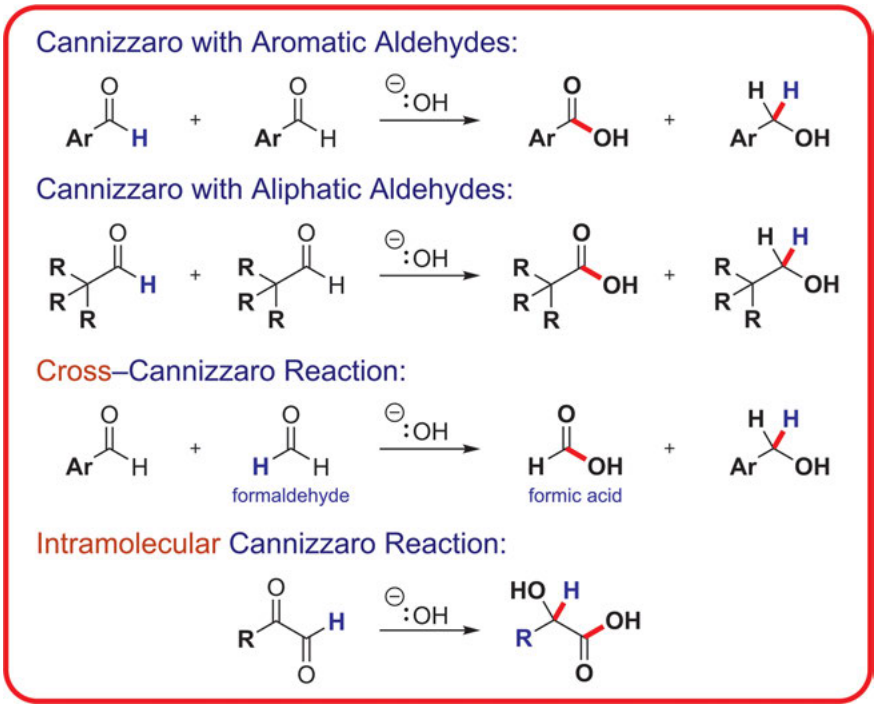


Fig. 22.2: Variations of the ***Cannizzaro*** *reaction*.[67]

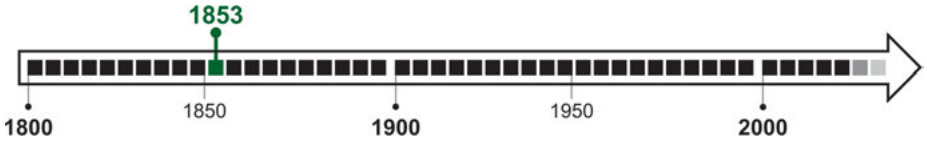


Fig. 22.3: The discovery of the ***Cannizzaro*** *reaction*.[68]

67 There are many variations of the ***Cannizzaro*** *reaction*: the ***Cannizzaro*** *reaction* with aromatic and aliphatic aldehydes containing no α–hydrogen atoms, and the *cross-**Cannizzaro** reaction* and the *intramolecular **Cannizzaro** reaction* [1].

68 The reaction was likely first described around 1853 [22].

23 Chan–Evans–Lam Cross Coupling

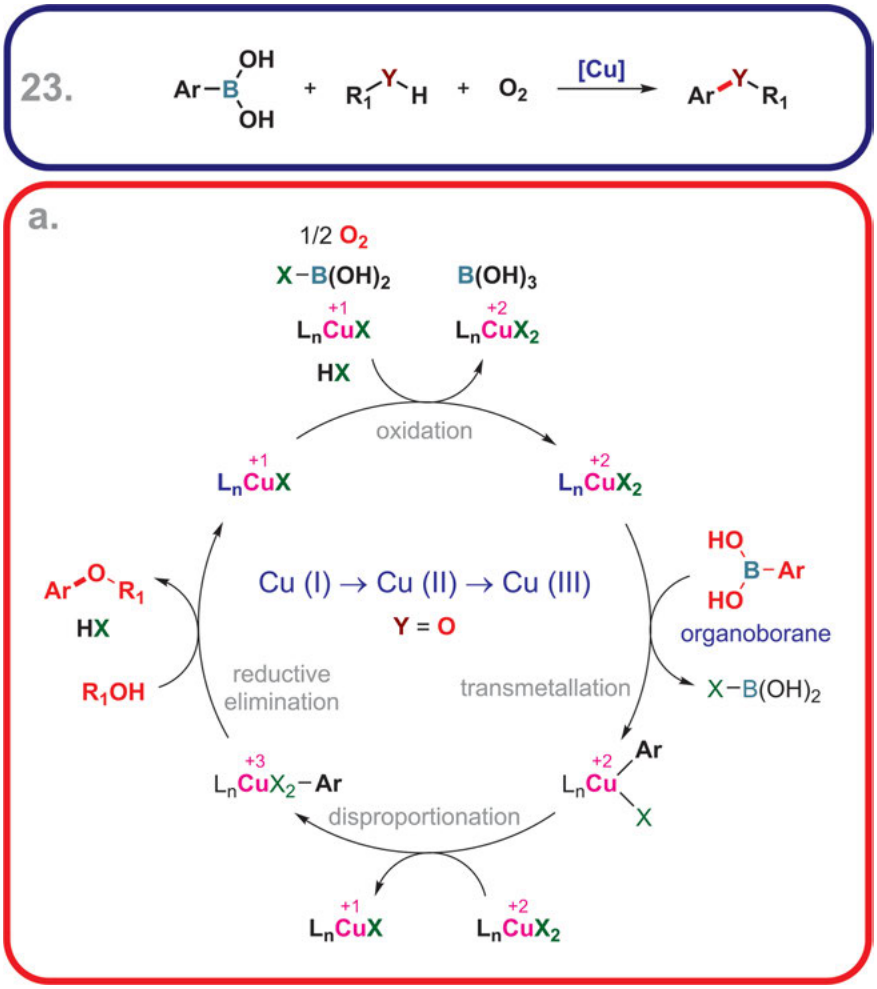


Fig. 23.1: The ***Chan–Evans–Lam*** *cross coupling* mechanism (Y = O).[69]

69 The ***Chan–Evans–Lam*** *cross coupling* (also simply called the ***Chan–Lam*** *cross coupling*) is a type of ***Cu****-catalyzed cross coupling* reaction (C–O and C–N bond formation using *aryl boronic acids* and *alcohols* or *amines*). The mechanism is not well-understood and is usually very substrate and ligand dependent. For teaching purposes, a simplified and general example is shown, which may take place in etherification reactions (C–O bond formation, Y = O) [23a, 23b].

https://doi.org/10.1515/9783110608373-023

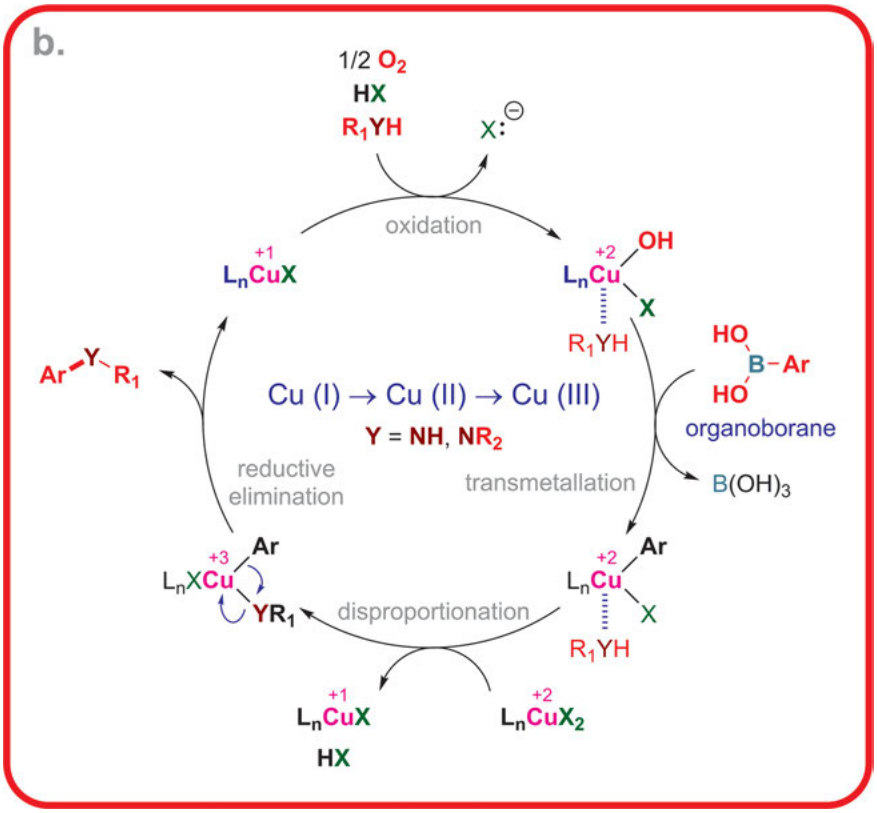


Fig. 23.2: The ***Chan–Evans–Lam*** *cross coupling* mechanism (Y = NH, NR_2).[70]

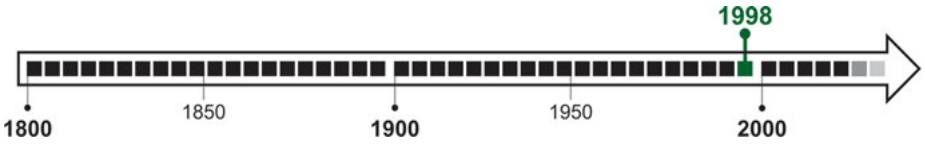


Fig. 23.3: The discovery of the ***Chan–Evans–Lam*** *cross coupling*.[71]

70 The mechanism is not well-understood and is usually very substrate and ligand dependent. For teaching purposes, a simplified and general example is shown, which may take place in amination reactions (C–N bond formation, Y = NH, NR_2) [23c].

71 The reaction was likely first described around 1998 [23d, 23e, 23f].

24 Chichibabin Amination

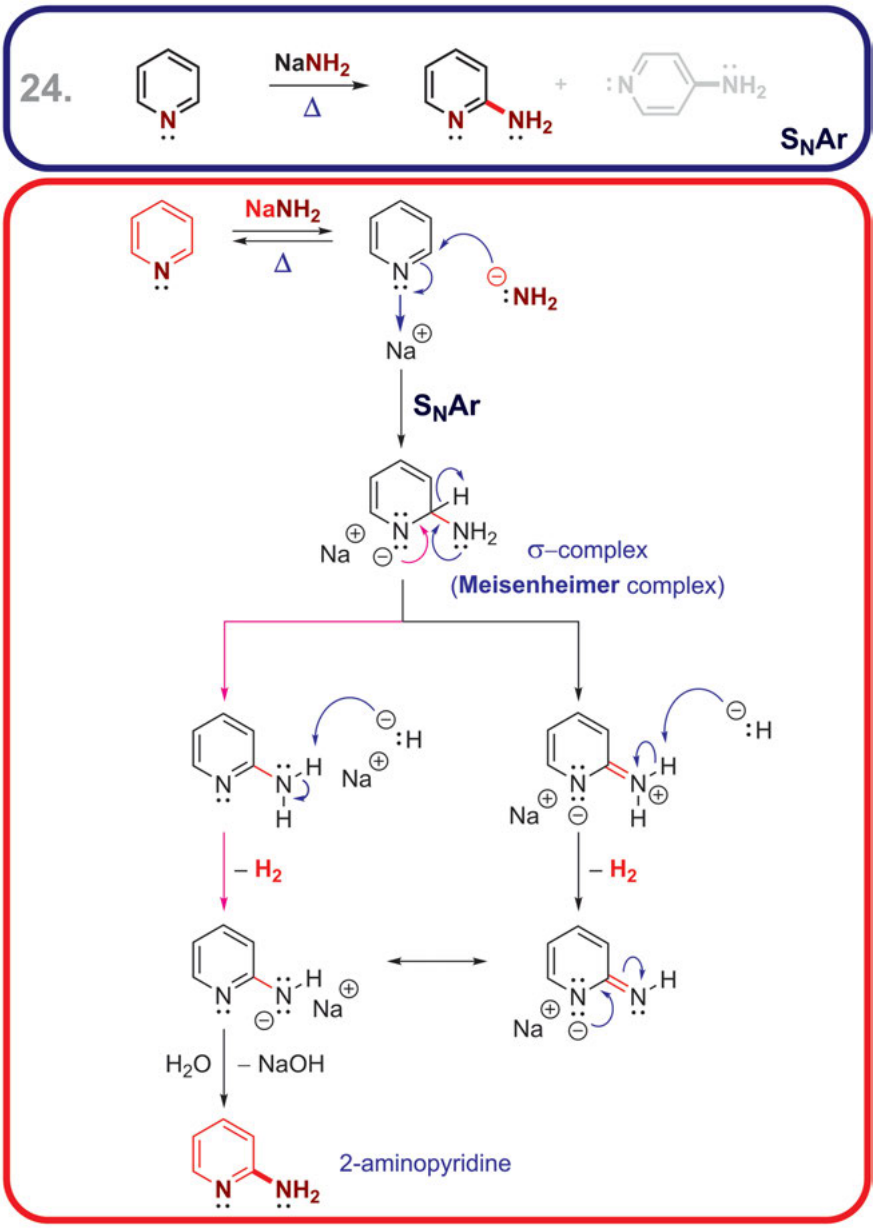


Fig. 24.1: The ***Chichibabin*** *amination* mechanism.[72]

https://doi.org/10.1515/9783110608373-024

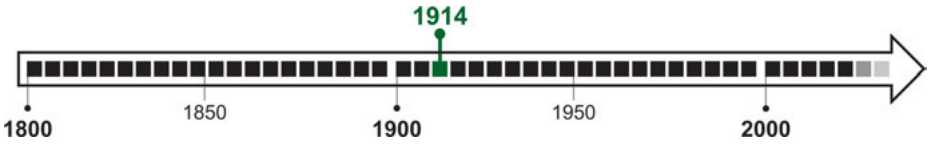


Fig. 24.2: The discovery of the ***Chichibabin*** *amination*.[73]

72 The ***Chichibabin*** *amination* (in Russian Чичибабин) is also called the ***Chichibabin*** *reaction*. It is a classic example of **aromatic nucleophilic substitution**. Specifically, it undergoes the *addition-elimination* mechanism: **S_NAr** (**S_N2Ar**), covered in Chapter 4.

73 The reaction was likely first described around 1914 [24].

25 Claisen Condensation

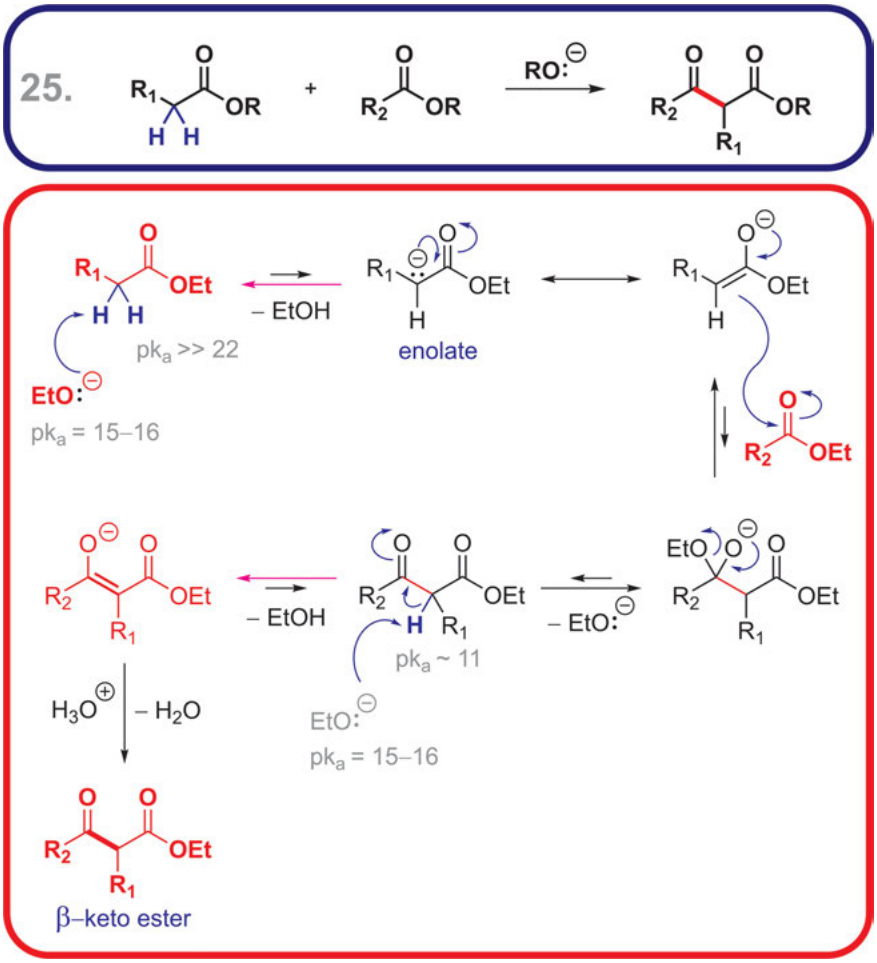


Fig. 25.1: The ***Claisen*** *condensation* mechanism.[74]

74 The ***Claisen*** *condensation* is a condensation reaction between an *ester* and another carbonyl compound containing two enolizable H-atoms (α–hydrogen atoms).

https://doi.org/10.1515/9783110608373-025

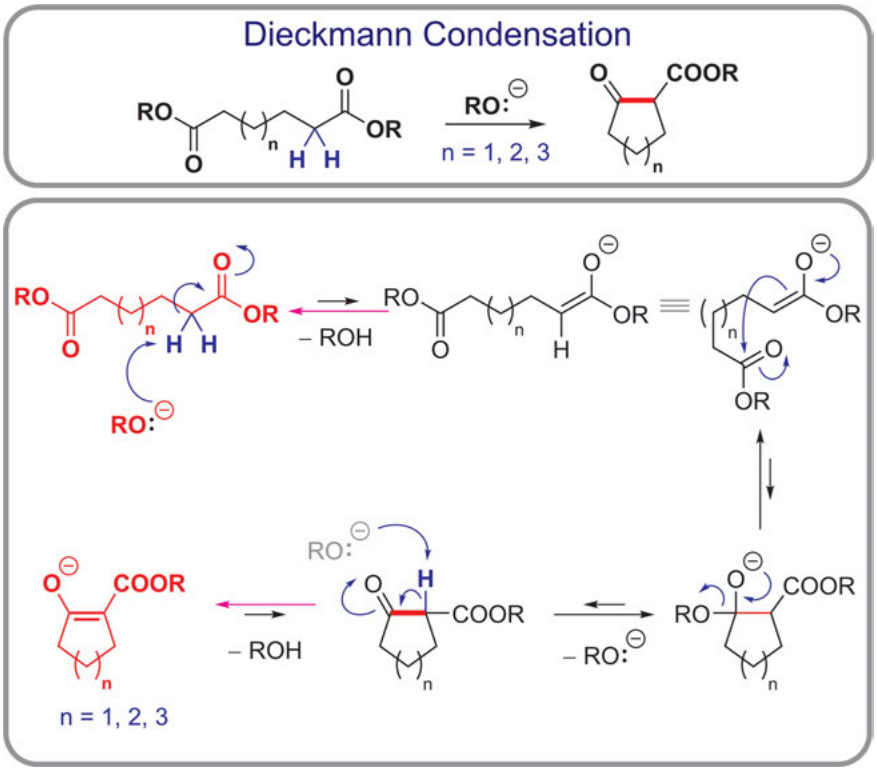


Fig. 25.2: The ***Dieckmann*** *condensation* mechanism.[75]

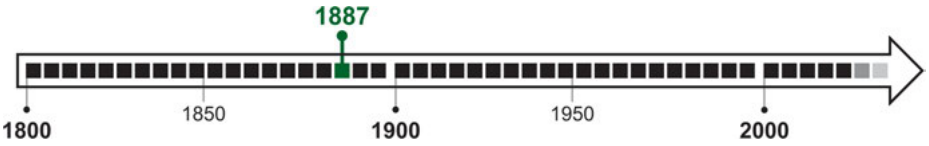


Fig. 25.3: The discovery of the ***Claisen*** *condensation*.[76]

75 The ***Dieckmann*** *condensation* is the *intramolecular* ***Claisen*** *condensation* and their mechanisms are almost identical. The ***Dieckmann*** *condensation* is ideal for the formation of 5-, 6-, and 7-membered rings [25a].

76 The reaction was likely first described around 1887 [25b].

26 Claisen Rearrangement

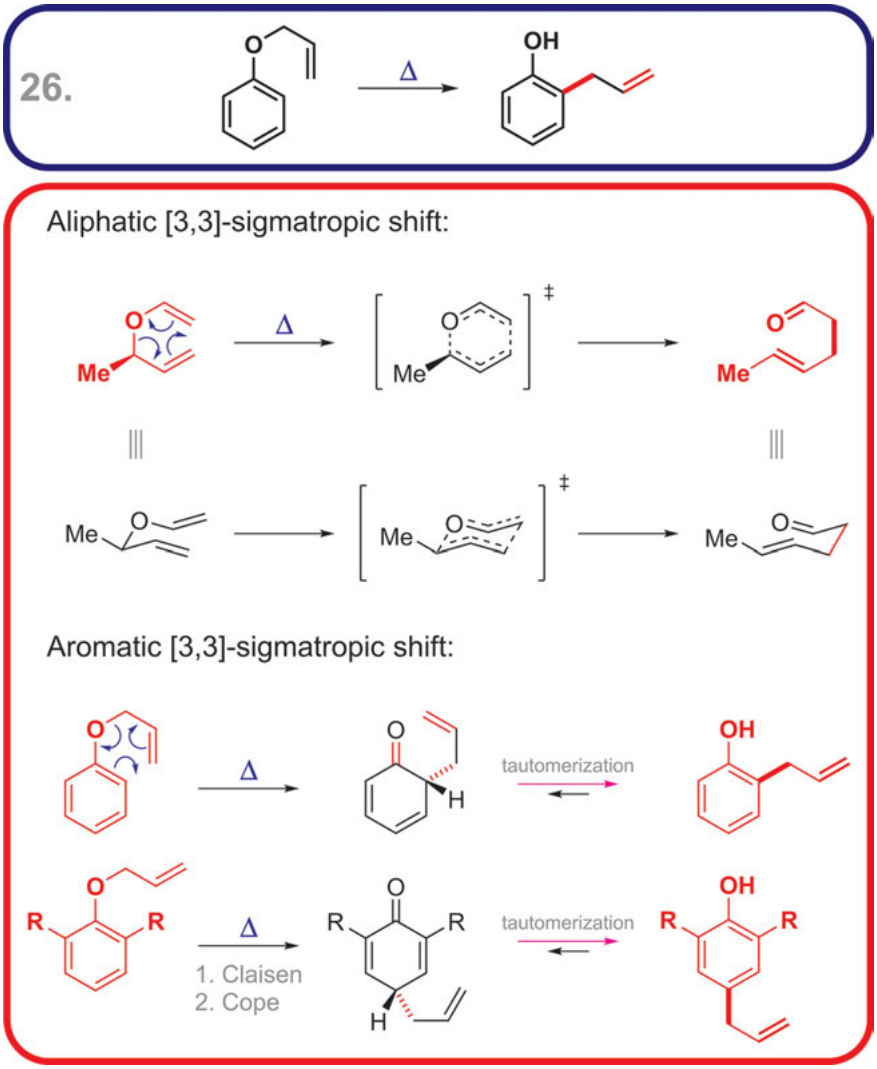


Fig. 26.1: The ***Claisen*** *rearrangement* mechanism.[77]

77 The ***Claisen*** *rearrangement* (different from the ***Claisen*** *condensation* and much like the ***Cope*** *rearrangement*, see Chapter 28) is a pericyclic reaction with a concerted mechanism. This is a classic example of a [3,3′]-*sigmatropic rearrangement (shift)*.

https://doi.org/10.1515/9783110608373-026

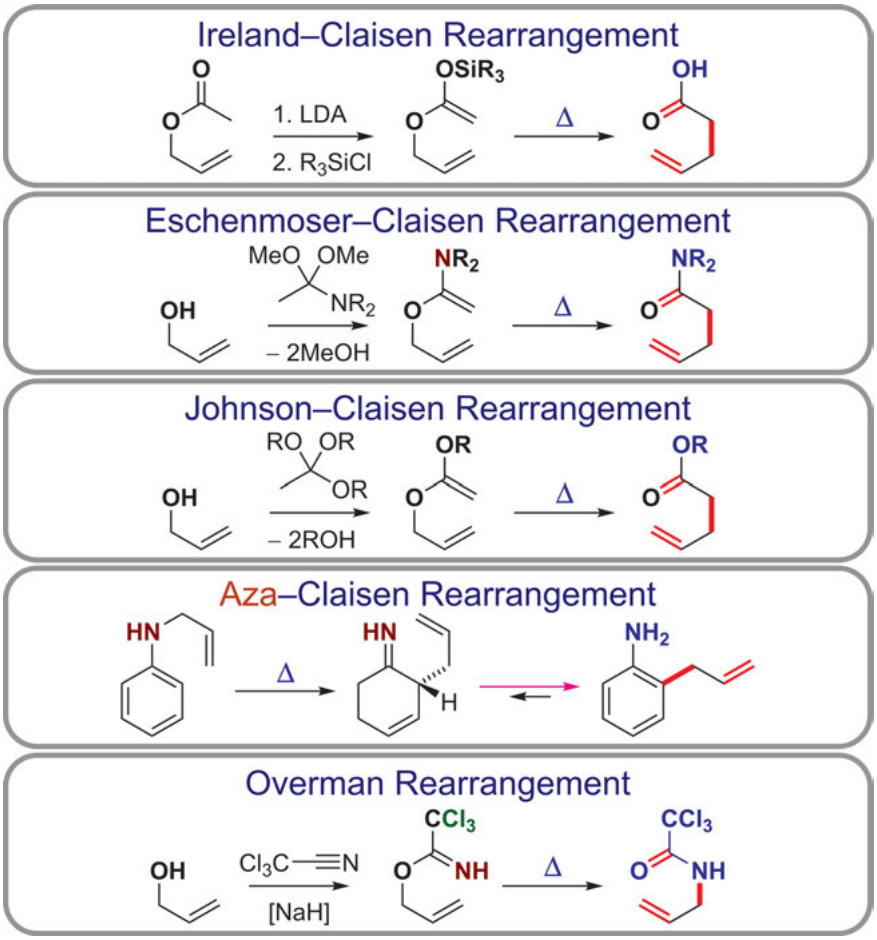


Fig. 26.2: Reactions related to the ***Claisen*** *rearrangement*.[78]

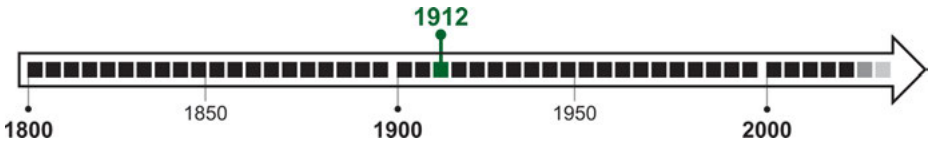


Fig. 26.3: The discovery of the ***Claisen*** *rearrangement*.[79]

78 There are numerous variations and modifications of the ***Claisen*** *rearrangement reaction*, to name a few: the ***Ireland–Claisen*** *rearrangement*, the ***Eschenmoser–Claisen*** *rearrangement*, the ***Johnson–Claisen*** *rearrangement*, the *aza-**Claisen** (aza-**Cope**) rearrangement*, the ***Overman*** *rearrangement*, and others [26a].

79 The reaction was likely first described around 1912 [26b].

27 Cope Elimination

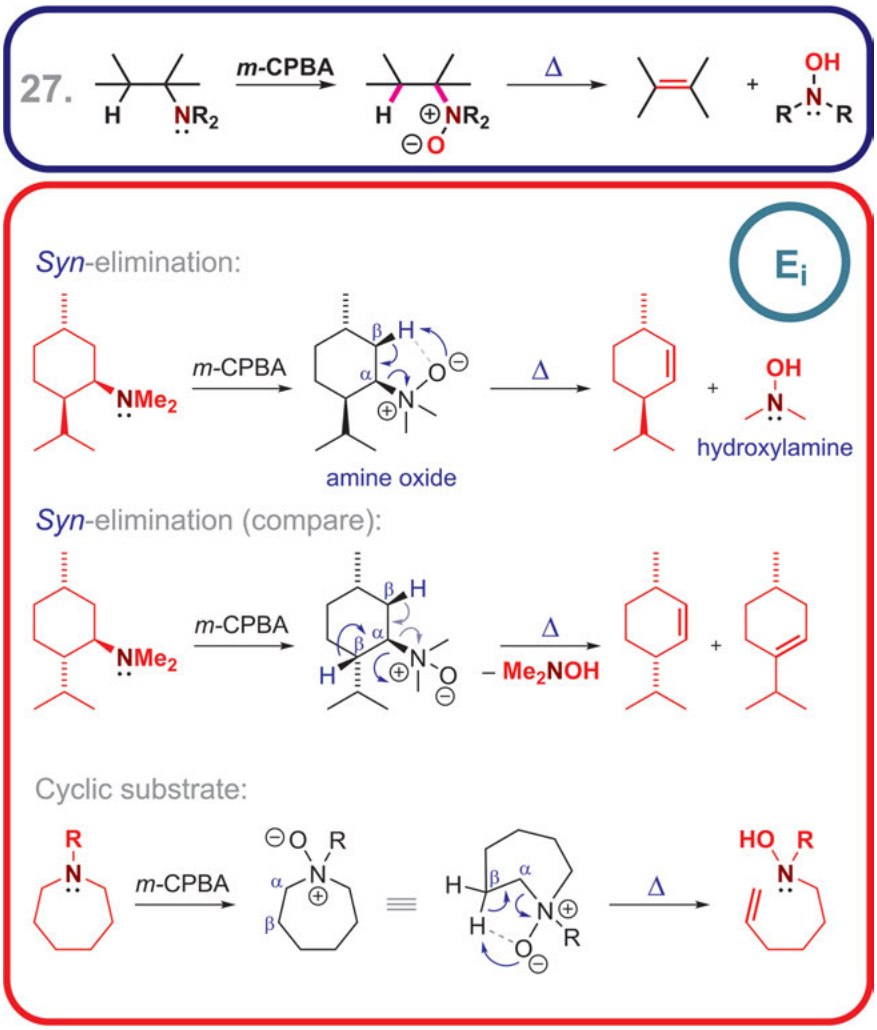


Fig. 27.1: The ***Cope*** *elimination* mechanism.[80]

80 The ***Cope*** *elimination* or the ***Cope*** *reaction* is an example of the *5-membered* **internal** or **intramolecular β–elimination** reaction ($\mathbf{E_i}$), mentioned in Chapter 6.

https://doi.org/10.1515/9783110608373-027

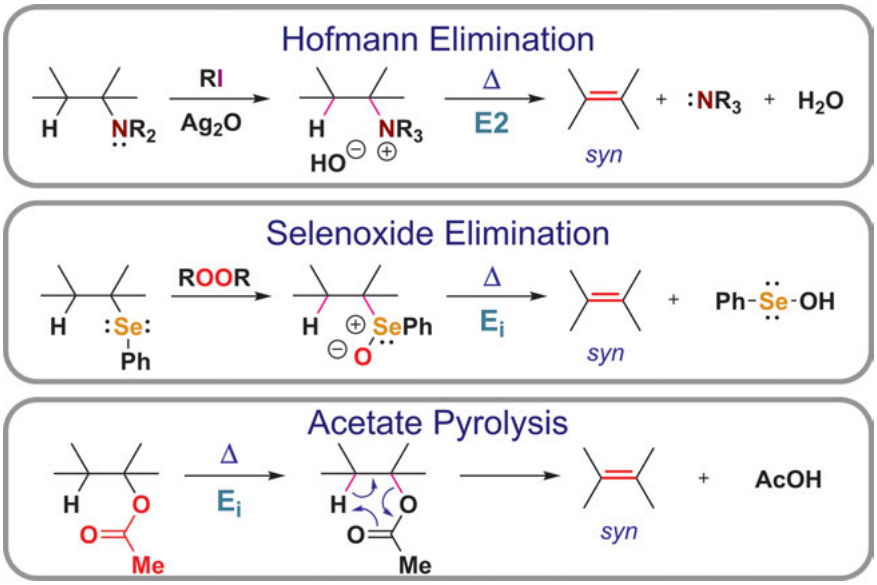


Fig. 27.2: Reactions related to the ***Cope*** *elimination*.[81]

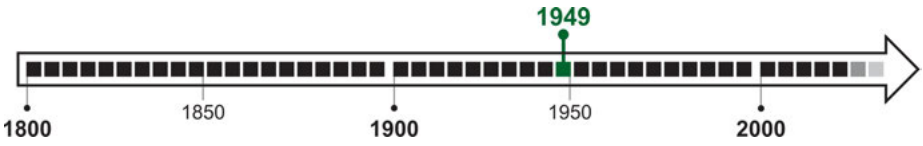


Fig. 27.3: The discovery of the ***Cope*** *elimination*.[82]

81 Several reactions are related to the ***Cope*** *elimination*: the ***Hofmann*** *elimination* (usually E2-type elimination, rarely E_i, covered in Chapter 49), the *selenoxide elimination* [27a, 27b], the *acetate pyrolysis* [1], and others (not mentioned here).

82 The reaction was likely first described around 1949 [27c].

28 Cope Rearrangement

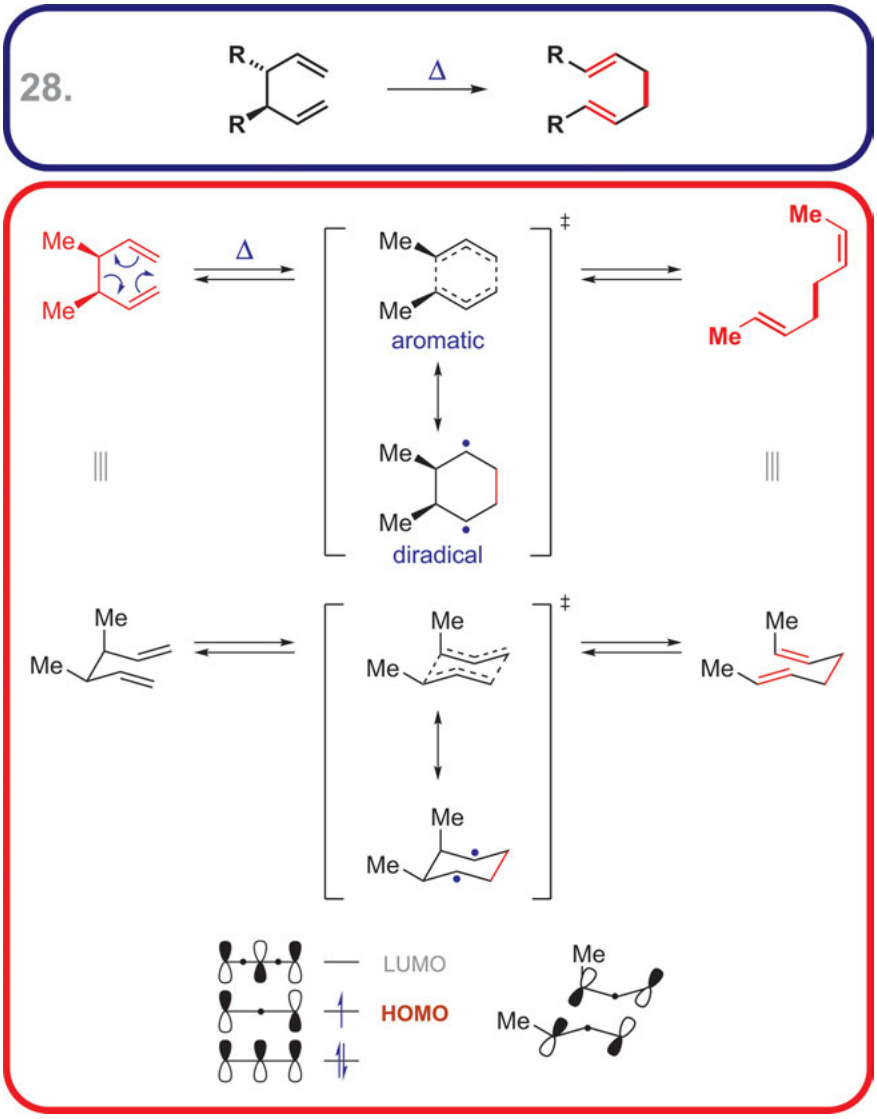


Fig. 28.1: The ***Cope*** *rearrangement* mechanism.[83]

83 The ***Cope*** *rearrangement* (different from the ***Cope*** *elimination* and much like the ***Claisen*** *rearrangement*, see Chapter 26) is a pericyclic reaction with a concerted mechanism. This is a classic example of a [3,3′]-*sigmatropic rearrangement* (also referred to as [3,3′]-*sigmatropic shift*).

https://doi.org/10.1515/9783110608373-028

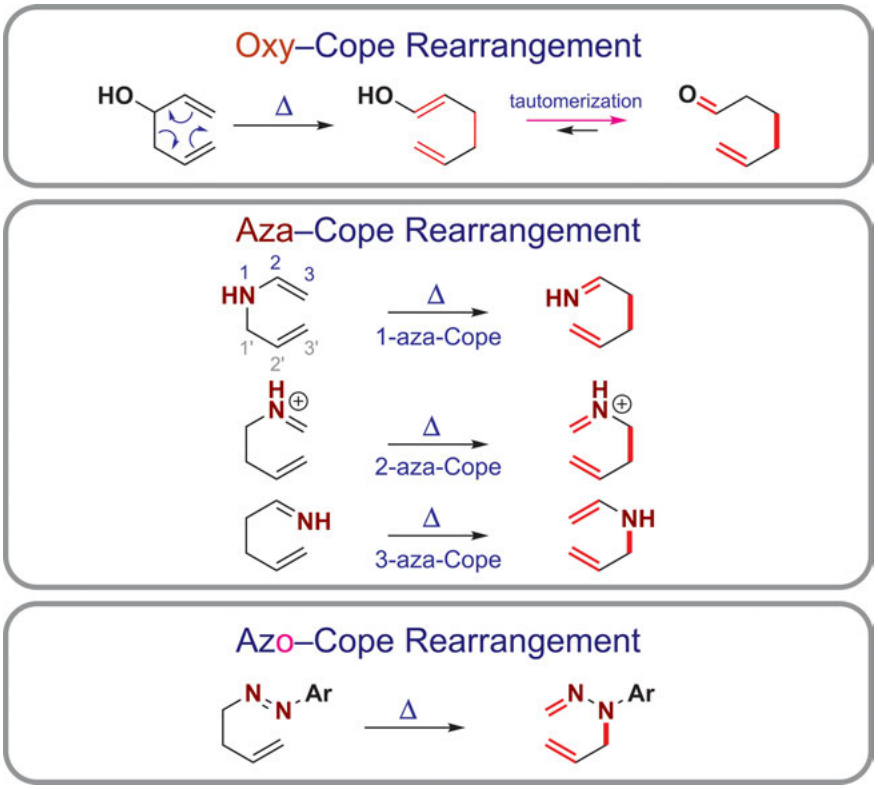


Fig. 28.2: Reactions related to the ***Cope*** *rearrangement*.[84]

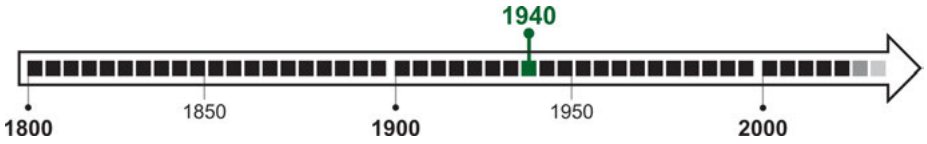


Fig. 28.3: The discovery of the ***Cope*** *rearrangement*.[85]

84 There are numerous variations of the ***Cope*** *rearrangement* [1], such as: the *(anionic) oxy-**Cope** rearrangement*, the *aza-**Cope*** and/or *aza-**Claisen** rearrangement* (confusing), the *azo-**Cope** rearrangement* [28a].

85 The reaction was likely first described around 1940 [28b].

29 Criegee & Malaprade Oxidation

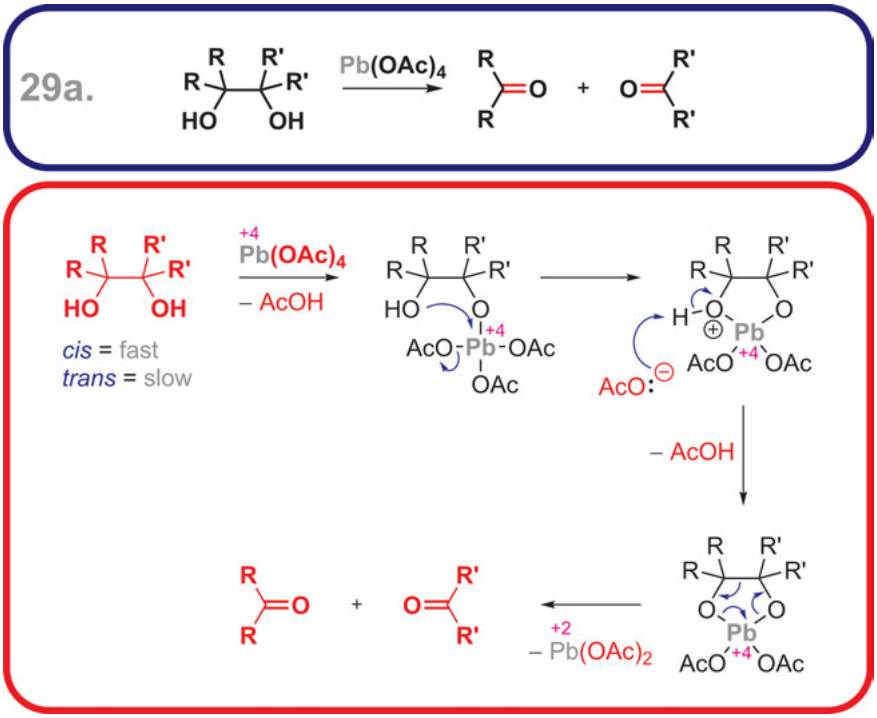


Fig. 29.1: The ***Criegee*** *oxidation* mechanism.[86]

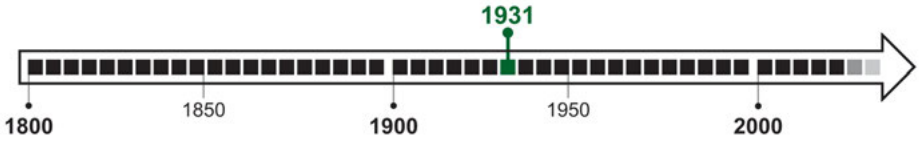


Fig. 29.2: The discovery of the ***Criegee*** *oxidation*.[87]

86 The ***Criegee*** *oxidation* or simply the ***Criegee*** *reaction* is different from the ***Criegee*** *mechanism* proposed for *ozonolysis* (covered in Chapter 70).

87 The reaction was likely first described around 1931 [29a].

https://doi.org/10.1515/9783110608373-029

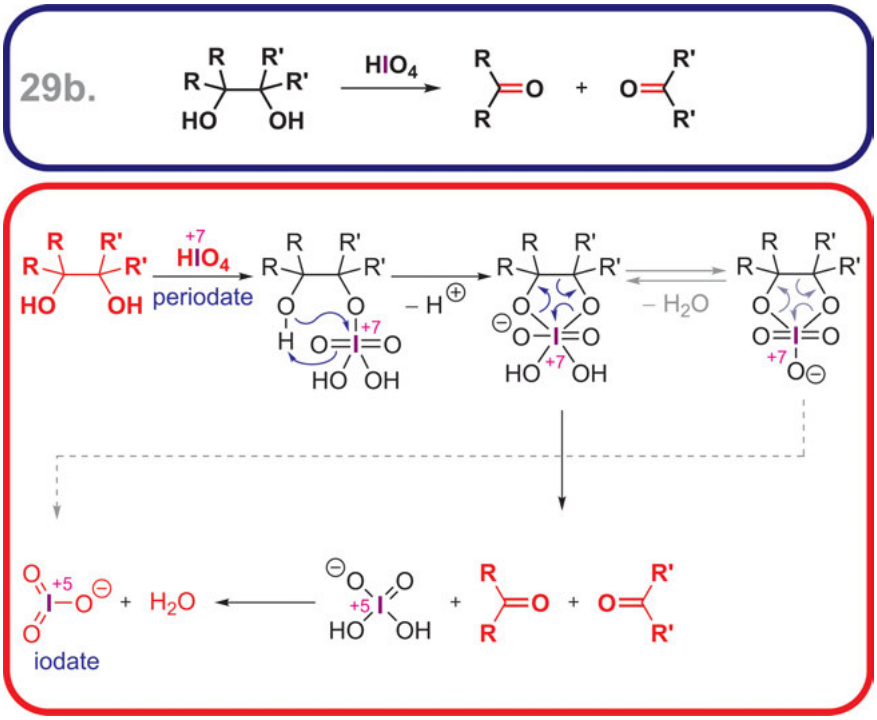


Fig. 29.3: The ***Malaprade*** *oxidation* mechanism.[88]

Fig. 29.4: The discovery of the ***Malaprade*** *oxidation*.[89]

88 The ***Malaprade*** *oxidation* is analogous to the ***Criegee*** *reaction*.

89 The reaction was likely first described between 1928 and 1934 [29b, 29c].

30 CuAAC

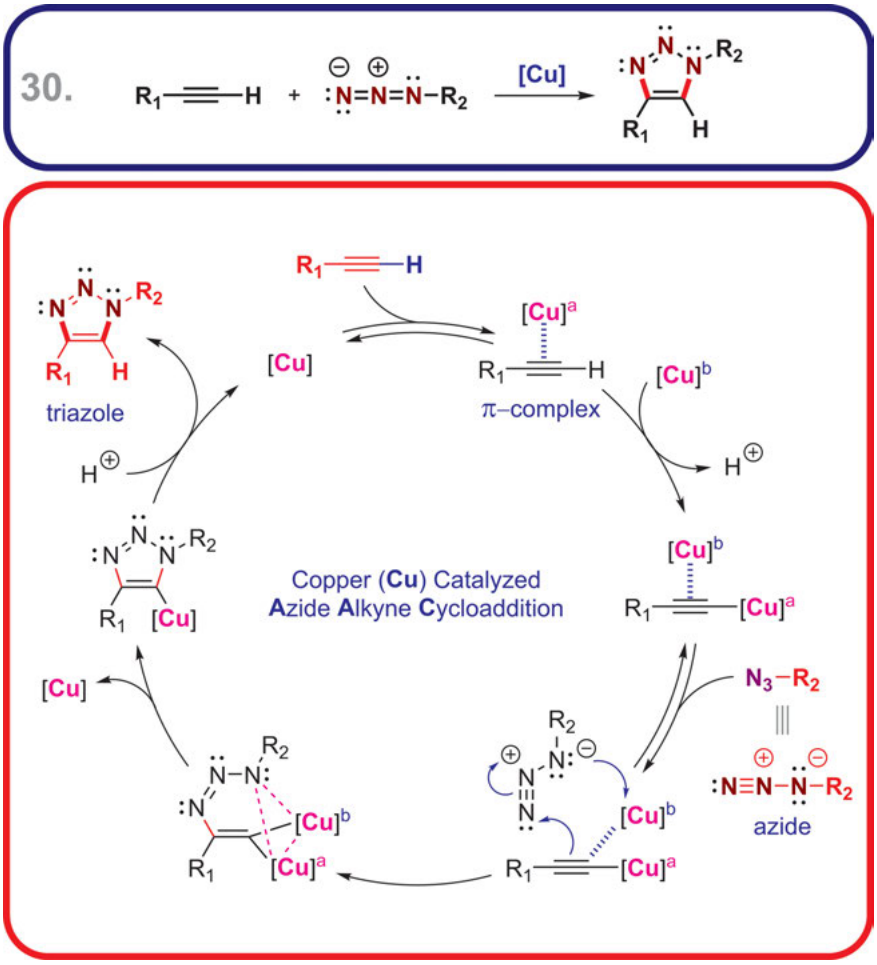


Fig. 30.1: The **CuAAC** mechanism.[90]

90 The acronym **CuAAC** stands for **Cu**-catalyzed **A**zide-**A**lkyne **C**ycloaddition (Copper(I)-catalyzed azide-alkyne cycloaddition). It is also often referred to as "**click chemistry**". Formally, it is a *1,3-dipolar cycloaddition reaction* or a (3+2)-*cycloadditon reaction*. Please note, the notation (3+2) means the atom count is used; the notation [4+2] means the electron count involved in the reaction is used [30a]. IUPAC does not recommend mixed usage, but it is seen frequently in the literature: [3+2].

https://doi.org/10.1515/9783110608373-030

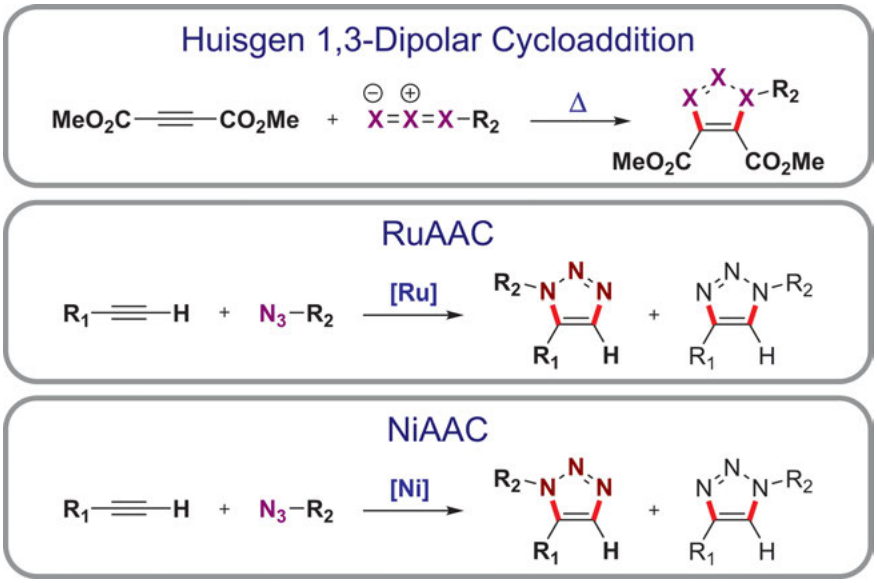


Fig. 30.2: Reactions related to the **CuAAC**.[91]

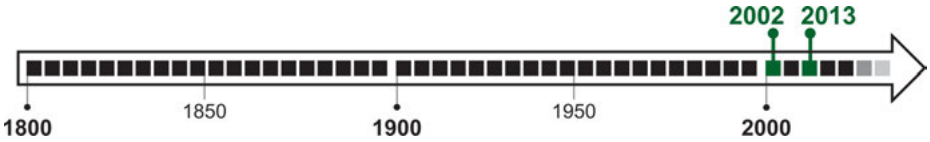


Fig. 30.3: The discovery of the **CuAAC**.[92]

91 The ***Huisgen*** *cycloaddition* [30b, 30c] is not catalytic but related to **CuAAC**. The *azide-alkyne cycloaddition* can also be catalyzed by Ruthenium (**RuAAC**) or Nickel (**NiAAC**), however, it undergoes a different mechanism (not shown).

92 The reaction was likely first described around 2002 [30d, 30e] and the mechanism, in its current form, proposed around 2013 [30f].

31 Curtius Rearrangement

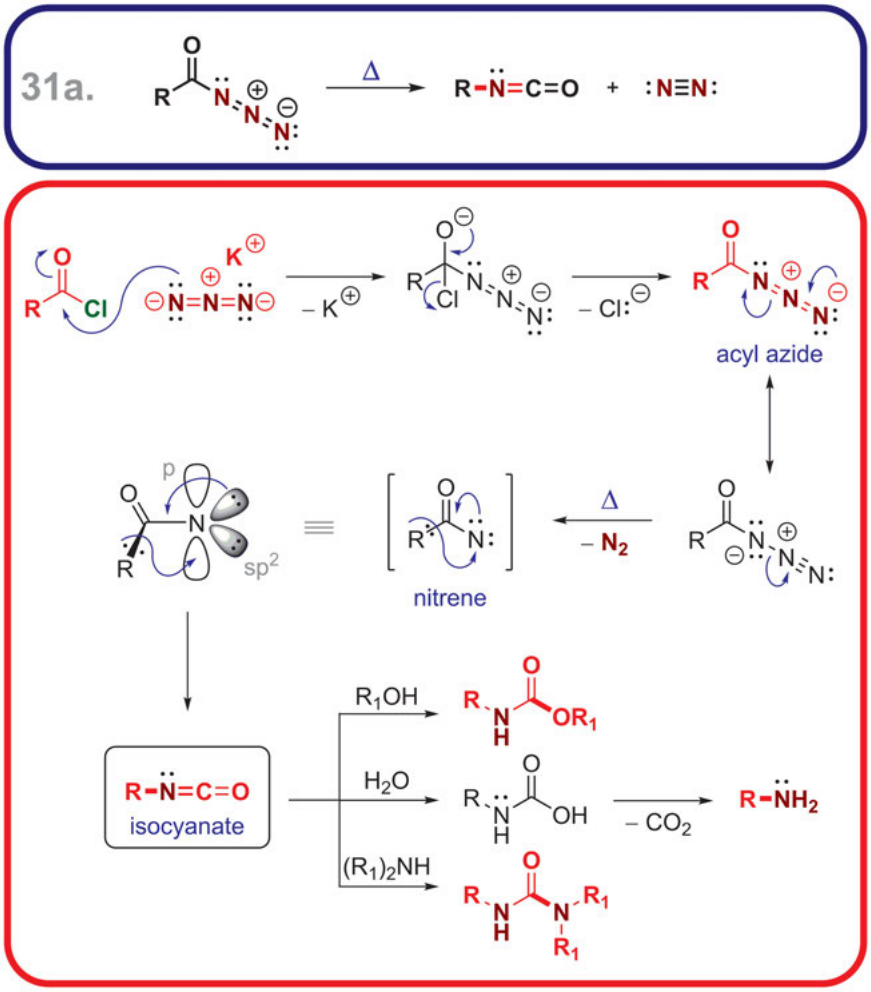


Fig. 31.1: The ***Curtius*** *rearrangement* mechanism.[93]

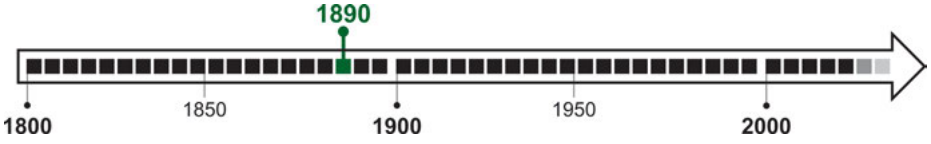


Fig. 31.2: The discovery of the ***Curtius*** *rearrangement*.[94]

93 The ***Curtius*** *rearrangement* is also called the ***Curtius*** *reaction*.

https://doi.org/10.1515/9783110608373-031

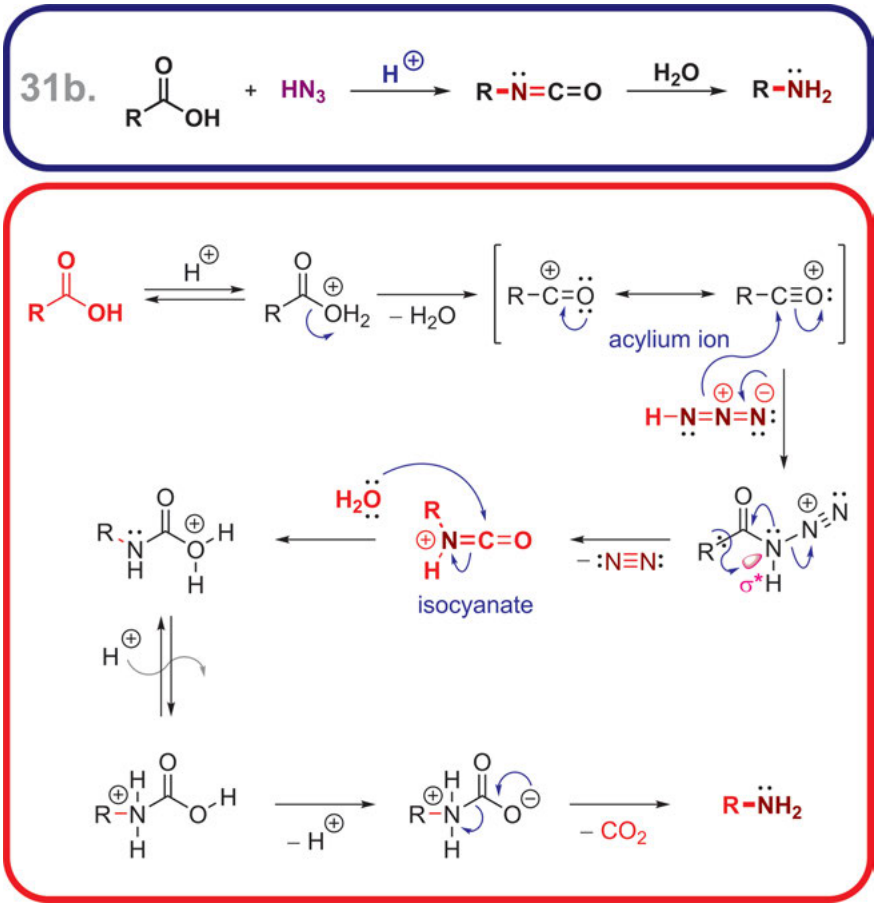


Fig. 31.3: The ***Schmidt*** *reaction* mechanism.[95]

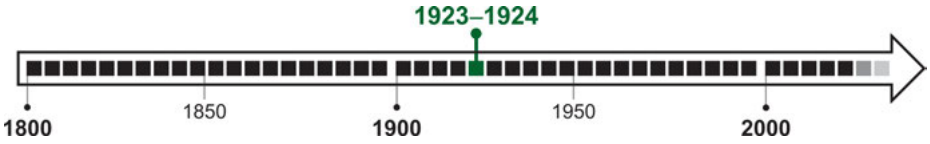


Fig. 31.4: The discovery of the ***Schmidt*** *reaction* mechanism.[96]

94 The reaction was likely first described around 1890 [31a, 31b].
95 The ***Schmidt*** *reaction* is also a rearrangement.
96 The reaction was likely first described between 1923–1924 [31c, 31d].

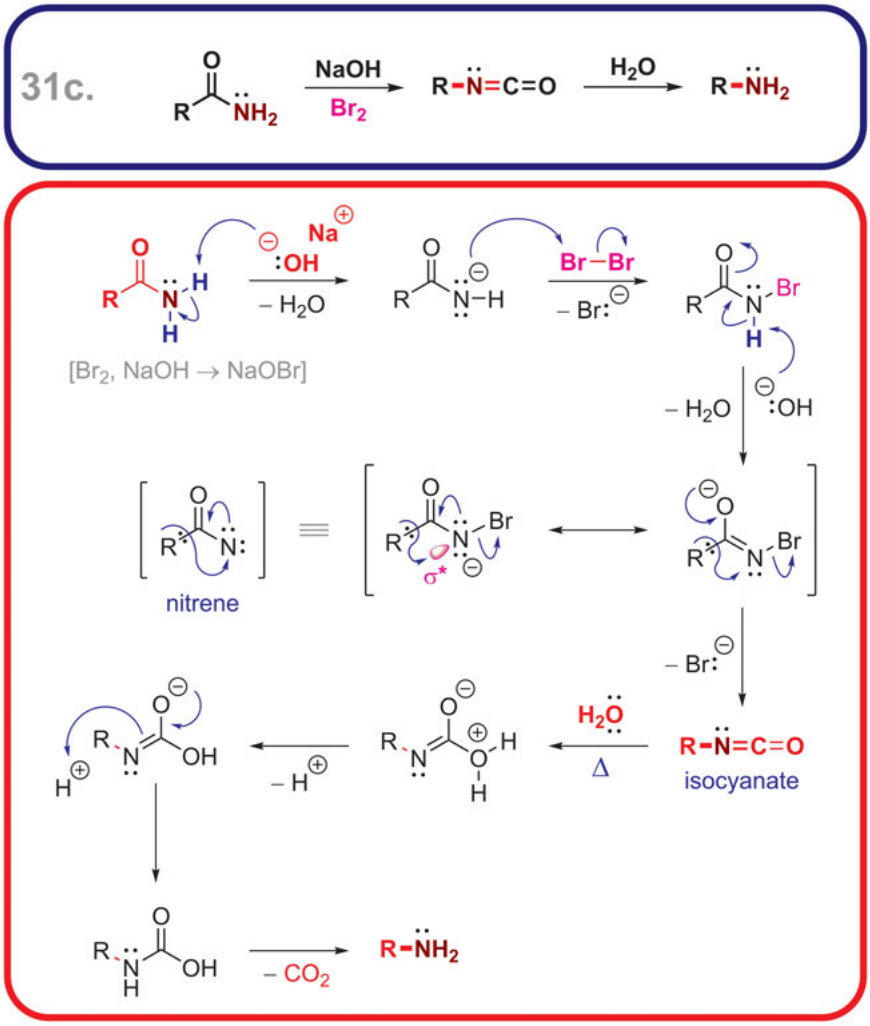


Fig. 31.5: The ***Hofmann*** *rearrangement* mechanism.[97]

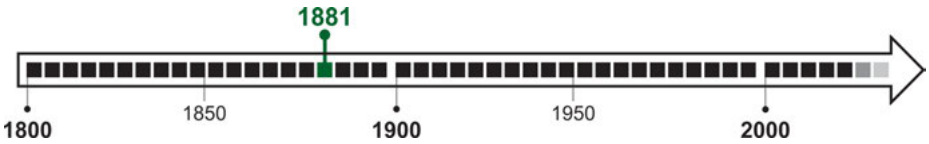


Fig. 31.6: The discovery of the ***Hofmann*** *rearrangement*.[98]

97 The ***Hofmann*** *rearrangement* is also known as the ***Hofmann*** *reaction*. It is completely different from the ***Hofmann*** *elimination*, see Chapter 49.

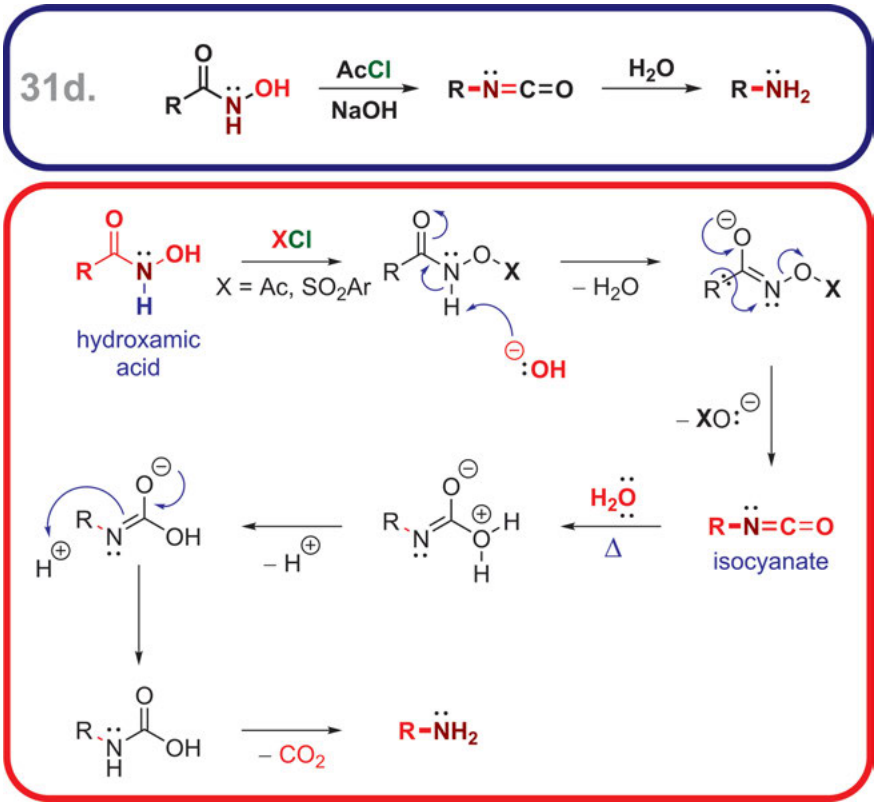


Fig. 31.7: The ***Lossen*** *rearrangement* mechanism.[99]

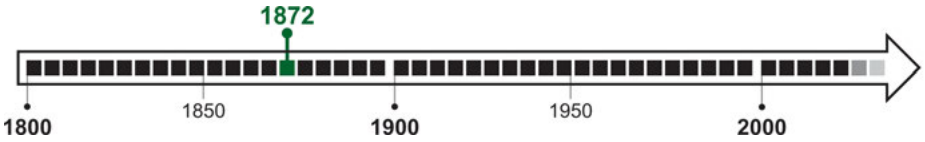


Fig. 31.8: The discovery of the ***Lossen*** *rearrangement*.[100]

98 The reaction was likely first described around 1881 [31e].

99 The ***Lossen*** *rearrangement* is much like these reactions and is related to the ***Beckmann*** *rearrangement*, covered in Chapter 14.

100 The reaction was likely first described around 1872 [31f].

32 Darzens Condensation

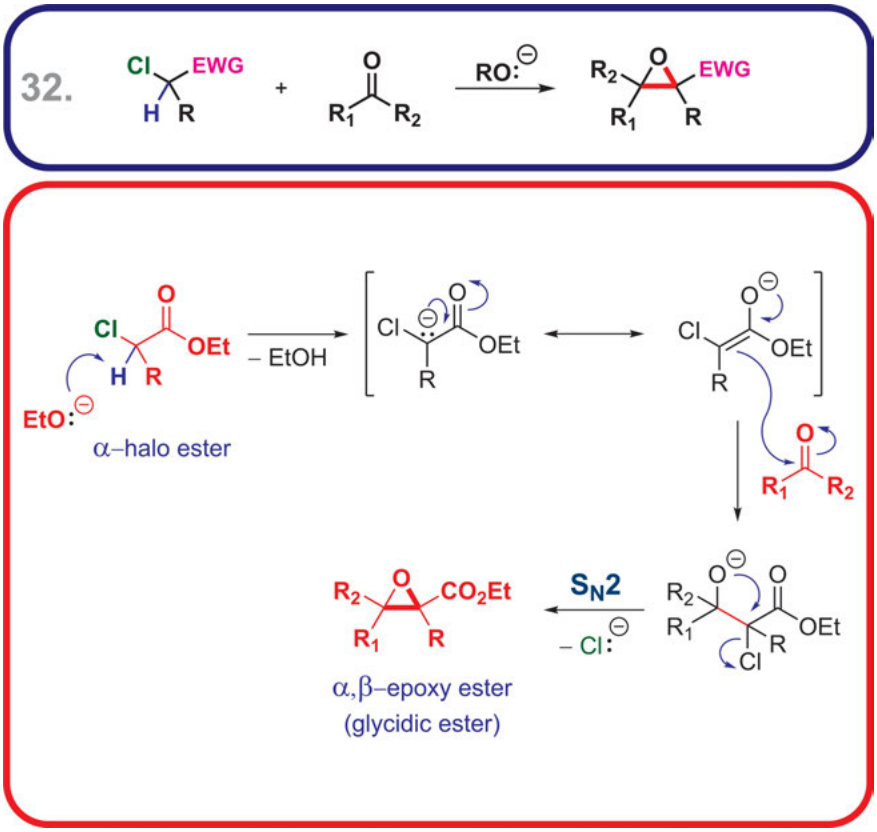


Fig. 32.1: The ***Darzens*** *condensation* mechanism.[101]

101 The ***Darzens*** *condensation* is also called the ***Darzens*** *glycidic ester condensation* or the ***Darzens*** *reaction*. Please note, a *glycidic ester* is an α,β–epoxy ester.

https://doi.org/10.1515/9783110608373-032

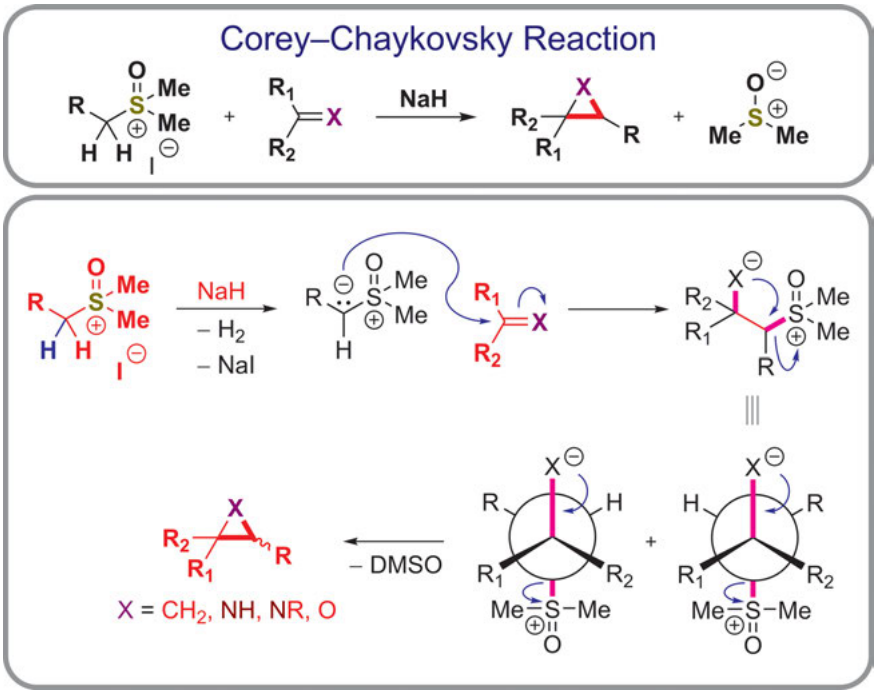


Fig. 32.2: The ***Corey–Chaykovsky*** *reaction* mechanism.[102]

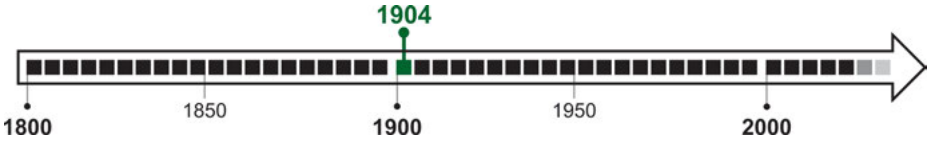


Fig. 32.3: The discovery of the ***Darzens*** *condensation*.[103]

102 The ***Corey–Chaykovsky*** *reaction* (also known as the ***Johnson–Corey–Chaykovsky*** *reaction*) [32a, 32b] is related to both the ***Darzens*** *condensation*, and the ***Wittig*** *reaction* (covered in Chapter 98).
103 The reaction was likely first described around 1904 [32c].

33 Dess–Martin Oxidation

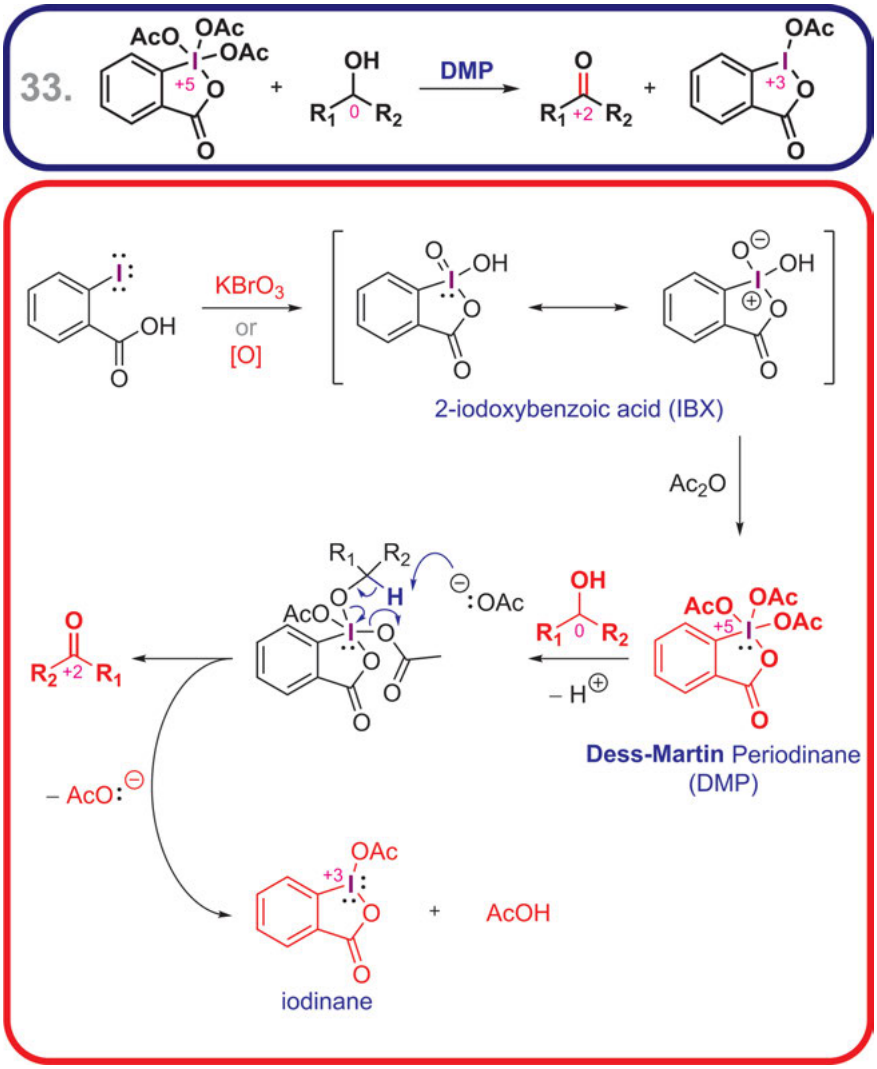


Fig. 33.1: The ***Dess–Martin*** *oxidation* mechanism.[104]

104 The ***Dess–Martin*** *oxidation* is based on the use of a named reagent: the ***Dess–Martin*** *periodinane* (**DMP**) [33a, 33b].

https://doi.org/10.1515/9783110608373-033

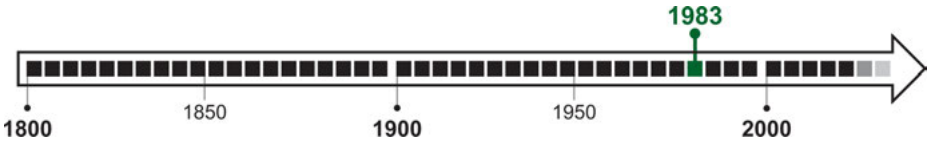


Fig. 33.2: The discovery of the ***Dess–Martin*** *oxidation*.[105]

105 The reaction was likely first described around 1983 [33c].

34 Diazotization (Diazonium Salt)

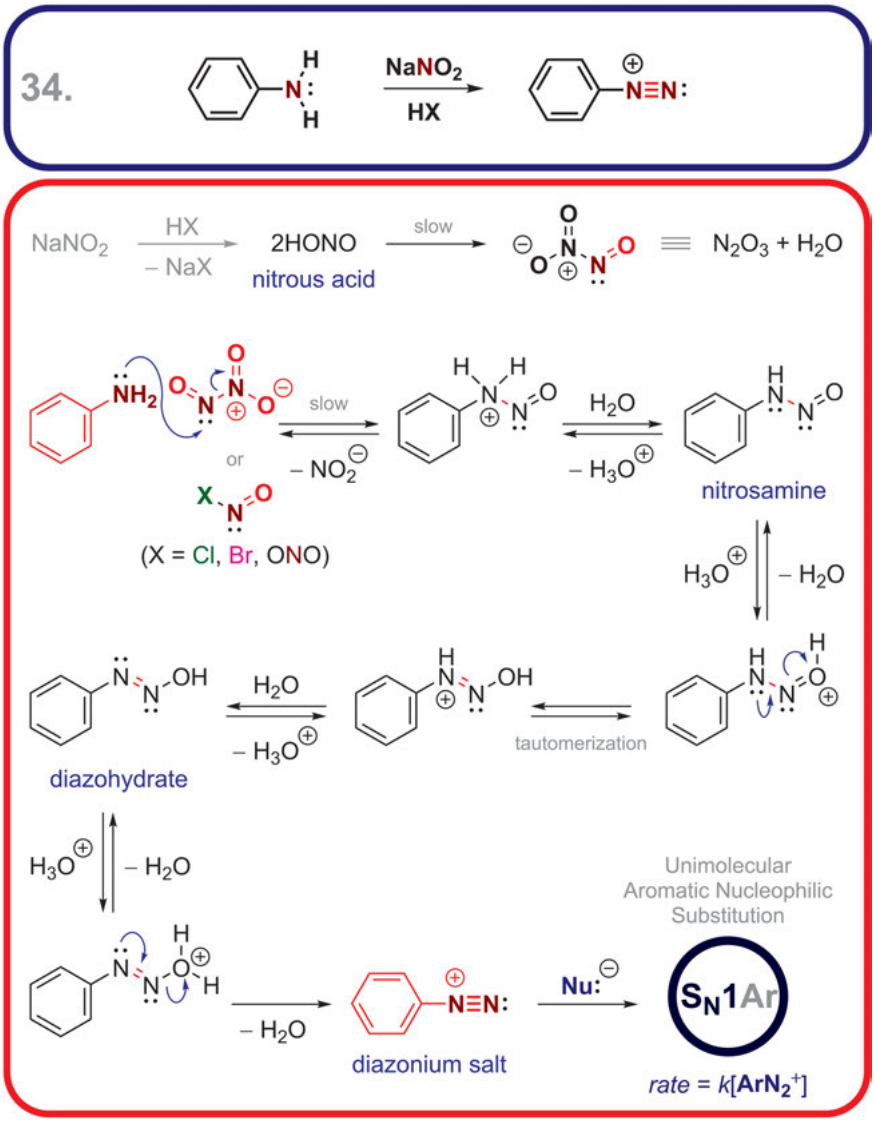


Fig. 34.1: The *diazonium salt formation (diazotization)* mechanism.[106]

106 The *diazonium salt formation reaction* is also known as the ***diazotization*** [1] (the term is also preferred in this book), or the *diazoniation* [1a], or the *diazotation* [34a].

https://doi.org/10.1515/9783110608373-034

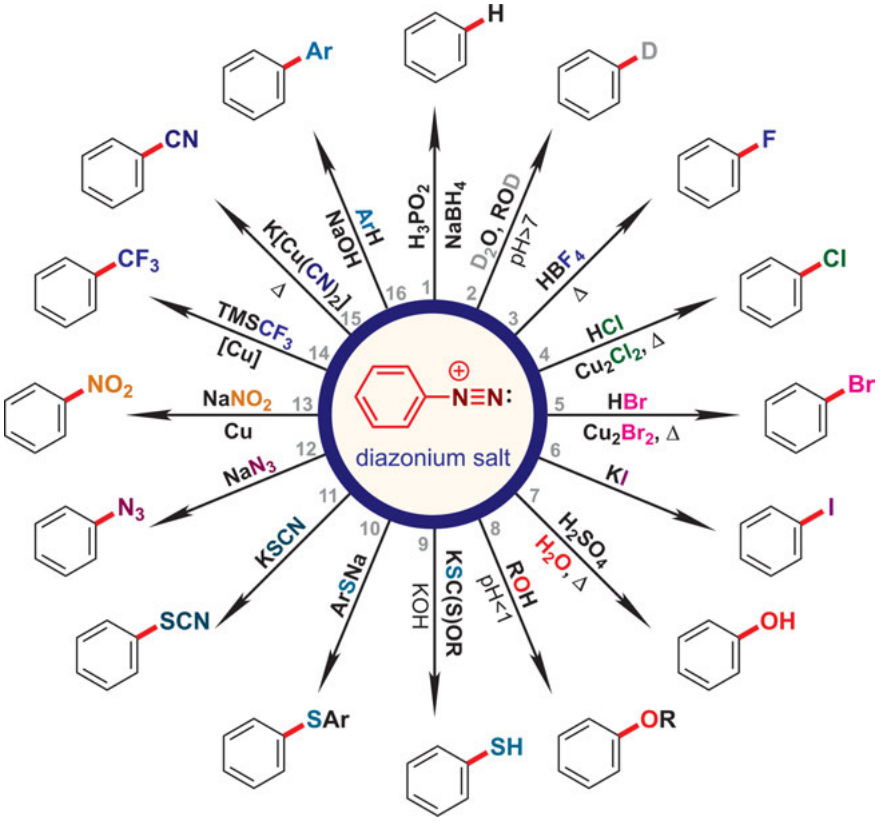


Fig. 34.2: Synthetic versatility of the diazonium salts.[107]

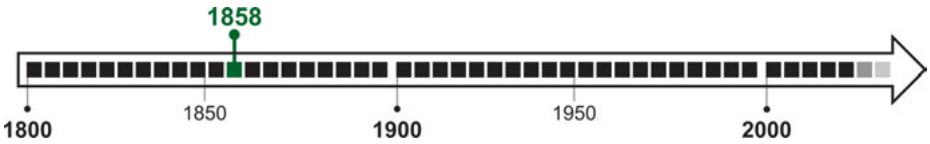


Fig. 34.3: The discovery of the *diazotization reaction*.[108]

107 The *diazonium salts* formed during the *diazotization* process have wide synthetic application and they can react with a variety of nucleophiles. These reactions go through the **aromatic nucleophilic substitution** mechanism (**S_N1Ar** or sometimes **$S_{RN}1$**). Symbol **S_N1Ar** stands for **S**ubstitution **N**ucleophilic **Ar**omatic. It is a **Uni**-molecular (1) reaction, that is, the rate of the reaction is first order and the rate-determining step (i.e., the slow step) depends on the concentration of one reactant, the diazonium salt (**ArN_2^+**): *rate* = k[**ArN_2^+**]**[1]**. This mechanism is different from the *addition-elimination* mechanism (**S_NAr** or **S_N2Ar**), covered in Chapter 4, because the first step is elimination and the formation of an *aryl cation*. Please note, it is also different from the *benzyne* mechanism (the *elimination-addition* mechanism) covered in Chapter 16.

108 The reaction was likely first described around 1858 [34b].

35 Diels–Alder Cycloaddition

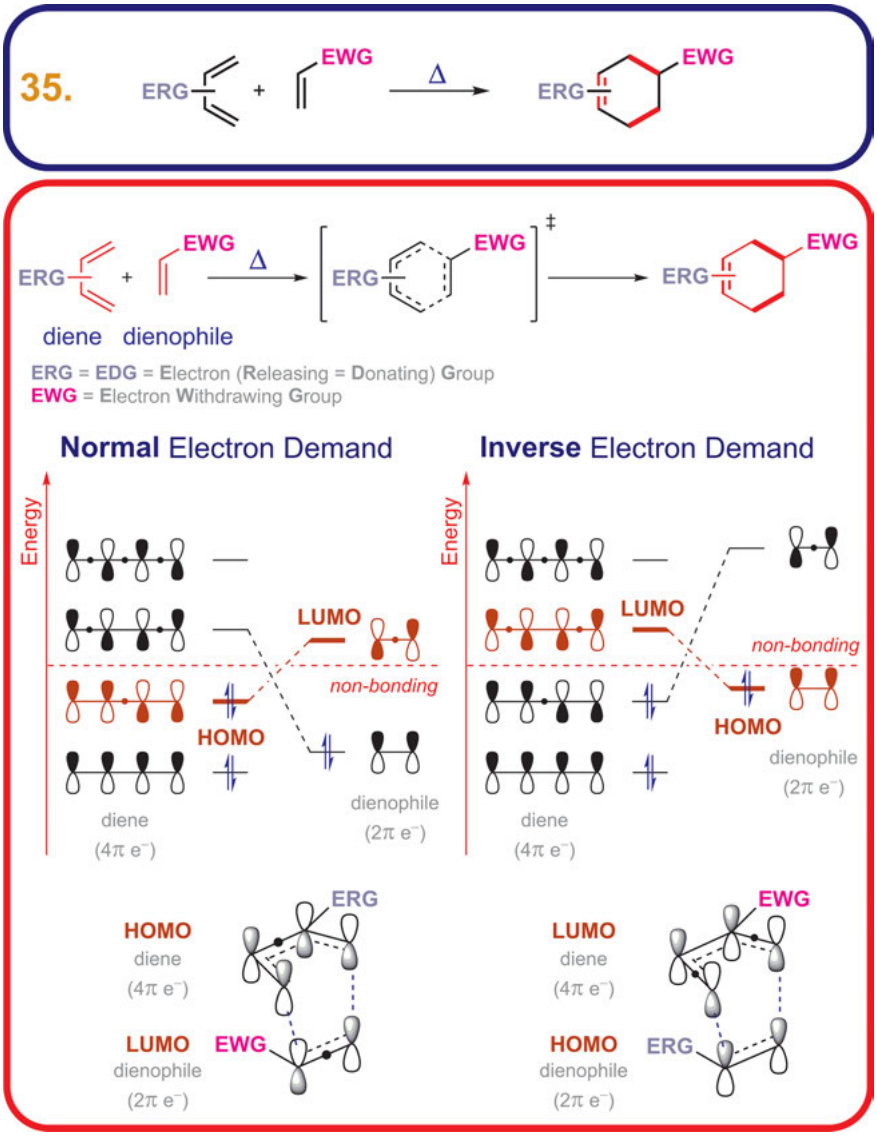


Fig. 35.1: The ***Diels–Alder*** *cycloaddition* mechanism.[109]

109 The ***Diels–Alder*** *cycloaddition*, the ***Diels–Alder*** *reaction* or the **[4+2]**-*cycloaddition reaction* is a pericyclic reaction with a concerted mechanism. Please note, the notation (4+2) means the atom count is used; the notation [4+2] means the electron count involved in the reaction is used [30a]. Compare to the *1,3-dipolar cycloaddition* (Chapter 30).

https://doi.org/10.1515/9783110608373-035

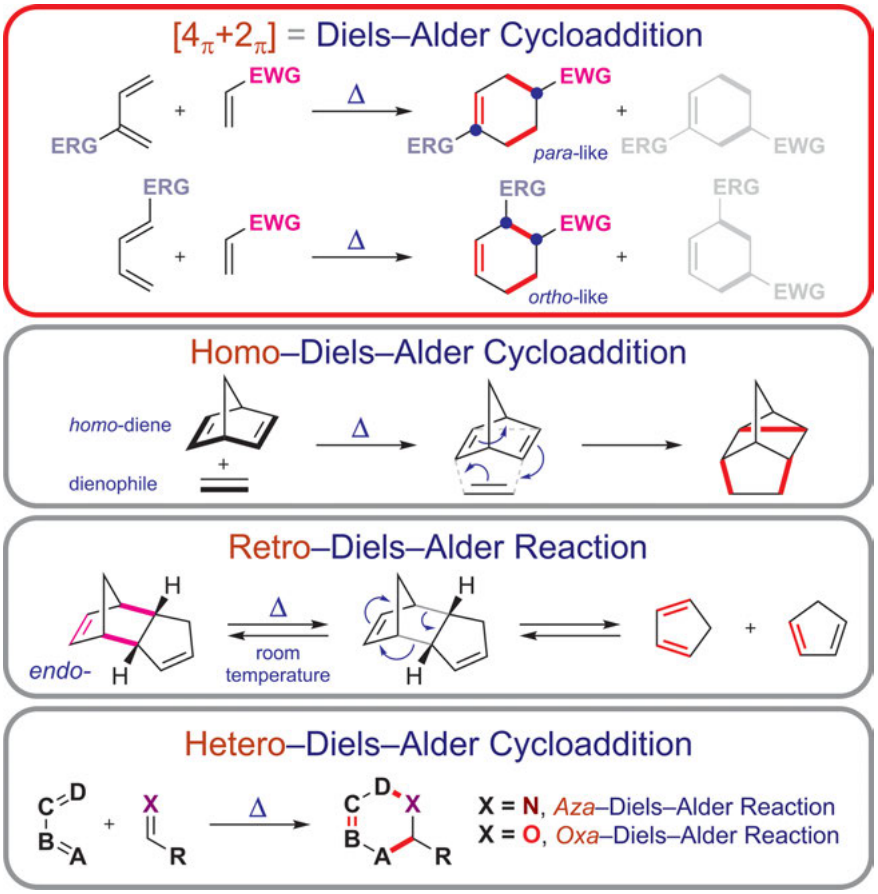


Fig. 35.2: Reactions related to the ***Diels–Alder*** *cycloaddition*.[110]

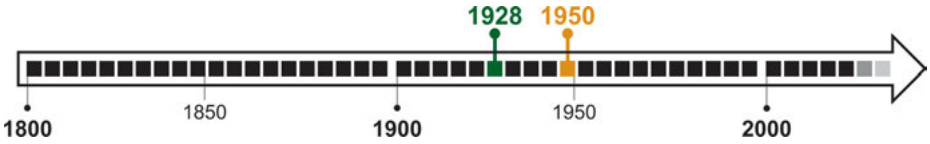


Fig. 35.3: The discovery of the ***Diels–Alder*** *cycloaddition*.[111]

110 There are numerous variations of this reaction: the *homo-**Diels–Alder** cycloaddition*, the *retro-**Diels–Alder** reaction*, the *hetero-**Diels–Alder** cycloaddition*, and many others (not shown). Please note the regiochemistry observed in the first case of the **[4_π+2_π]** = ***Diels–Alder*** *cycloaddition*.

111 The reaction was likely first described around 1928 [35a, 35b]. In **1950**, Otto Paul Hermann Diels and Kurt Alder received the Nobel Prize in Chemistry for the discovery of the diene synthesis [35c].

36 Di–π–Methane Rearrangement

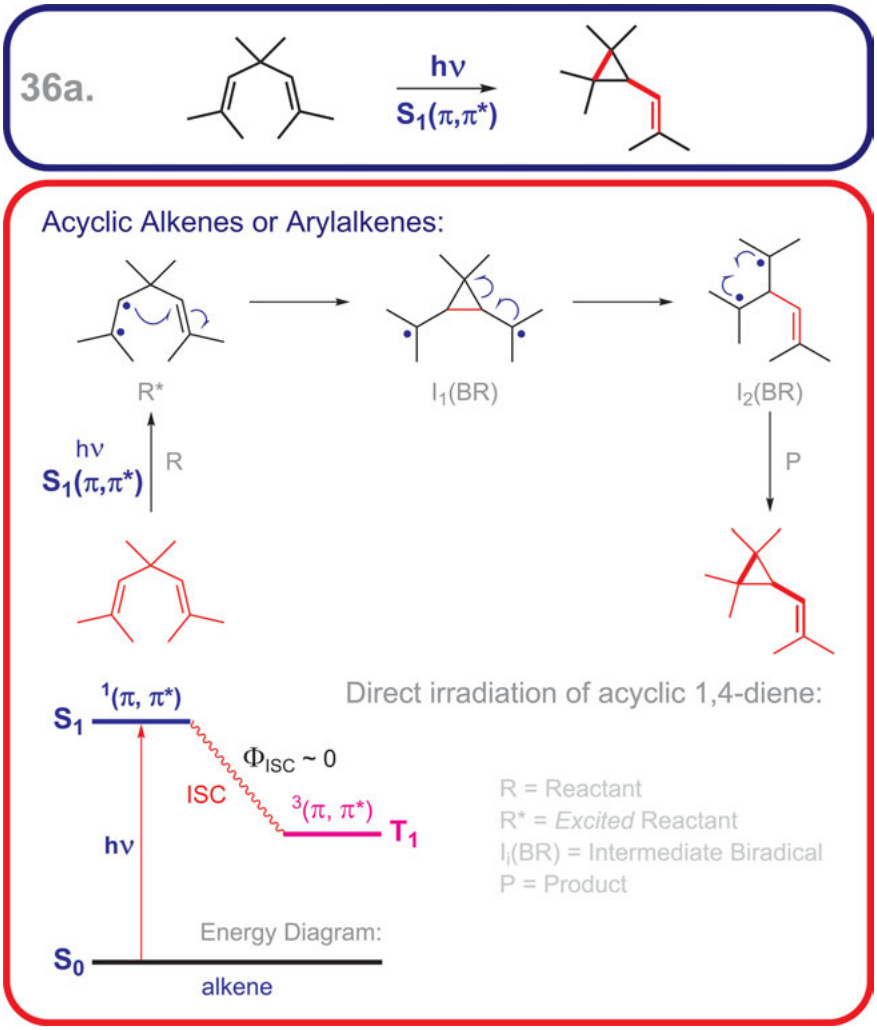


Fig. 36.1: The *Di–π–Methane rearrangement* mechanism: direct irradiation.[112]

112 The *Di–π–Methane rearrangement* (**DPM**) is rarely called the ***Zimmerman*** *reaction*. If the reaction undergoes *direct irradiation*: the reaction occurs from the singlet excited state $\mathbf{S_1}$, in this case $\mathbf{^1(\pi, \pi^*)}$ [2b].

https://doi.org/10.1515/9783110608373-036

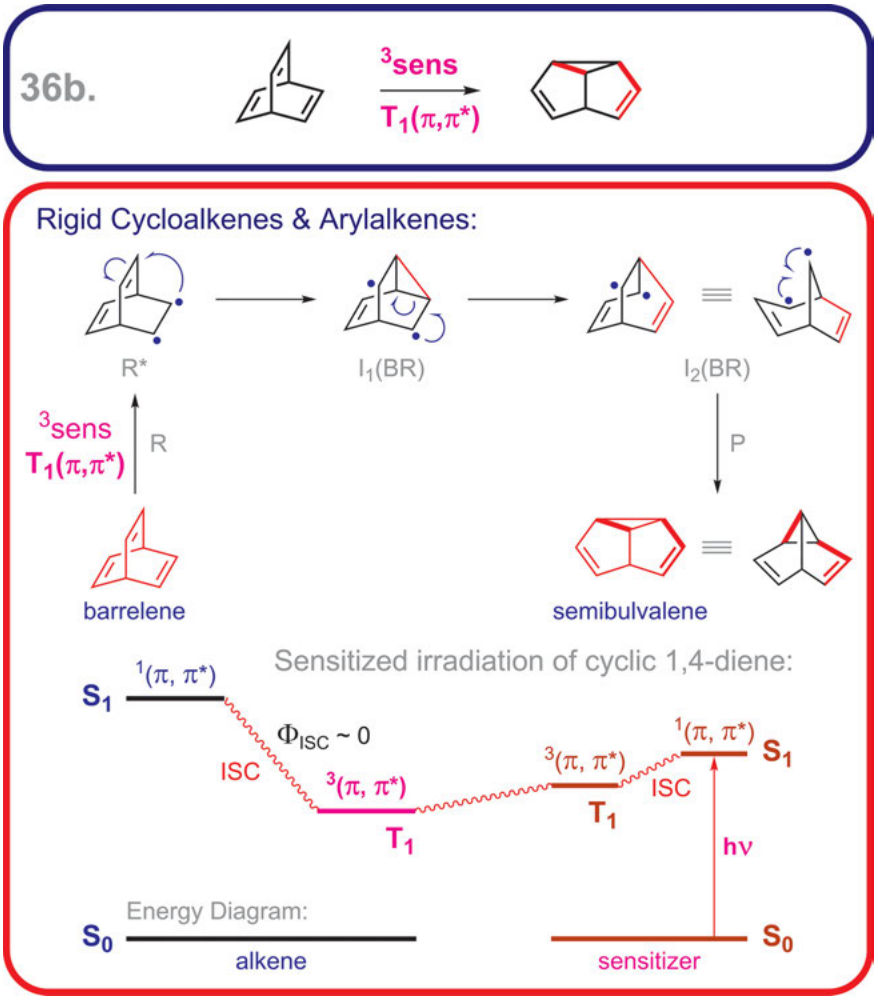


Fig. 36.2: The *Di–π–Methane rearrangement* mechanism: sensitized irradiation.[113]

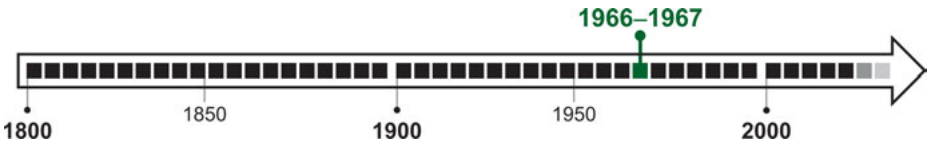


Fig. 36.3: The discovery of the *Di–π–Methane rearrangement*.[114]

113 The *Di–π–Methane rearrangement* in the presence of a *photosensitizer*, that is the reaction undergoes the *sensitized irradiation*: the product formation occurs from the triplet excited state $\mathbf{T_1}$, here $^3\mathbf{(\pi, \pi^*)}$ [2b].

114 The reaction was likely first described between 1966–1967 [36].

37 Favorskii Rearrangement

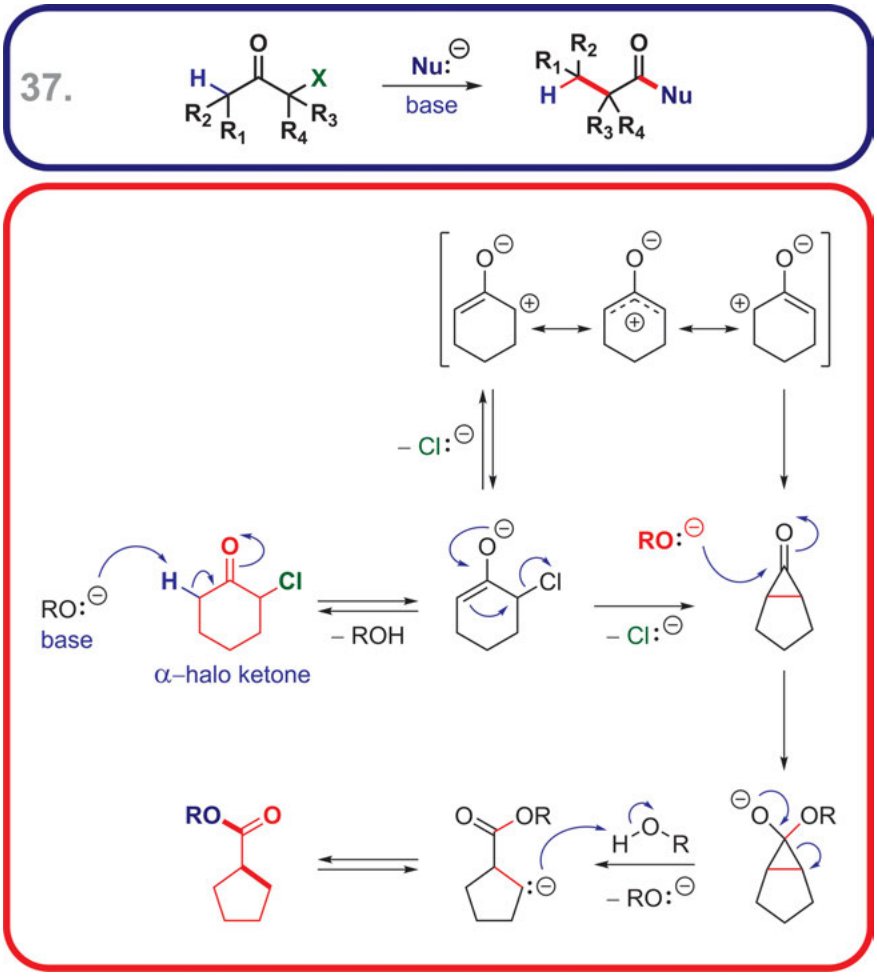


Fig. 37.1: The ***Favorskii*** *rearrangement* mechanism.[115]

115 The ***Favorskii*** *rearrangement* (also spelled Favorsky, in German transliteration Faworsky, and in Russian Алексей Евграфович Фаворский or А. Е. Фаворский) is different from the ***Favorskii*** *reaction* (not shown here).

https://doi.org/10.1515/9783110608373-037

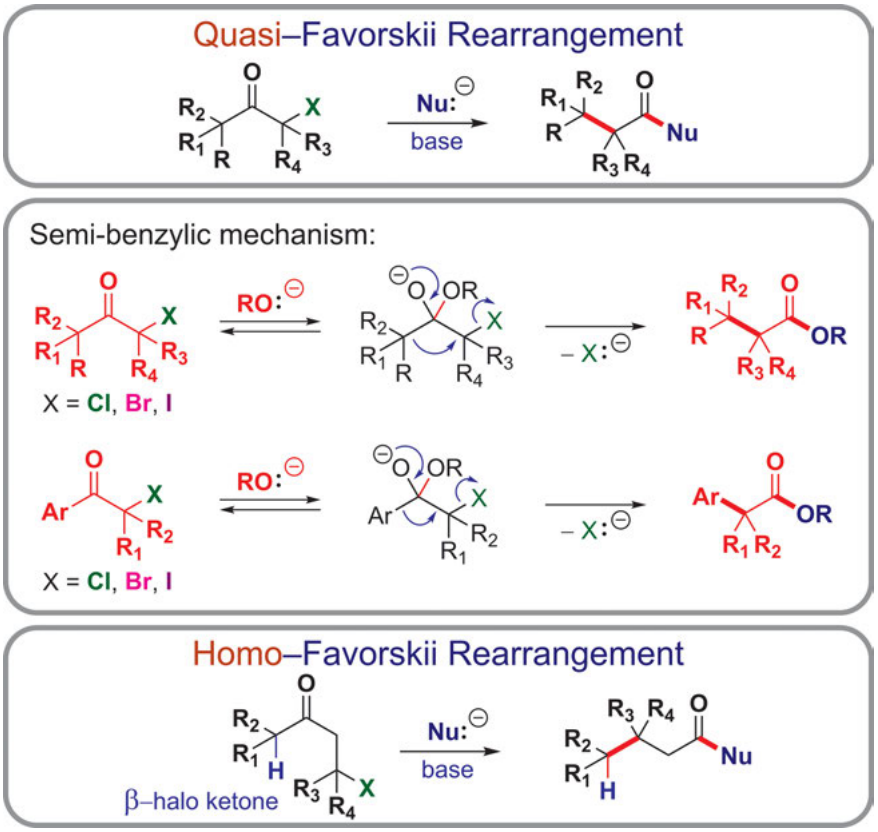


Fig. 37.2: The *quasi-**Favorskii** rearrangement* mechanism and related reactions.[116]

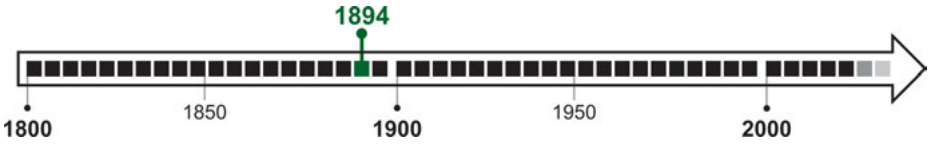


Fig. 37.3: The discovery of the ***Favorskii** rearrangement*.[117]

116 There are numerous variations of this reaction: for example, the *quasi-**Favorskii** rearrangement*, which undergoes a process similar to the *semi-benzylic* mechanism [37a, 37b], the *homo-**Favorskii** rearrangement*, and others (not shown).

117 The reaction was likely first described around 1894 [37c, 37d].

38 Fischer Indole Synthesis

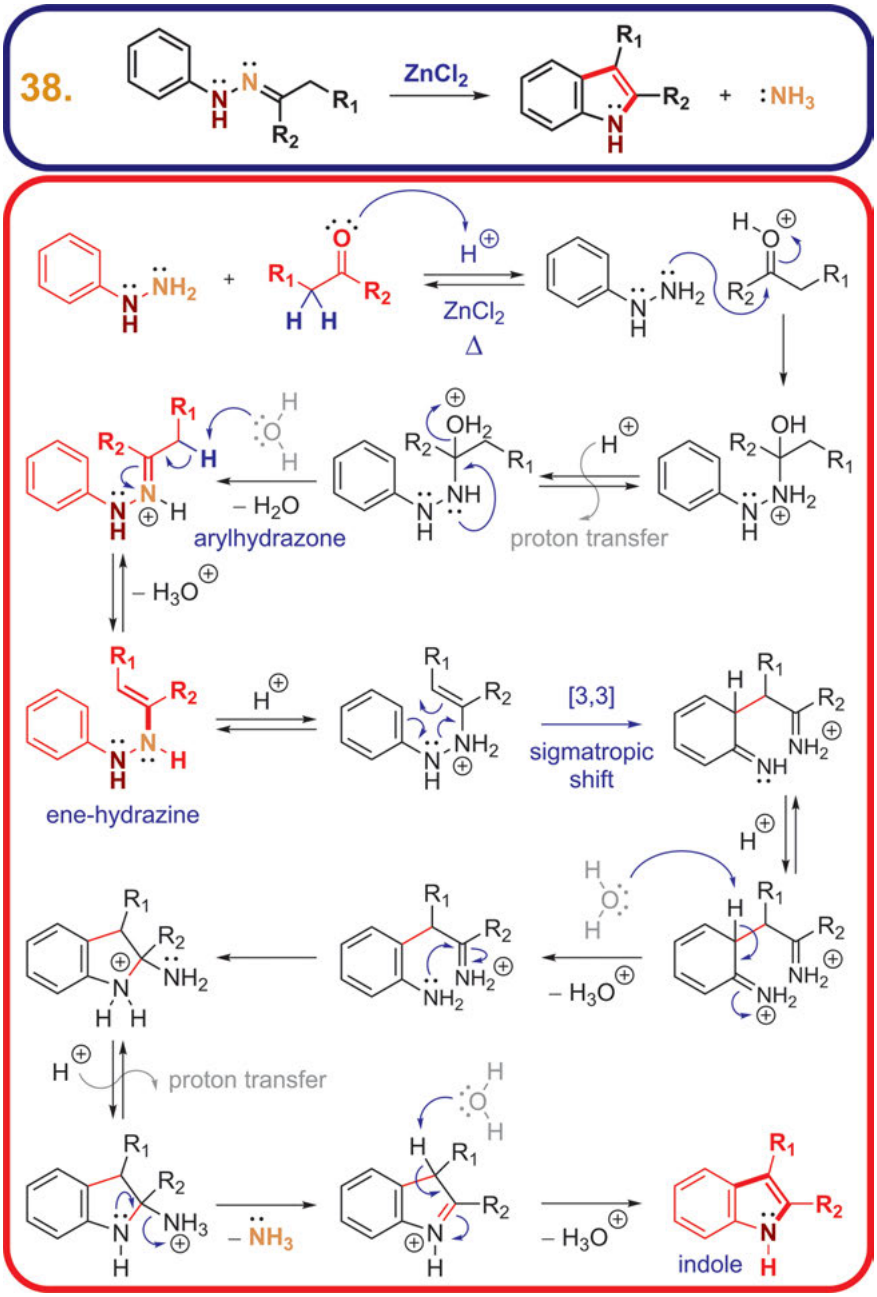


Fig. 38.1: The ***Fischer*** *indole synthesis* mechanism.[118]

https://doi.org/10.1515/9783110608373-038

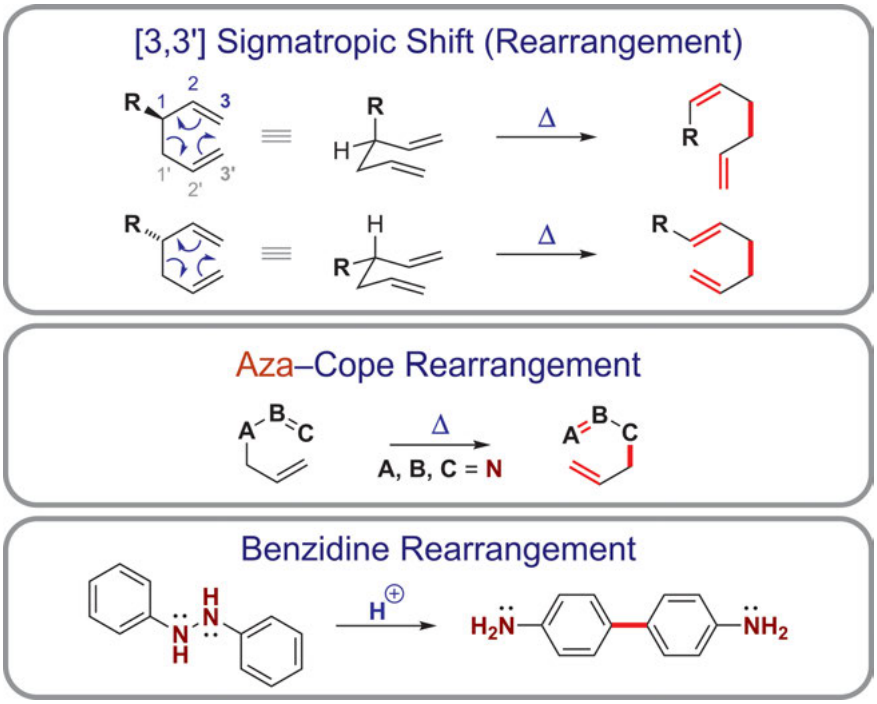


Fig. 38.2: Reactions related to the ***Fischer*** *indole synthesis*.[119]

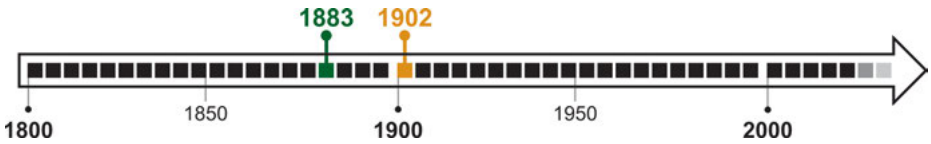


Fig. 38.3: The discovery of the ***Fischer*** *indole synthesis*.[120]

118 he ***Fischer*** *indole synthesis* (different from the ***Fischer*** *esterification*) is one of the most important reactions in organic chemistry. The key mechanistic step is the [3,3′]-*sigmatropic shift (rearrangement)*.
119 The key mechanistic step is related to the ***Cope*** *rearrangement*, the *aza*-***Cope*** and/or *aza*-***Claisen*** *rearrangement* (Chapter 28). Other reactions related to this transformation include the ***Benzidine*** *rearrangement* (its mechanism is not well-understood) [1, 38a].
120 The reaction was likely first described around 1883 [38b, 38c]. In **1902**, Emil Fischer received the Nobel Prize in Chemistry [38d].

39 Friedel–Crafts Acylation & Alkylation

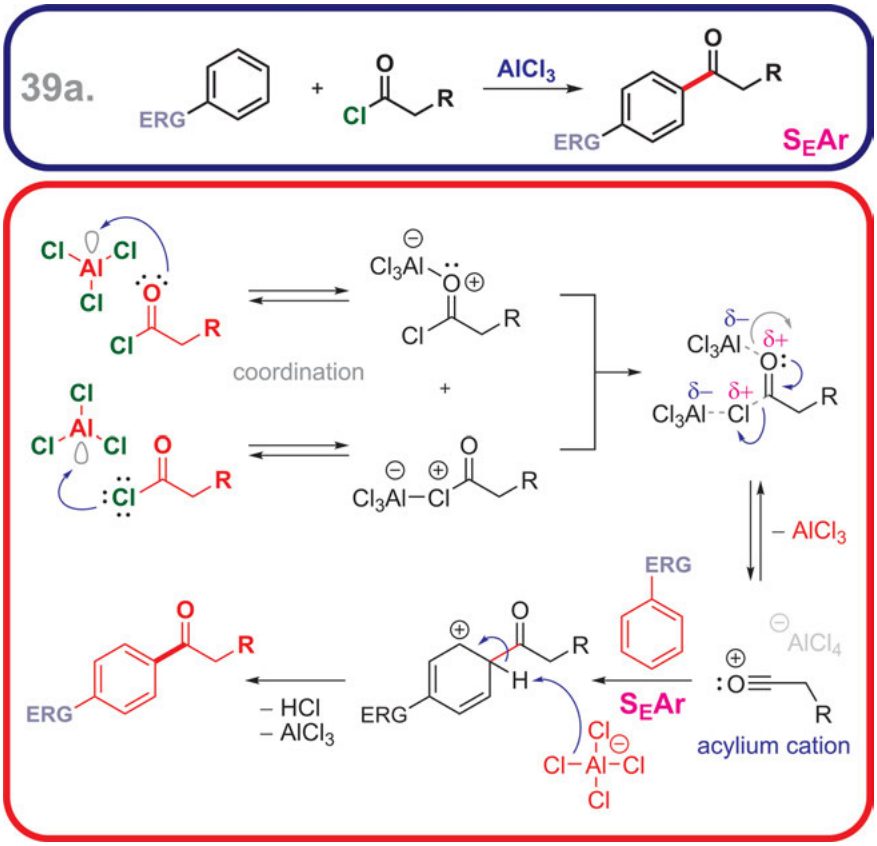


Fig. 39.1: The ***Friedel–Crafts*** *acylation* mechanism.[121]

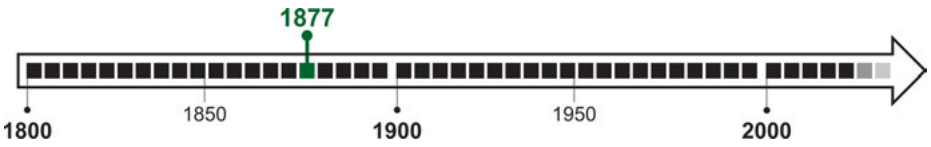


Fig. 39.2: The discovery of the ***Friedel–Crafts*** *acylation*.[122]

121 The ***Friedel–Crafts*** *acylation* mechanism is an example of the **aromatic electrophilic substitution** (the *arenium ion* mechanism or **S_EAr**, covered in Chapter 3). The linear *acyl halides* react via *acylium cation* and form *aryl ketones* with linear alkyl chains.

122 The reaction was likely first described around 1877 [39a].

https://doi.org/10.1515/9783110608373-039

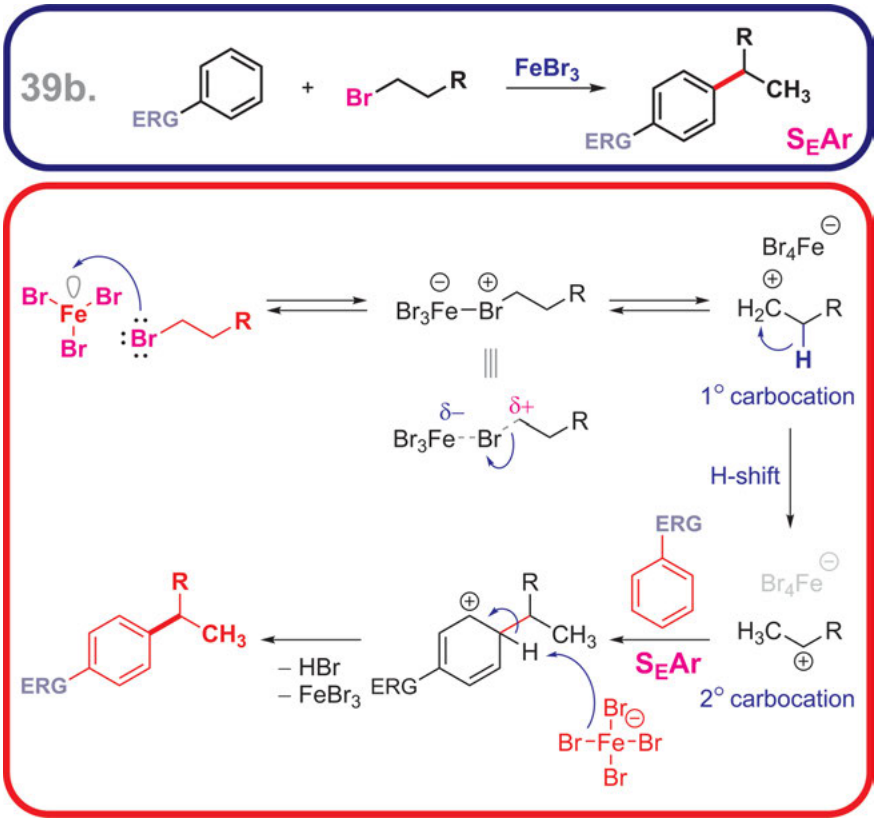


Fig. 39.3: The ***Friedel–Crafts*** *alkylation* mechanism.[123]

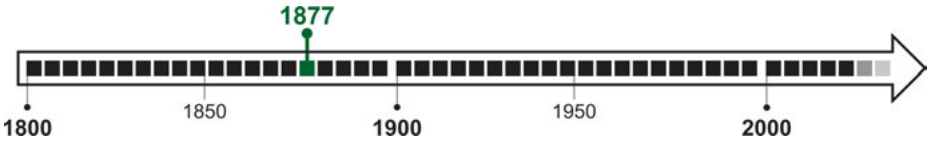


Fig. 39.4: The discovery of the ***Friedel–Crafts*** *alkylation*.[124]

123 The ***Friedel–Crafts*** *alkylation* is also the **aromatic electrophilic substitution**. The linear *alkyl halides* undergo the *carbocation rearrangement* (also called the ***Wagner–Meerwein*** *rearrangement* covered in Chapter 96) and always produce branched products.

124 The reaction was likely first described around 1877 [39b].

40 Gabriel Synthesis

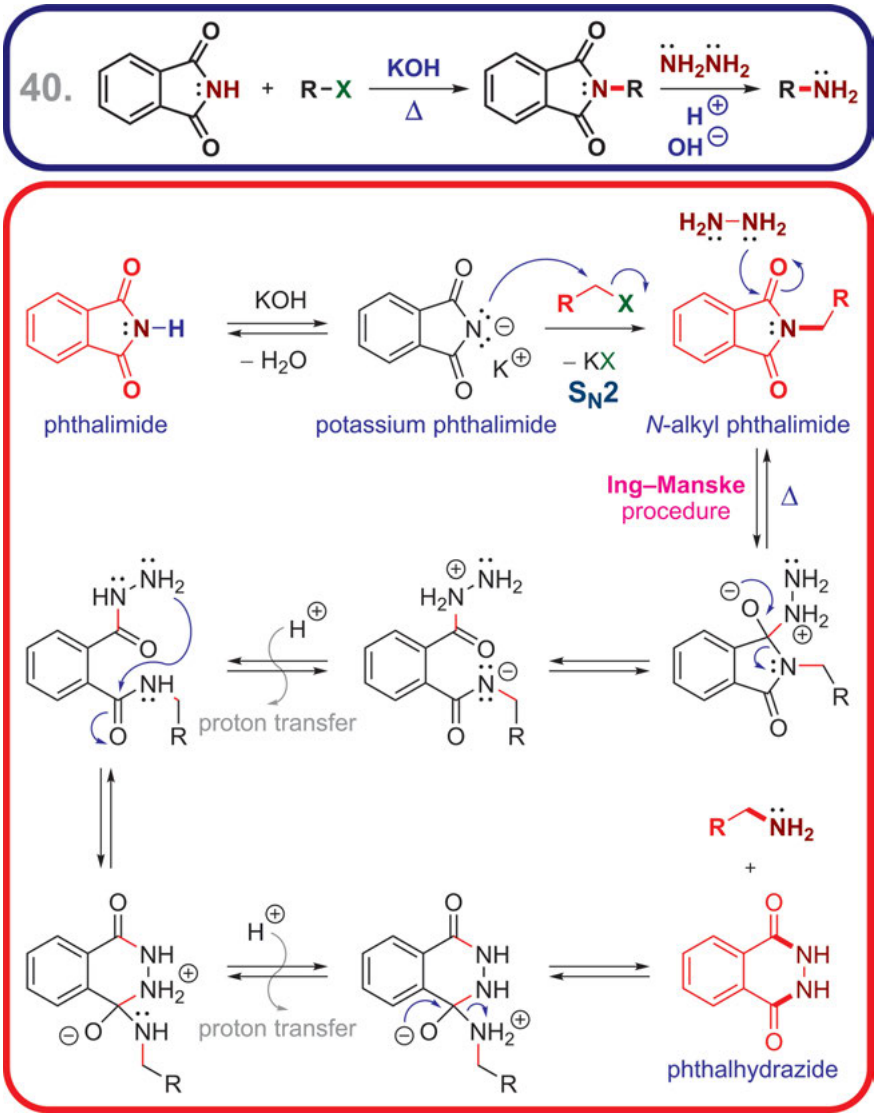


Fig. 40.1: The ***Gabriel*** *synthesis* mechanism.[125]

125 The ***Gabriel*** *synthesis* is a chemical reaction that converts *alkyl halides* to *primary (1°) amines* via the **S_N2** reaction using *phthalimide*. The ***Ing–Manske*** *procedure* [40a] is a chemical reaction that converts *N-alkyl phthalimide* to *primary (1°) amine* using *hydrazine*.

https://doi.org/10.1515/9783110608373-040

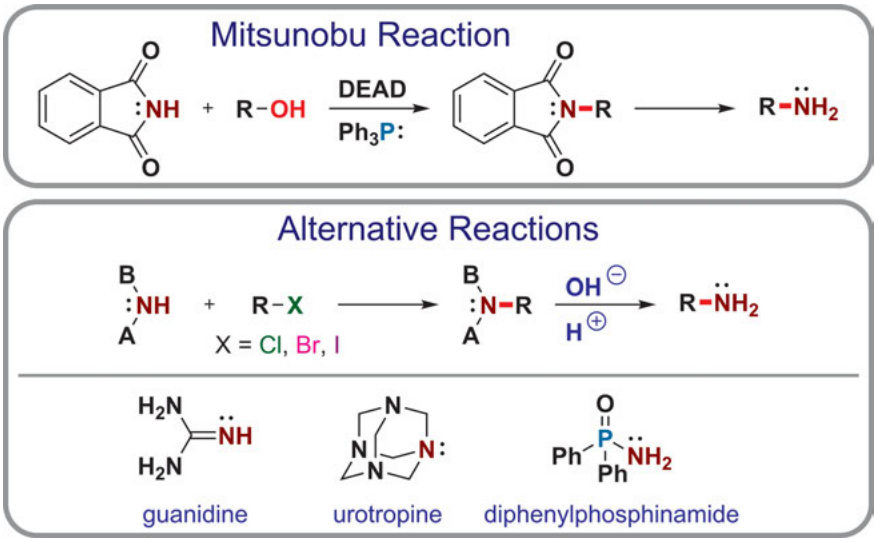


Fig. 40.2: Reactions related to the ***Gabriel*** *synthesis*.[126]

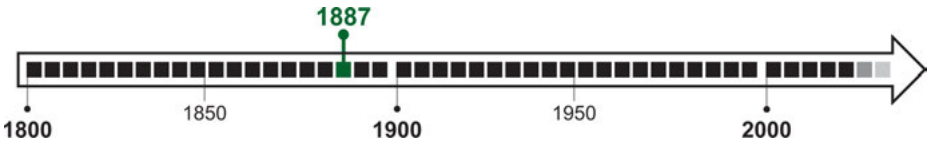


Fig. 40.3: The discovery of the ***Gabriel*** *synthesis*.[127]

126 There are alternative synthetic transformations to yield *primary amines*: the ***Mitsunobu*** *reaction* (covered in Chapter 61) or other $\mathbf{S_N2}$ reactions using various **N** (nitrogen) nucleophiles. Some of them are named reactions as well: the ***Delépine*** *reaction* (*urotropine* is the nitrogen nucleophile) [40b].
127 The reaction was likely first described around 1887 [40c].

41 Gewald Reaction

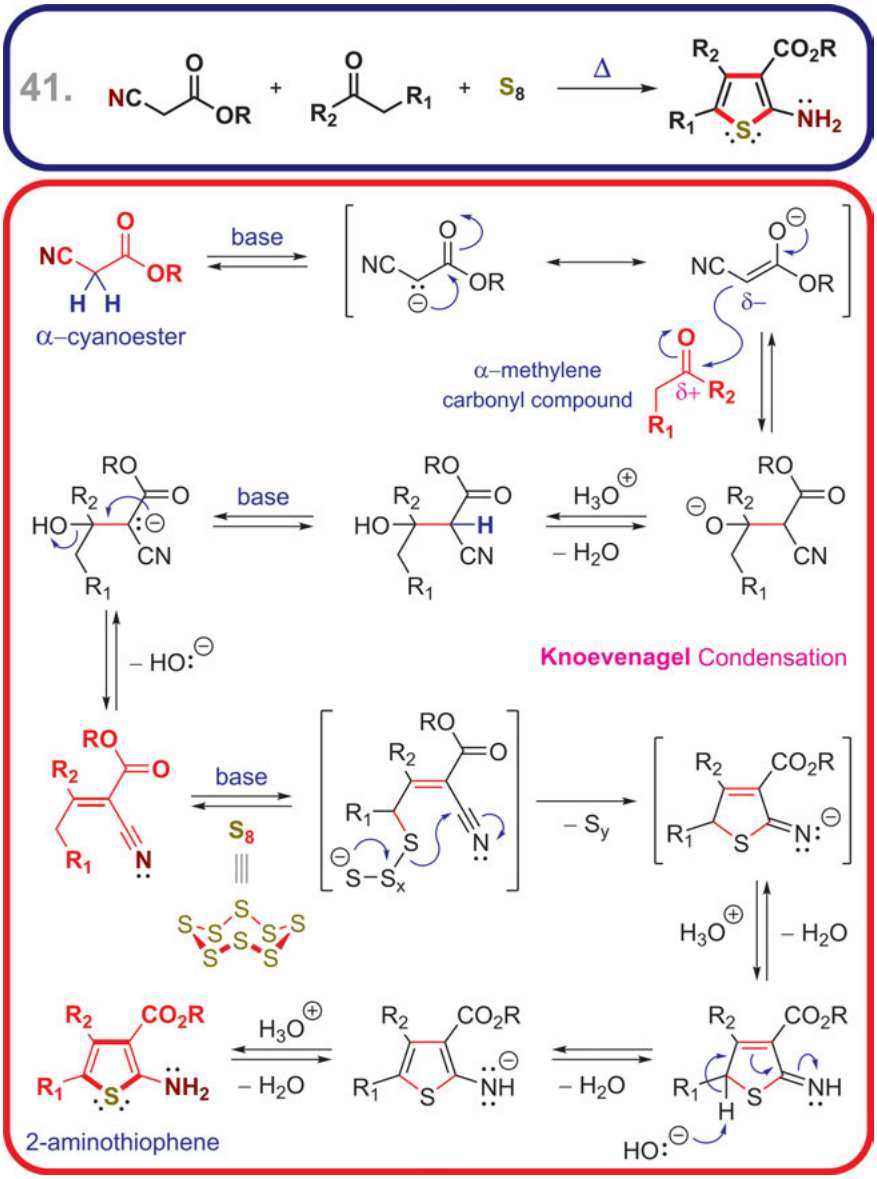


Fig. 41.1: The ***Gewald*** *reaction* mechanism.[128]

128 The ***Gewald*** *reaction*, also called the ***Gewald*** *condensation*, is a three-component reaction (3-CR) producing *2-aminothiophenes*. The key condensation step is the ***Knoevenagel*** *condensation* [41a].

https://doi.org/10.1515/9783110608373-041

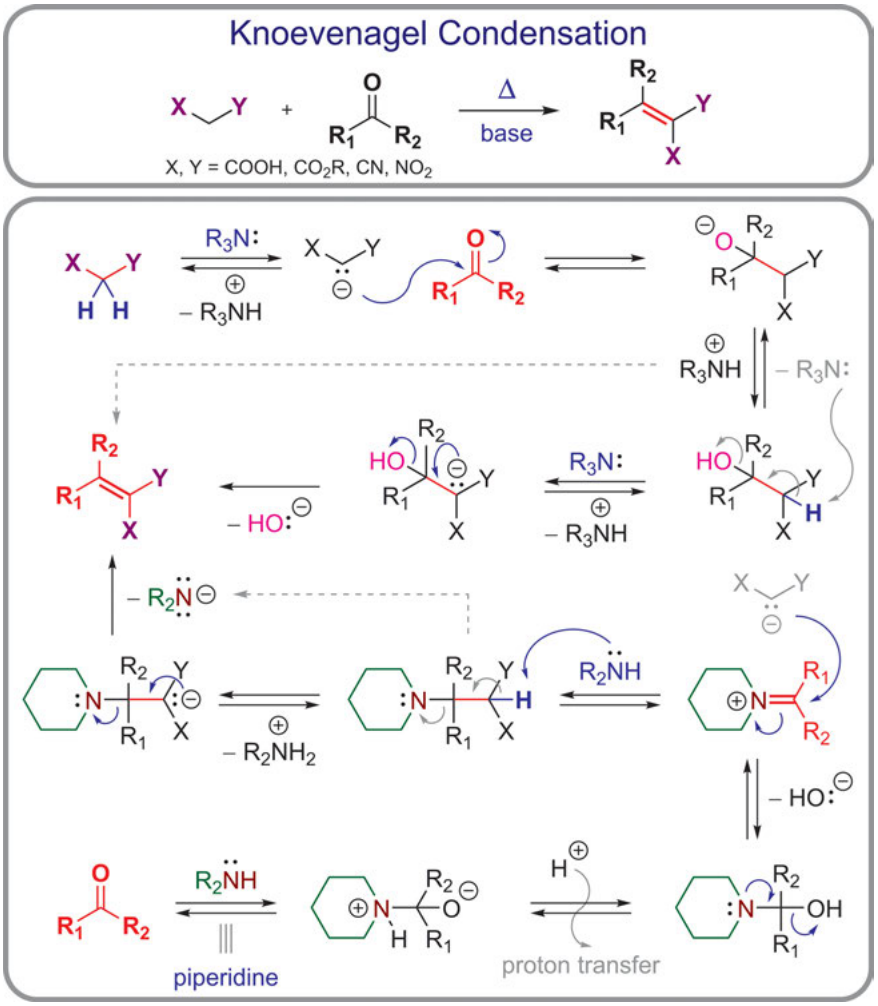


Fig. 41.2: The ***Knoevenagel*** *condensation* mechanism.[129]

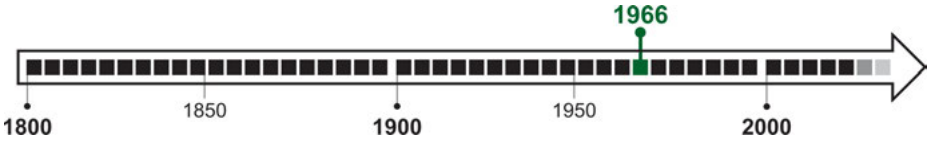


Fig. 41.3: The discovery of the ***Gewald*** *reaction*.[130]

129 The ***Knoevenagel*** *condensation* is a variation of the *aldol condensation* followed by *crotonation* (covered in Chapter 83). The reaction is often catalyzed by *piperidine*.

130 The reaction was likely first described around 1966 [41b].

42 Glaser–Eglinton–Hay Coupling

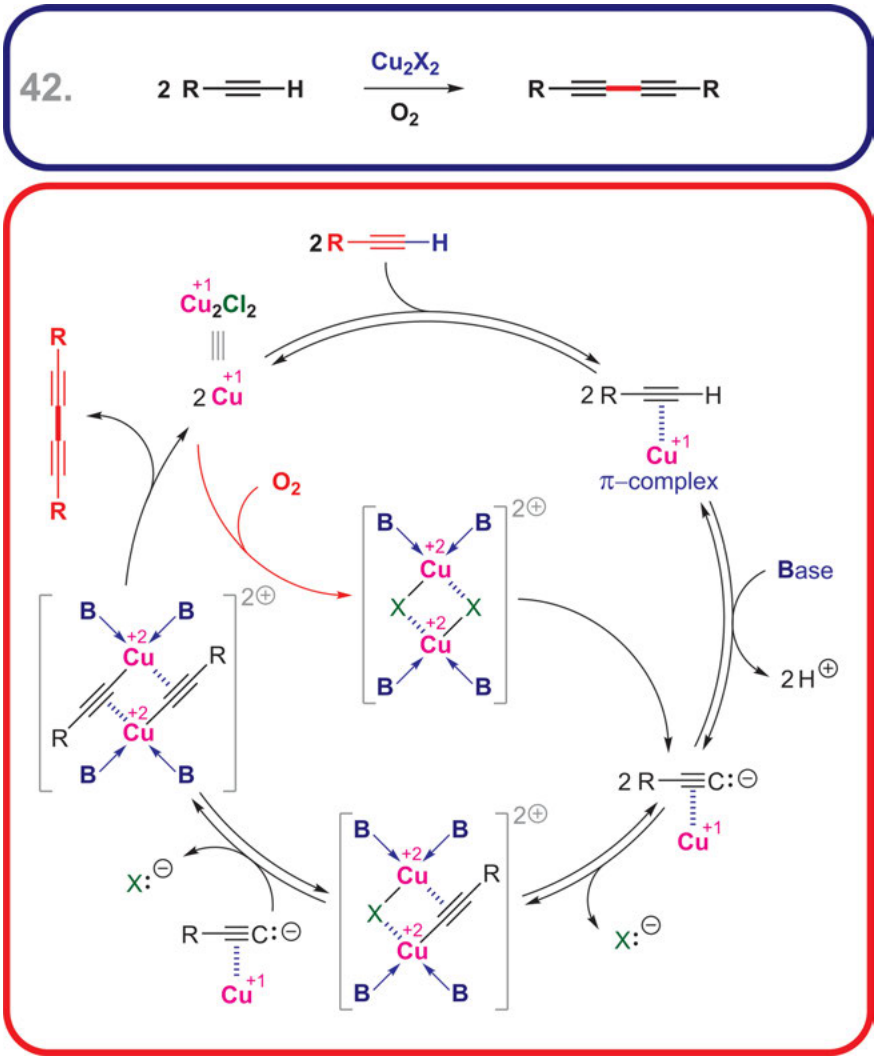


Fig. 42.1: The ***Glaser–Eglinton–Hay*** *coupling* mechanism.[131]

131 The ***Glaser–Eglinton–Hay*** *coupling* is a general name for three named reactions: the ***Glaser*** *coupling*, the ***Eglinton*** *coupling*, and the ***Hay*** *coupling*. It is one of many examples of ***Cu****-mediated dimerization* of *terminal alkynes*. In all three cases, the formed products are symmetrical.

https://doi.org/10.1515/9783110608373-042

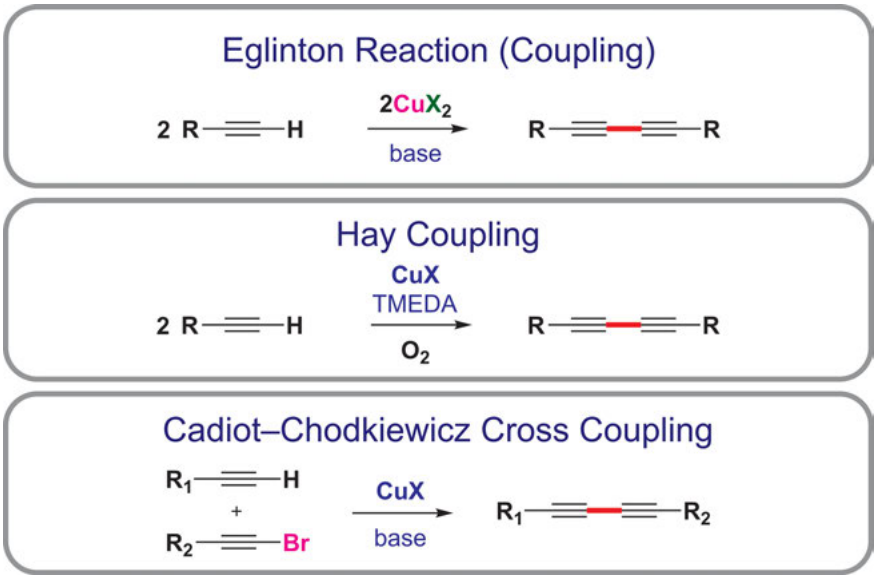


Fig. 42.2: Reactions related to the ***Glaser–Eglinton–Hay*** *coupling*.[132]

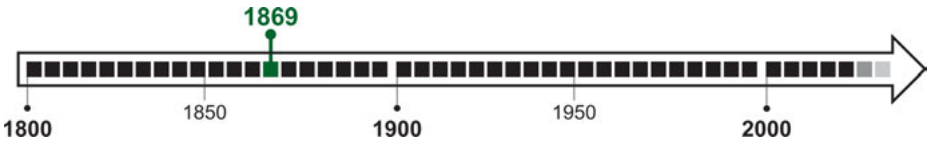


Fig. 42.3: The discovery of the ***Glaser–Eglinton–Hay*** *coupling*.[133]

132 More specifically: in the ***Eglinton*** *coupling*, the product is (a) symmetrical, (b) **Cu** is used as a stoichiometric reagent [42a, 42b]; in the ***Glaser*** *coupling*, the product is (a) symmetrical, (b) **CuX** is used as a catalyst with NH_3 or NH_4OH [42c]; in the ***Hay*** *coupling*, the product is (a) symmetrical, (b) **CuX**•TMDA complex is used as a catalyst [42d, 42e]; in the ***Cadiot–Chodkiewicz*** *coupling*, the product is (a) **asymmetrical**, (b) **Cu** is used as a catalyst [42f], and other examples [1, 4].

133 The reaction was likely first described around 1869 [42c].

43 Grignard Reaction

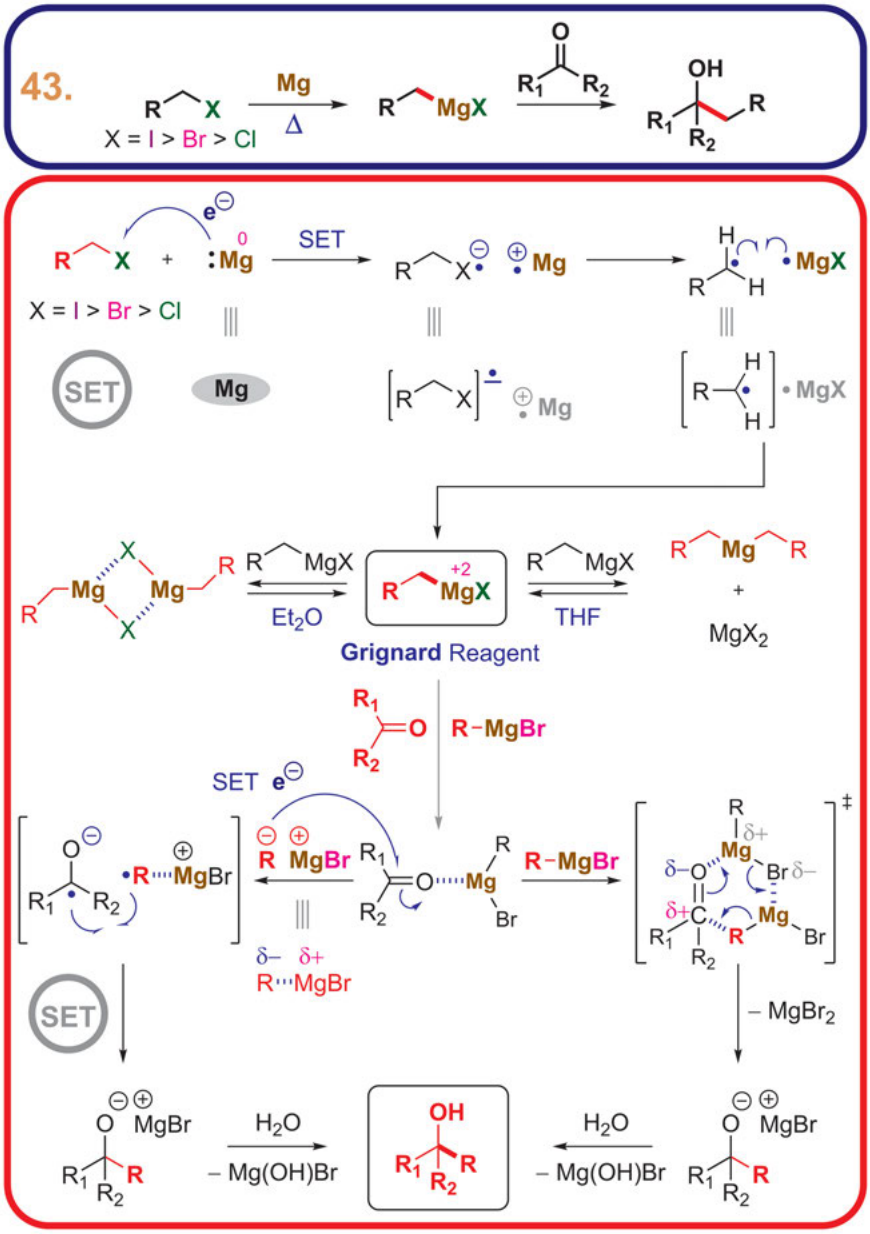


Fig. 43.1: The ***Grignard*** *reaction* mechanism.[134]

https://doi.org/10.1515/9783110608373-043

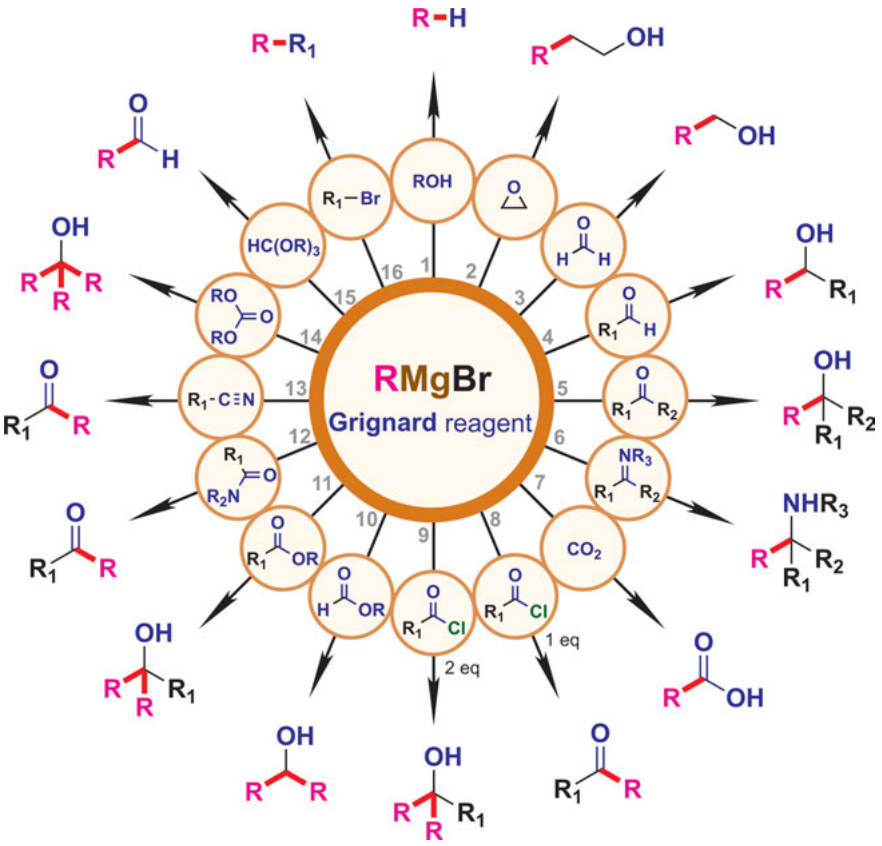


Fig. 43.2: Synthetic versatility of the ***Grignard*** *reagent*.[135]

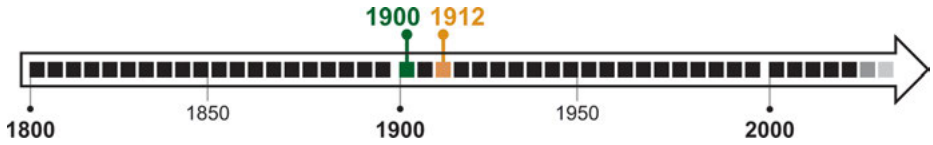


Fig. 43.3: The discovery of the ***Grignard*** *reaction*.[136]

---

134 The ***Grignard*** *reaction* is based on the use of a named reagent: the ***Grignard*** *reagent* (**RMgX**). The mechanism is not well-understood and most likely involves a **single electron transfer** (**SET**) (Chapter 5).
135 The ***Grignard*** *reagent* has wide synthetic applications, it can react with a variety of electrophiles (electrophilic centers): 1. alcohols, deuterated water; 2. epoxides; 3. formaldehyde; 4. aldehydes; 5. ketones; 6. imines; 7. carbon dioxide (disulfide); 8. acyl chlorides (1 eq); 9. acyl chlorides (excess); 10. formates; 11. esters; 12. amides; 13. nitriles; 14. carbonates; 15. orthoesters; 16. alkyl halides; and others [1].
136 The reaction was likely first described around 1900 [43a]. In **1912**, Victor Grignard (jointly with Paul Sabatier) received the Nobel Prize in Chemistry for the discovery of the ***Grignard*** *reagent* (and other achievements in chemistry) [43b].

44 Grob Fragmentation

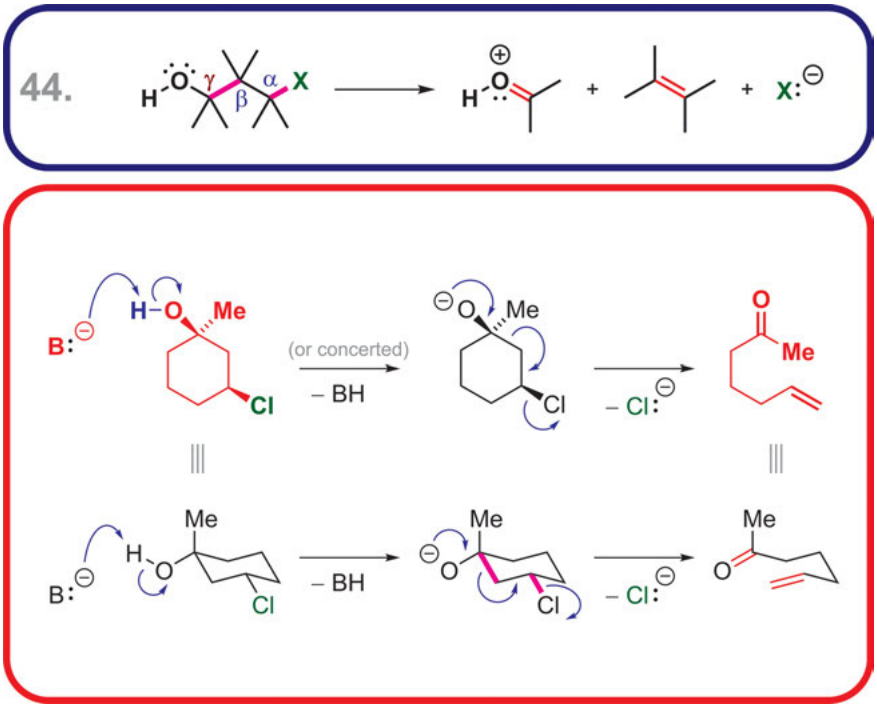


Fig. 44.1: The ***Grob*** *fragmentation* mechanism.[137]

137 The ***Grob*** *fragmentation* mechanism is most likely related to the **β–elimination** mechanisms (in this case 1,4-elimination) covered in Chapter 6. The common feature of this fragmentation is the formation of three species: positively charged *(electrofuge)*, neutral unsaturated fragment, and negatively charged *(nucleofuge)*. A stepwise or concerted mechanism can take place.

https://doi.org/10.1515/9783110608373-044

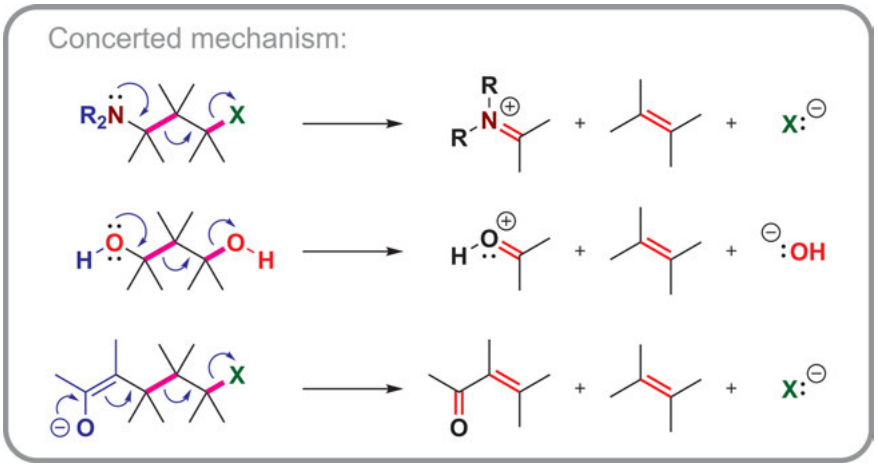


Fig. 44.2: Variations of the ***Grob*** *fragmentation*.[138]

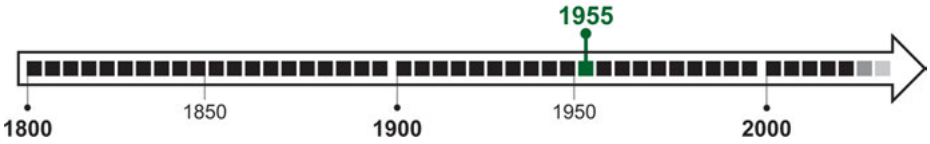


Fig. 44.3: The discovery of the ***Grob*** *fragmentation*.[139]

138 There are many variations of the ***Grob*** *fragmentation* involving: γ–hydroxy halides (shown here); γ–amino halides; 1,3-diols; and others [44a].

139 The reaction was likely first described around 1955 [44b, 44c].

45 Haloform Reaction

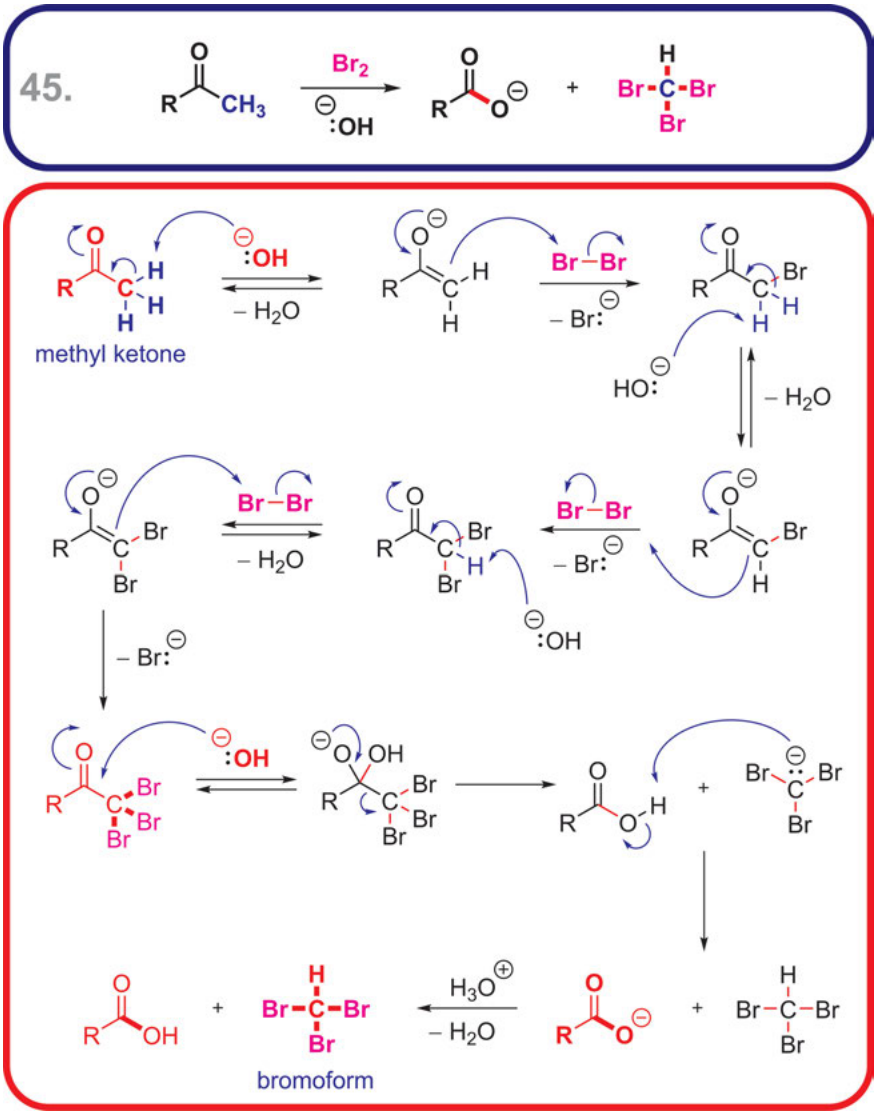


Fig. 45.1: The *haloform reaction* mechanism.[140]

140 The *haloform reaction* is one of the oldest reactions in organic chemistry. It is an example of **aliphatic electrophilic substitution**, which is not covered in this book (Chapter 3).

https://doi.org/10.1515/9783110608373-045

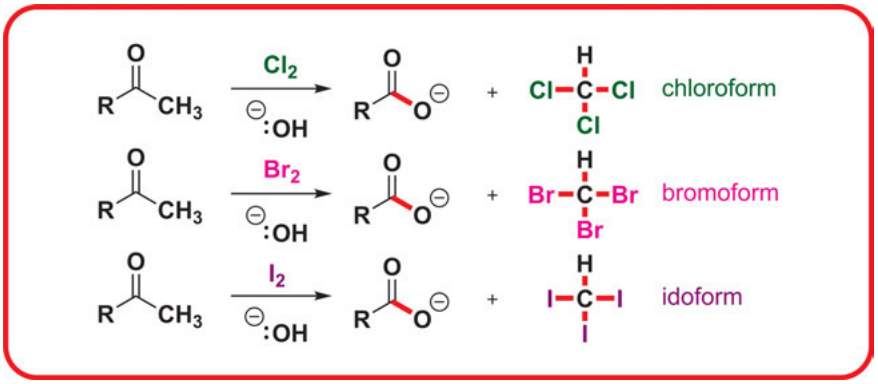


Fig. 45.2: Variations of the *haloform reaction*.[141]

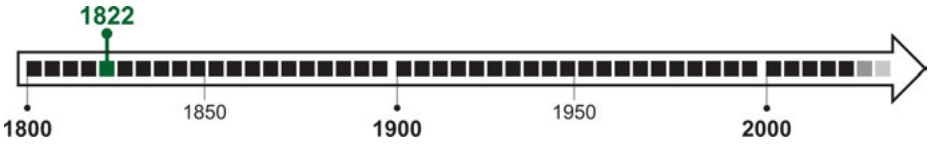


Fig. 45.3: The discovery of the *haloform reaction*.[142]

141 The *haloform reaction* can be carried out with most halogens: (Cl) the *chloroform reaction*; (Br) the *bromoform reaction*, (I) the *iodoform reaction*, also known as the *iodoform test* or the ***Lieben iodoform test*** (it is used as an indication of the methyl ketones presence) [45].

142 The reaction was likely first described between 1822 and 1870 [45].

46 Heck Cross Coupling

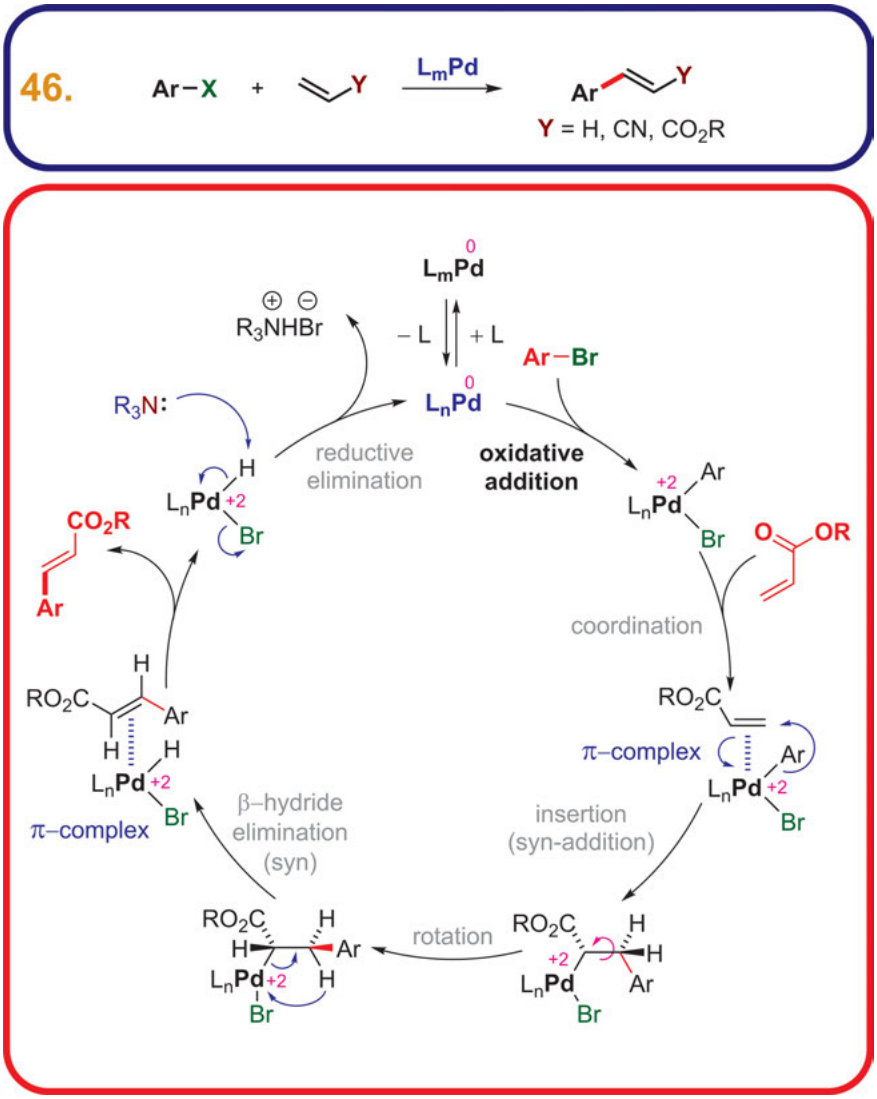


Fig. 46.1: The ***Heck*** *cross coupling* mechanism.[143]

143 The ***Heck*** *cross coupling* or the ***Heck*** *reaction* is also called the ***Mizoroki–Heck*** *reaction*. It is one of the most important types of ***Pd***-*catalyzed cross coupling* reactions (C–C bond formation using *aryl halides* and *alkenes*). For teaching purposes, a simplified and general mechanism is shown.

https://doi.org/10.1515/9783110608373-046

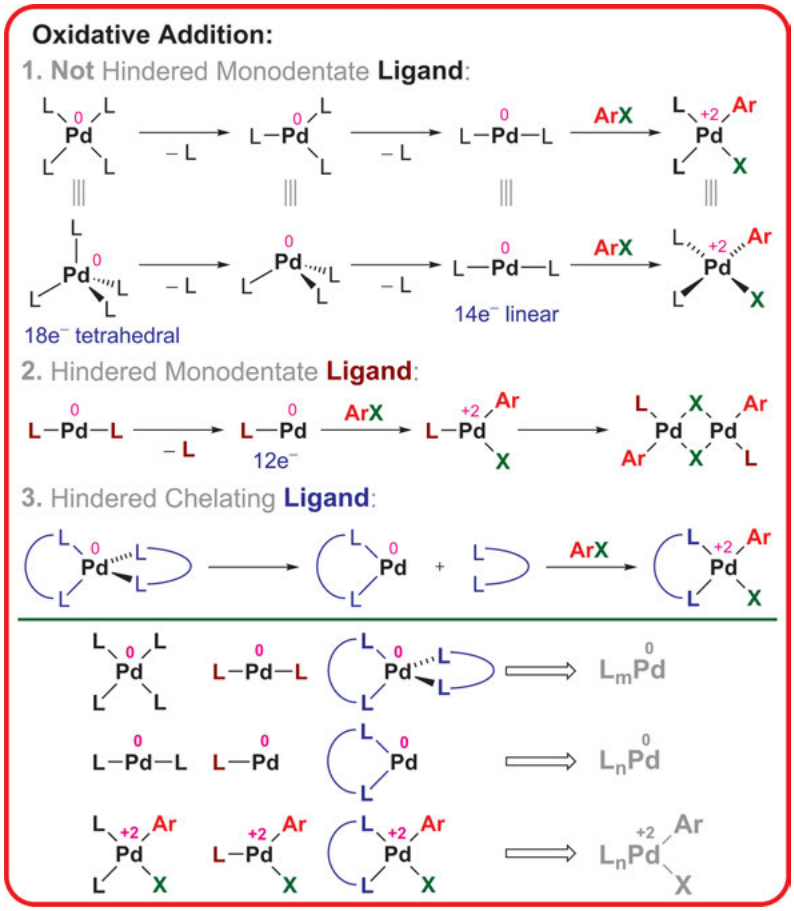


Fig. 46.2: General illustration of the *oxidative addition* step.[144]

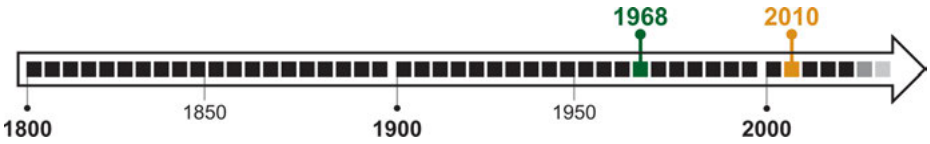


Fig. 46.3: The discovery of the ***Heck*** *cross coupling*.[145]

144 The *oxidative addition* step can be represented in several ways in the literature; including a catalyst with: 1. a *not (less) hindered monodentate ligand*; 2. a *large hindered monodentate ligand*; 3. a *hindered chelating (bidentate) ligand*. For simplicity, unspecified representation will be used henceforth: **L_mPd** or **L_nPd** [2a].

145 The reaction was likely first described around 1968 [46a, 46b]. In **2010**, Richard F. Heck (jointly with Ei-ichi Negishi and Akira Suzuki) received the Nobel Prize in Chemistry for the development of **Pd**-catalyzed cross coupling reactions [46c].

47 Hell–Volhard–Zelinsky Reaction

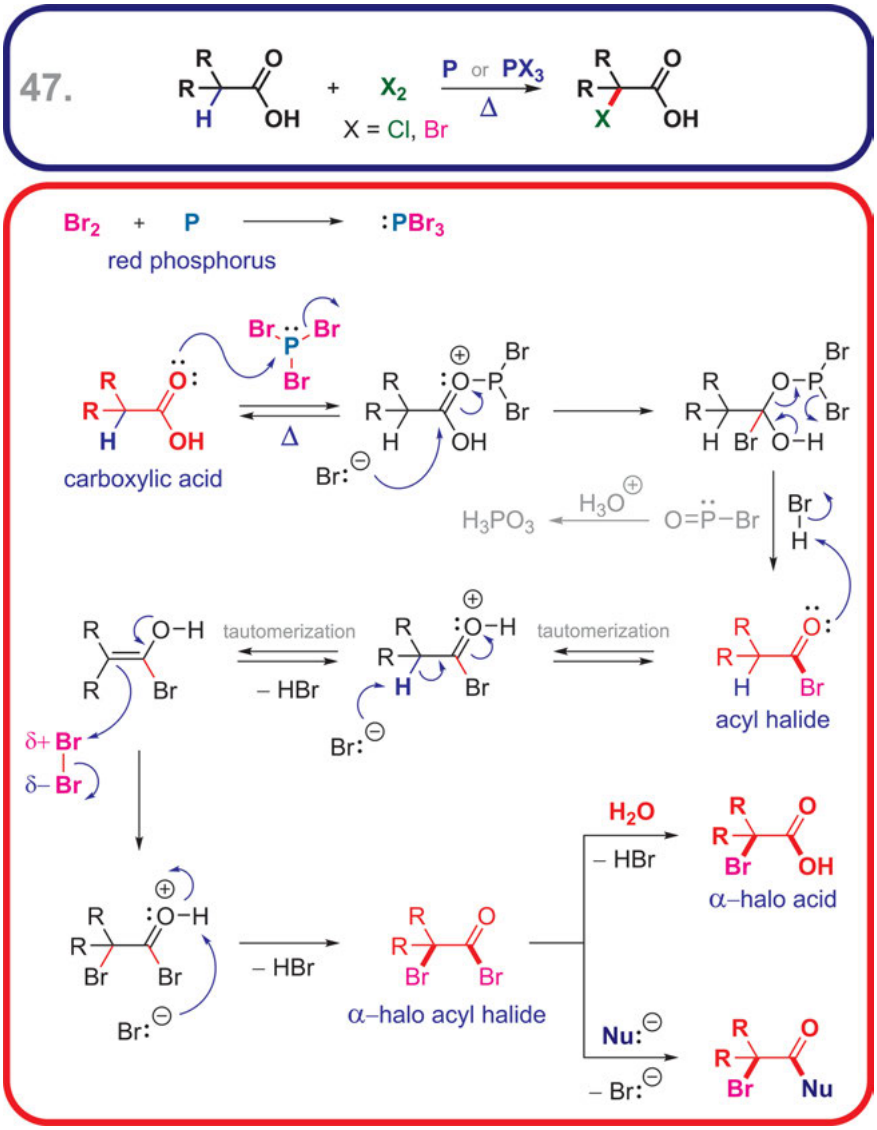


Fig. 47.1: The ***Hell–Volhard–Zelinsky*** *reaction* mechanism.[146]

146 The ***Hell–Volhard–Zelinsky*** *reaction* is also known as the ***Hell–Volhard–Zelinsky*** *(HVZ) halogenation*. It is a type of *aliphatic electrophilic substitution* (briefly mentioned in Chapter 3). Mechanistically, it is also related to the *haloform reaction* (see Chapter 45).

https://doi.org/10.1515/9783110608373-047

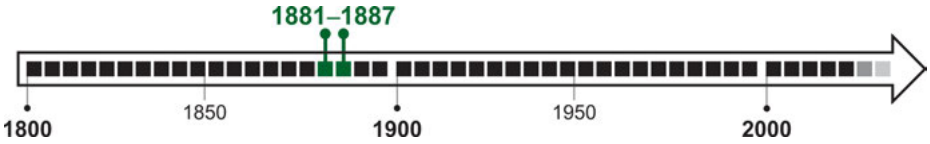


Fig. 47.2: The discovery of the ***Hell–Volhard–Zelinsky*** *reaction*.[147]

147 The reaction was likely first described around 1881 by Hell [47a], and around 1887 by both Volhard and Zelinsky [47b] and [47c].

48 Hiyama Cross Coupling

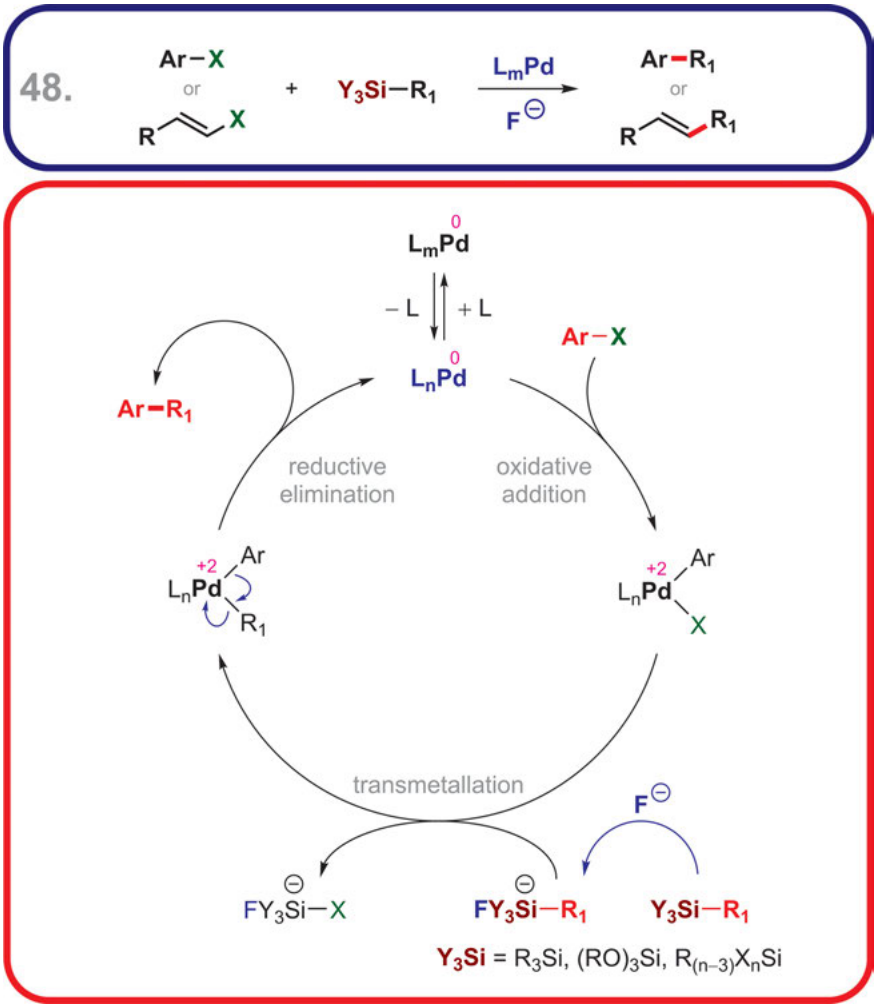


Fig. 48.1: The ***Hiyama*** *cross coupling* mechanism.[148]

148 The ***Hiyama*** *cross coupling* is a type of ***Pd****-catalyzed cross coupling* reaction (C–C bond formation using *aryl halides* and *organosilanes*). For teaching purposes, a simplified and general mechanism is shown.

https://doi.org/10.1515/9783110608373-048

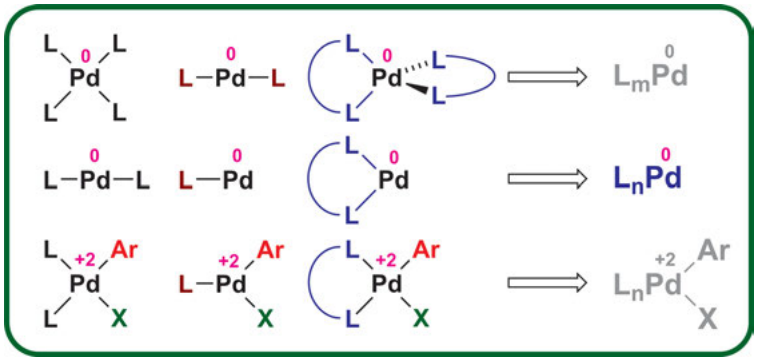


Fig. 48.2: The *oxidative addition* step representation.[149]

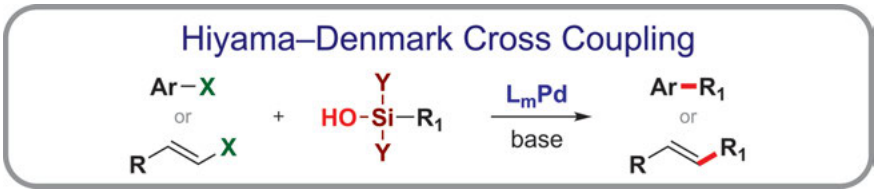


Fig. 48.3: Variations of the ***Hiyama*** *cross coupling*.[150]

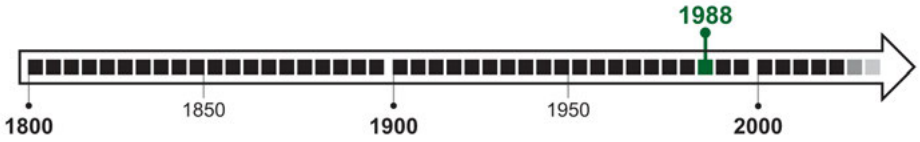


Fig. 48.4: The discovery of the ***Hiyama*** *cross coupling*.[151]

149 As it was explained in Chapter 46, the representation of the *oxidative addition* step can vary. For simplicity and consistency, a general depiction of a *catalyst-ligand* complex is used: **L_mPd** or **L_nPd** [2a].

150 A modification of the ***Hiyama*** *cross coupling* is called the ***Hiyama–Denmark*** *cross coupling* reaction [48a]. It is also a type of ***Pd****-catalyzed cross coupling* reaction (C–C bond formation using *aryl halides* and *organosilanols*).

151 The reaction was likely first described around 1988 [48b].

49 Hofmann Elimination

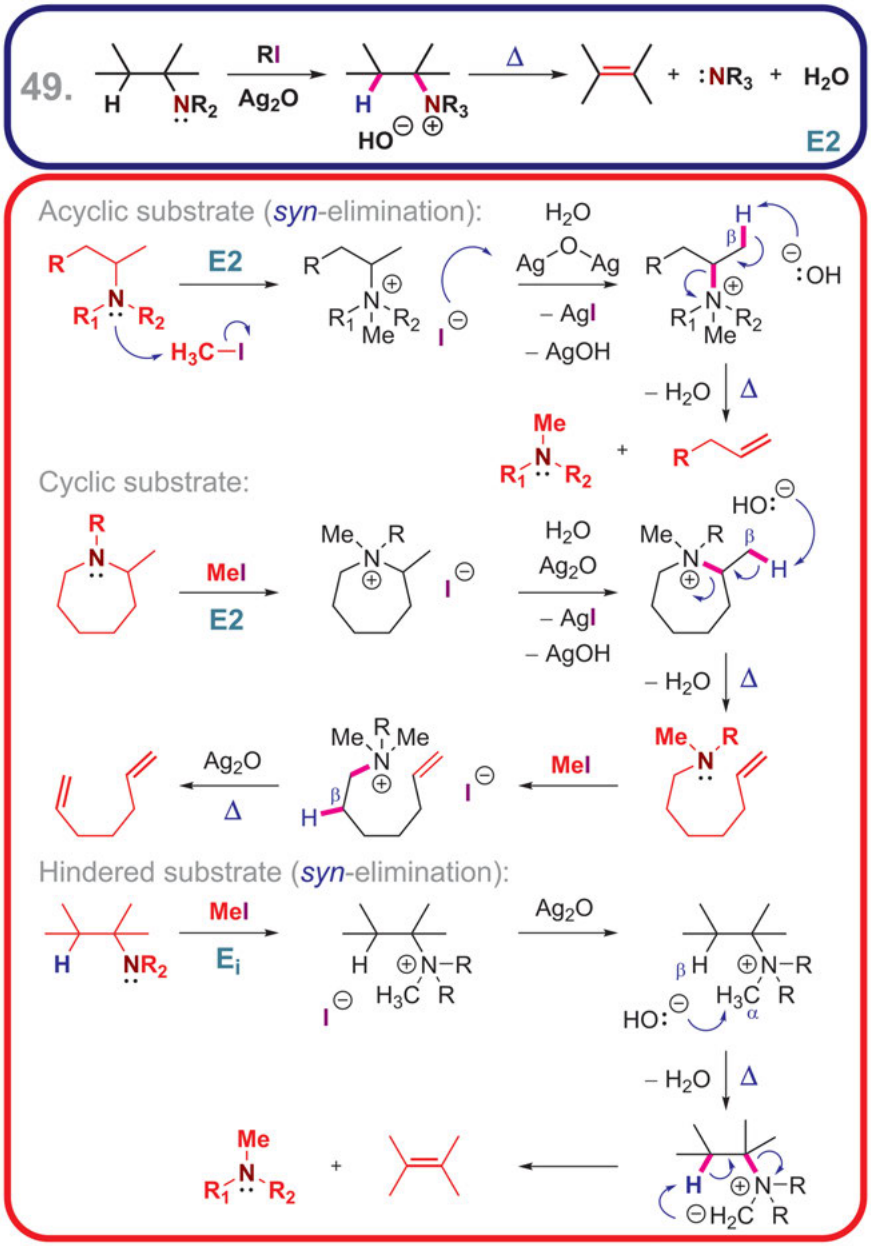


Fig. 49.1: The ***Hofmann*** *elimination* mechanism.[152]

https://doi.org/10.1515/9783110608373-049

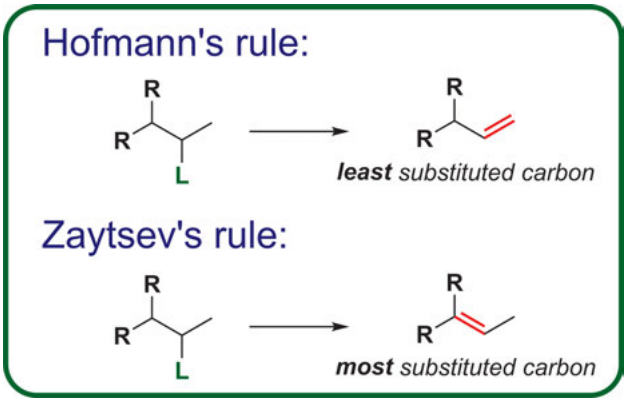


Fig. 49.2: ***Hofmann's*** *rule* and ***Zaytsev's*** *rule*.[153]

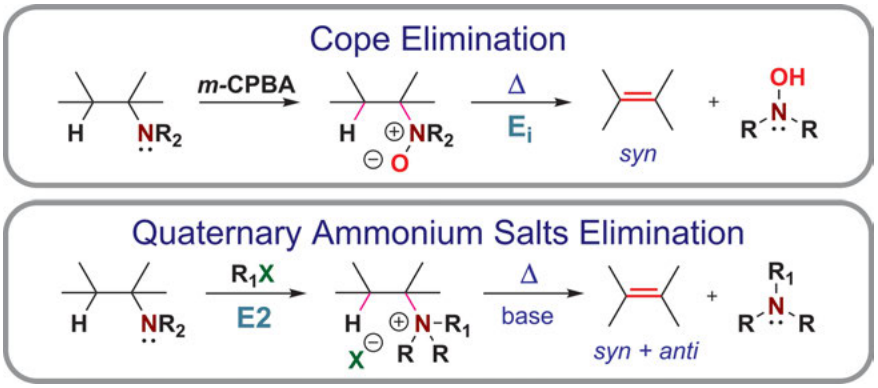


Fig. 49.3: Reactions related to the ***Hofmann*** *elimination*.[154]

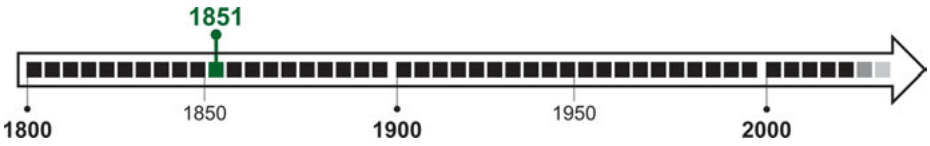


Fig. 49.4: The discovery of the ***Hofmann*** *elimination*.[155]

---

152 The ***Hofmann*** *elimination* is also known as the ***Hofmann*** *degradation*. This should not be confused with the ***Hofmann*** *rearrangement* (Chapter 31). It is an example of **β–elimination** reaction, Chapter 6.

153 The products of the ***Hofmann*** *elimination* obey *Hofmann's rule*: the double bond is at the *least substituted carbon*. If the double bond is at the *most substituted carbon*, then it conforms with *Zaytsev's rule* (also spelled Saytzeff, and in Russian Александр Михайлович Зайцев or A. M. Зайцев) [49a].

154 Several reactions are related to the ***Hofmann*** *elimination*: the ***Cope*** *elimination* ($\mathbf{E_i}$ mechanism, Chapter 27), the fragmentation of quaternary ammonium salts (**E2** mechanism), and others [1, 49b].

155 The reaction was likely first described around 1851 [49c, 49d].

50 Horner–Wadsworth–Emmons Olefination

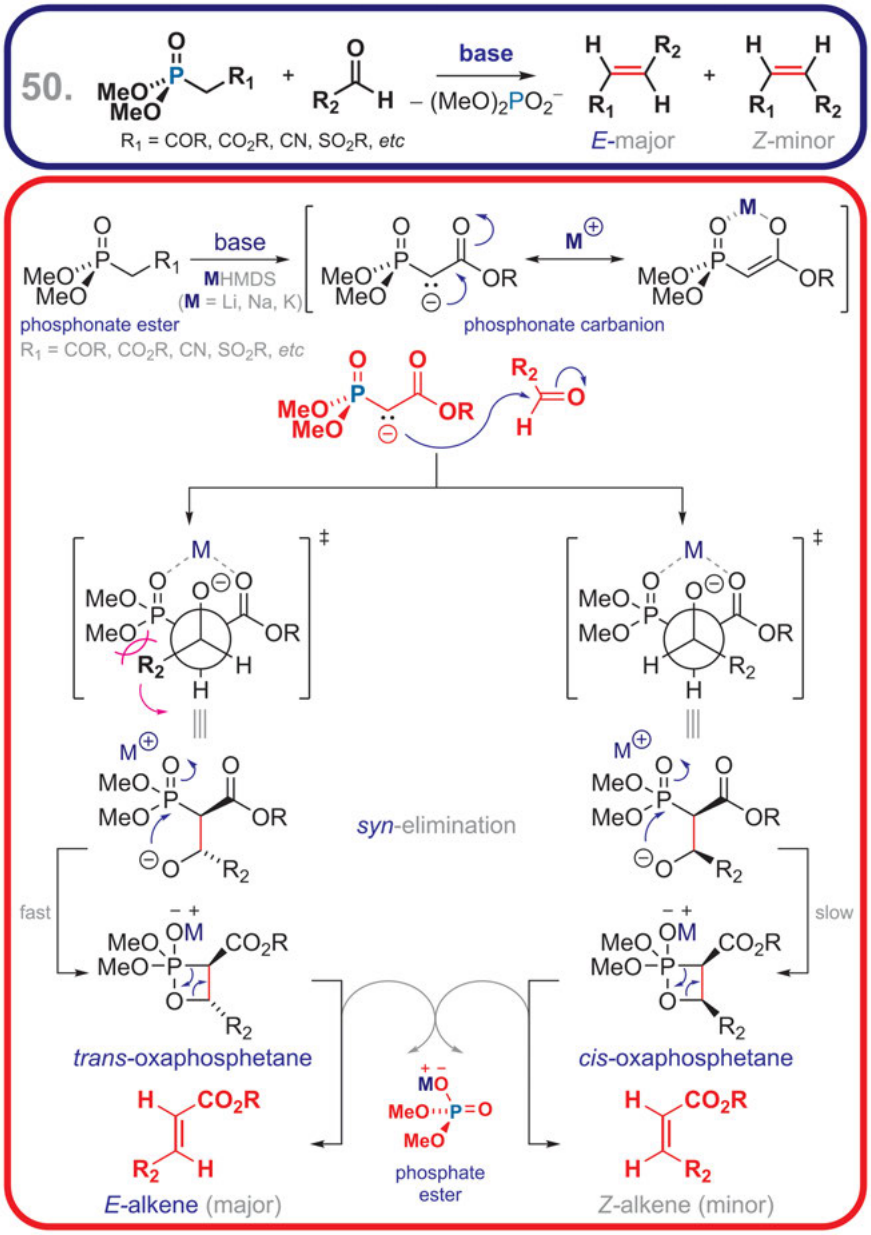


Fig. 50.1: The ***Horner–Wadsworth–Emmons*** *olefination* mechanism.[156]

https://doi.org/10.1515/9783110608373-050

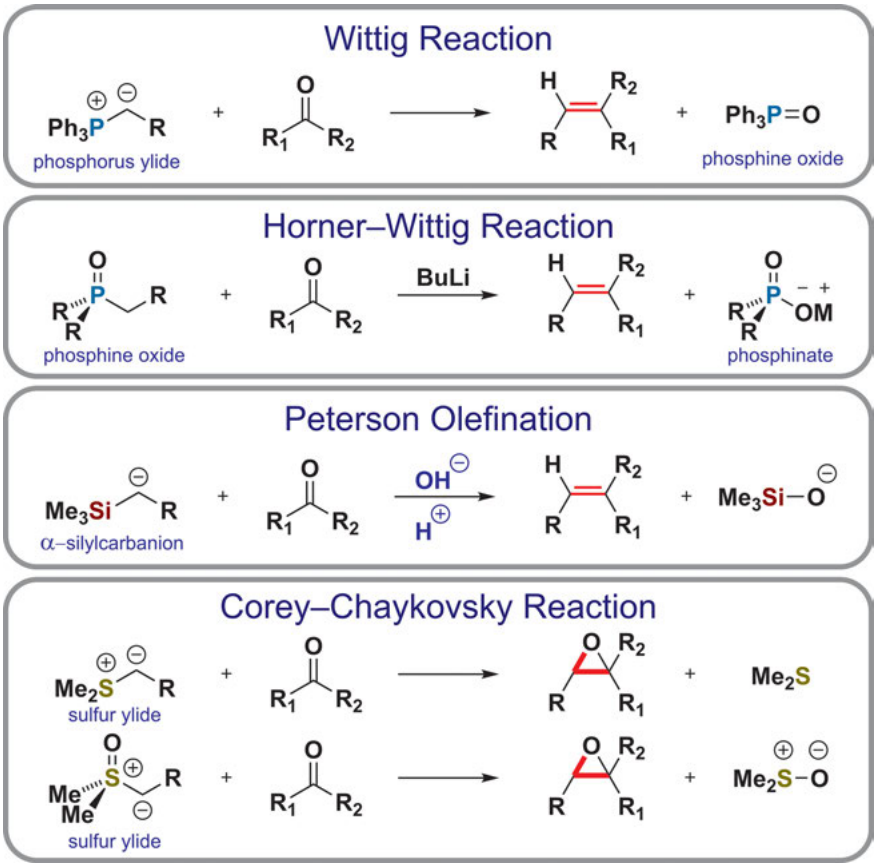


Fig. 50.2: Reactions related to the ***Horner–Wadsworth–Emmons*** *olefination*.[157]

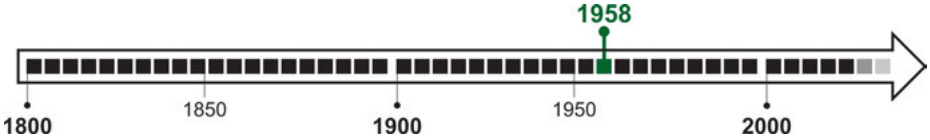


Fig. 50.3: The discovery of the ***Horner–Wadsworth–Emmons*** *olefination*.[158]

156 The ***Horner–Wadsworth–Emmons*** *(HWE) olefination* is also called the ***HWE*** *reaction*. The reaction relies on the use of *phosphonates* prepared via the ***Arbuzov*** *reaction* (Chapter 9).

157 Several reactions are related to the ***HWE*** *olefination*: the ***Wittig*** *reaction* (Chapter 98, it relies on the *phosphorus ylides* formed from the *phosphonium salts*), the ***Horner–Wittig*** *reaction* (relies on the *ylides* formed from the *phosphine oxides*) [1] and [50a], the ***Peterson*** *olefination* (relies on the *organosilanes*) [50b], the ***Corey–Chaykovsky*** *reaction* (relies on the *sulfur ylides*, Chapter 32).

158 The reaction was likely first described around 1958 [50c, 50d, 50e].

51 Jones Oxidation

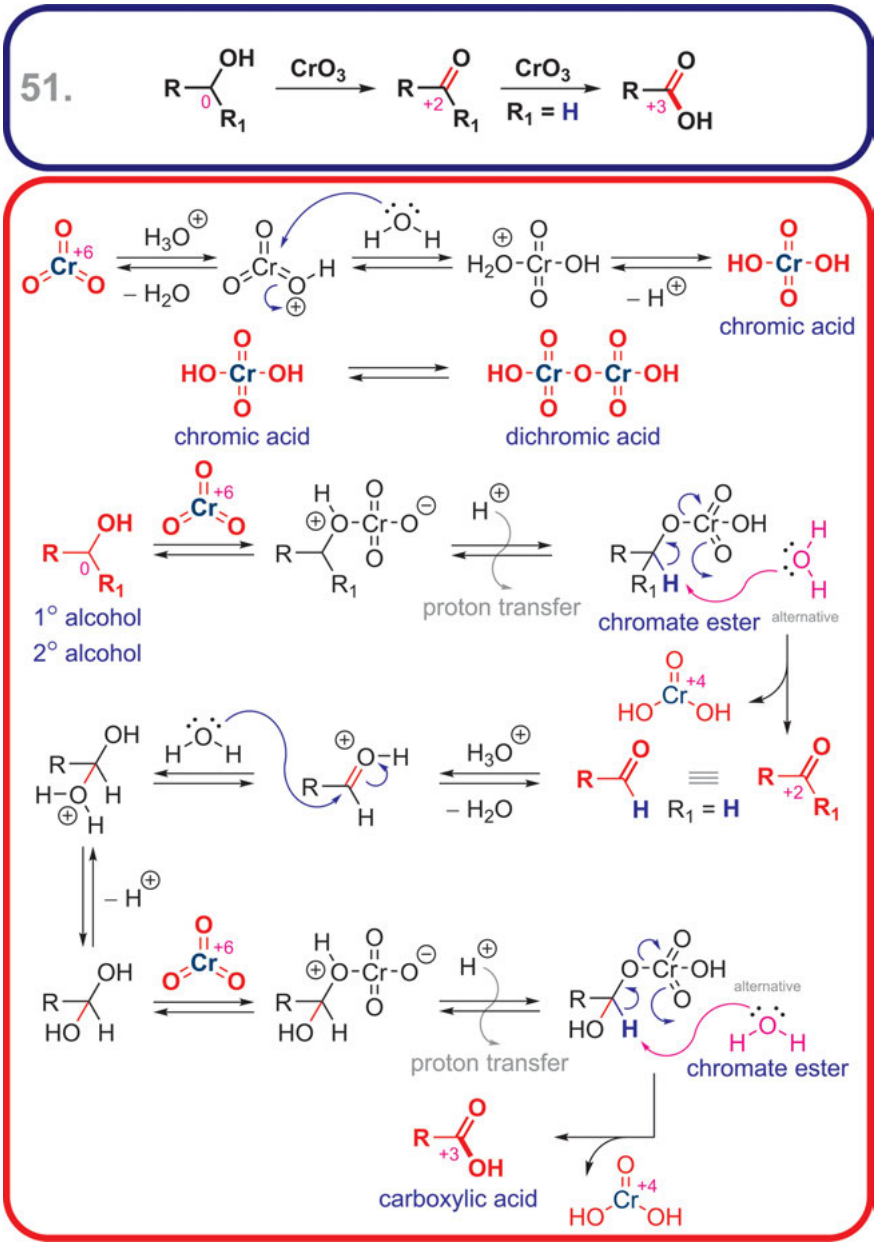


Fig. 51.1: The ***Jones*** *oxidation* mechanism.[159]

https://doi.org/10.1515/9783110608373-051

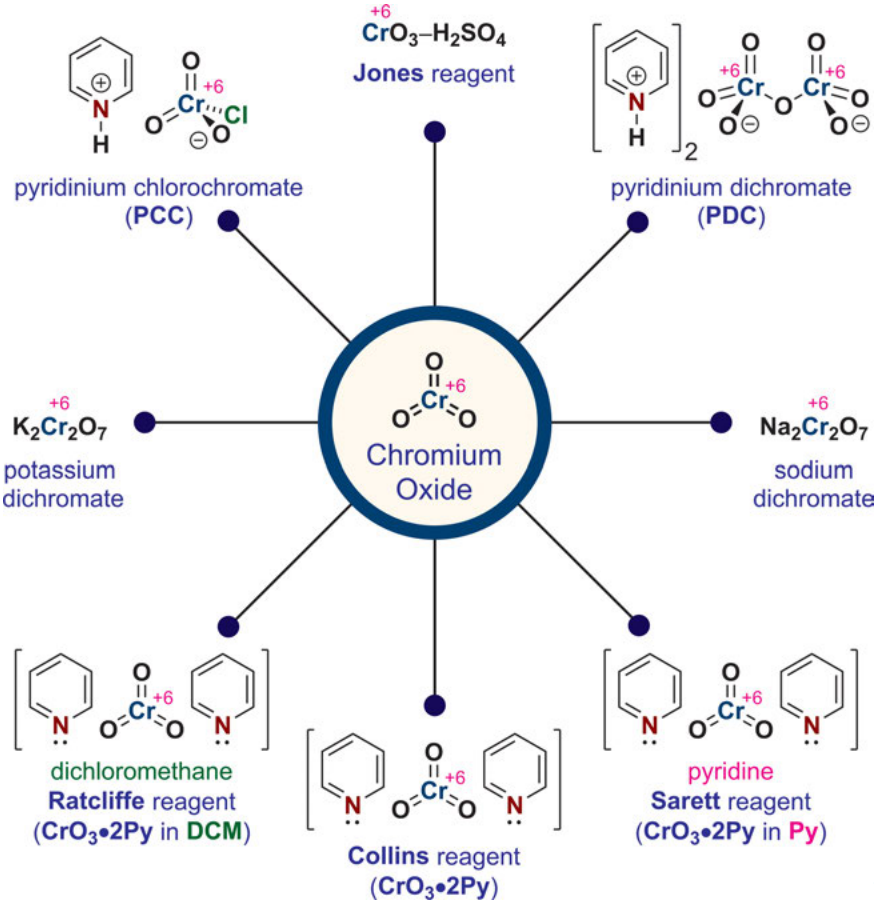


Fig. 51.2: Various oxidizing reagents formed from chromium oxide (VI).[160]

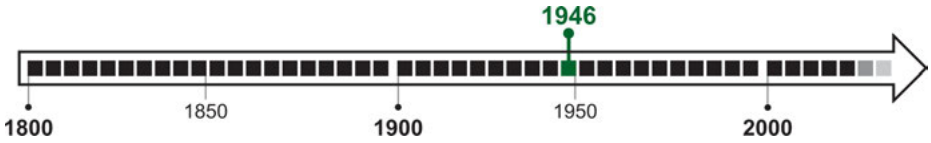


Fig. 51.3: The discovery of the ***Jones*** *oxidation*.[161]

159 The ***Jones*** *oxidation* is based on the use of the same named reagent: the ***Jones*** *reagent* [51a].

160 There are numerous examples of chromium oxidizing reagents, which can be prepared from chromium oxide (VI): *pyridinium chlorochromate* (PCC) [51b, 51c] is one of the most important among them.

161 The reaction was likely first described around 1946 [51d].

52 Kucherov Reaction

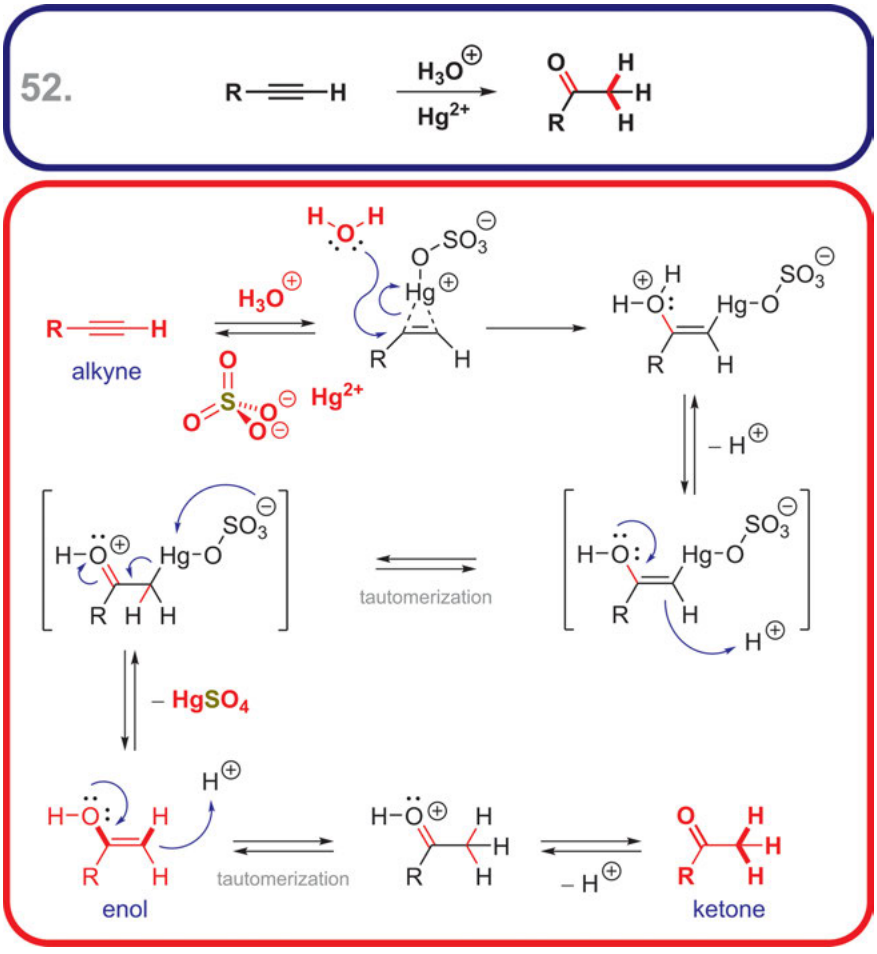


Fig. 52.1: The ***Kucherov*** *reaction* mechanism.[162]

162 The ***Kucherov*** *reaction* (in Russian Кучеров) is rare and very seldom called by its name. Mechanistically, it is an example of the **electrophilic addition** (to an alkyne) more broadly covered in Chapter 1. The reaction follows *Markovnikov's rule* (in Russian Владимир Васильевич Марковников or В. В. Марковников): hydrogen (H^+, or any other electrophilic part of a molecule) is at the least substituted carbon (or H adds to the carbon with more H atoms) [52a].

https://doi.org/10.1515/9783110608373-052

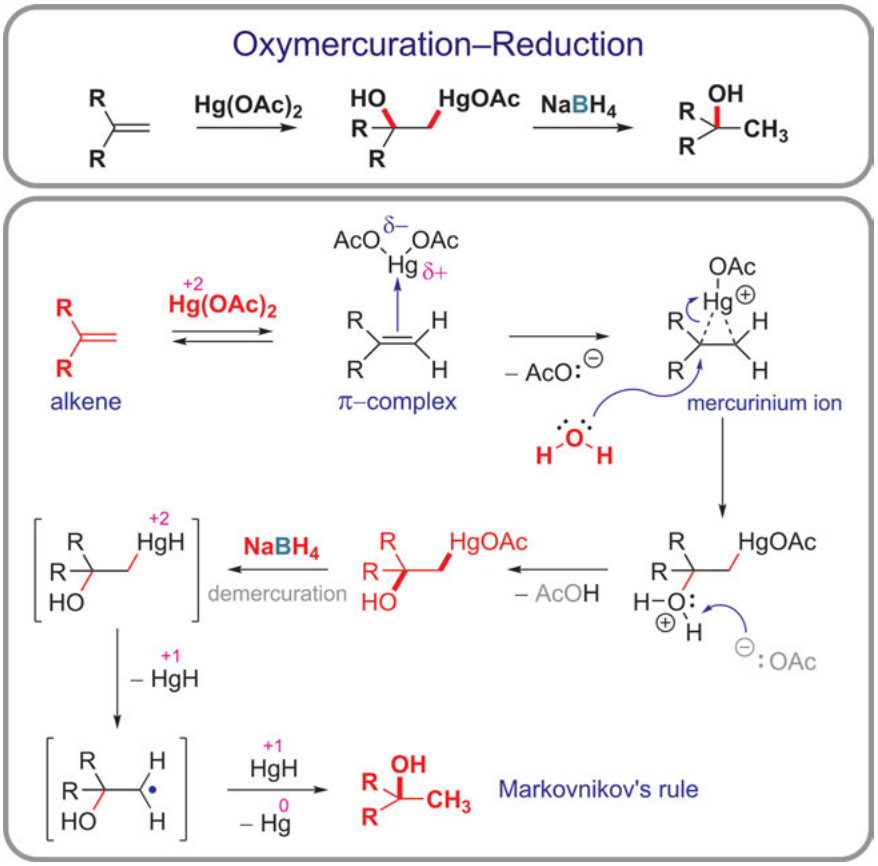


Fig. 52.2: The *oxymercuration reaction* mechanism.[163]

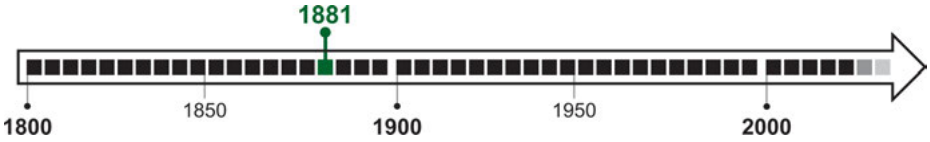


Fig. 52.3: The discovery of the ***Kucherov*** *reaction*.[164]

163 The *oxymercuration reaction* (the *oxymercuration-reduction reaction*) is related to the ***Kucherov*** *reaction*. It is also an **electrophilic addition** reaction predominantly forming products (alcohols) according to *Markovnikov's rule*. Please note, the *hydroboration-oxidation* (Chapter 20), yields ***anti-Markovnikov's*** products: hydrogen is at the most substituted carbon (or H adds to the carbon with less H atoms).

164 The reaction was likely first described around 1881 [52b].

53 Kumada Cross Coupling

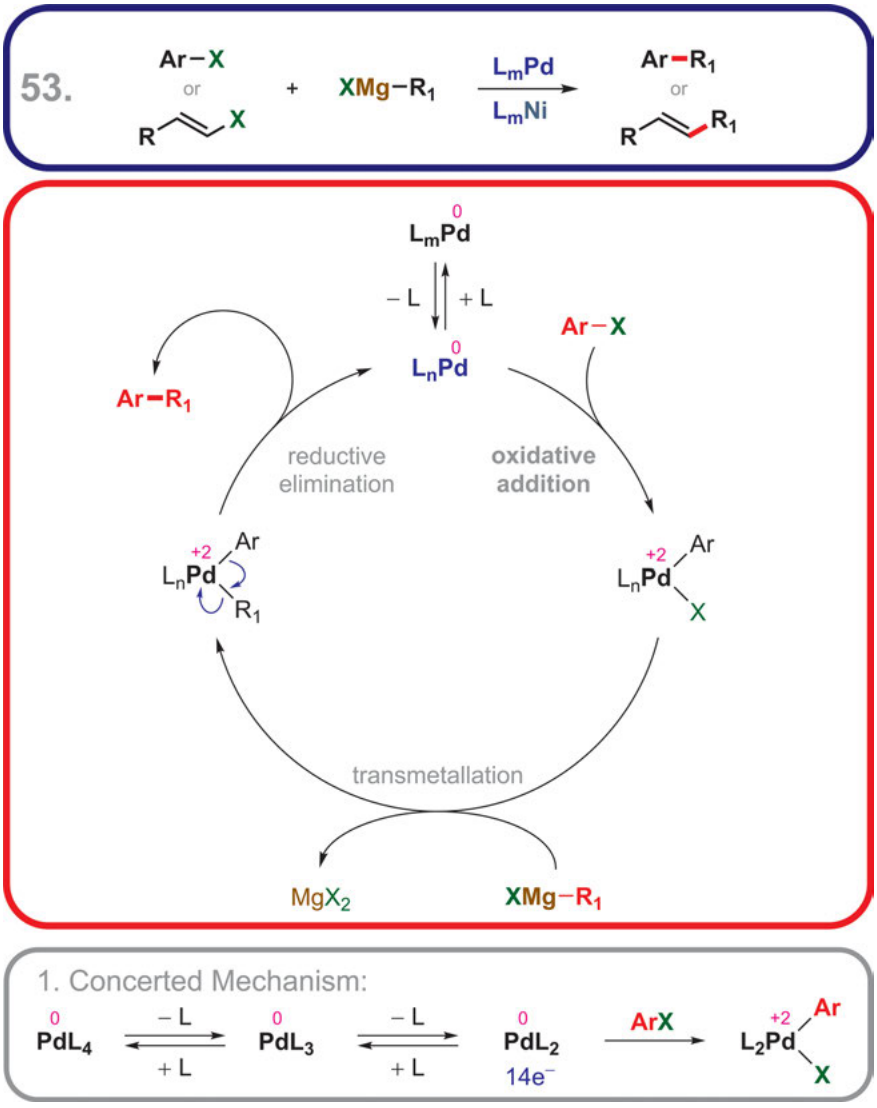


Fig. 53.1: The **Pd**-catalyzed ***Kumada*** *cross coupling* mechanism.[165]

165 The ***Kumada*** *cross coupling* (or the ***Kumada–Corriu*** cross coupling) is a type of ***Pd****-catalyzed cross coupling* reaction (C–C bond formation using *aryl halides* and the ***Grignard*** *reagent = organomagnesium compound*). For teaching purposes, a simplified and general mechanism is shown. Note, (1) *concerted oxidative addition* step to a low-coordinate ($14e^-$) **Pd**-complex is more complicated [2a].

https://doi.org/10.1515/9783110608373-053

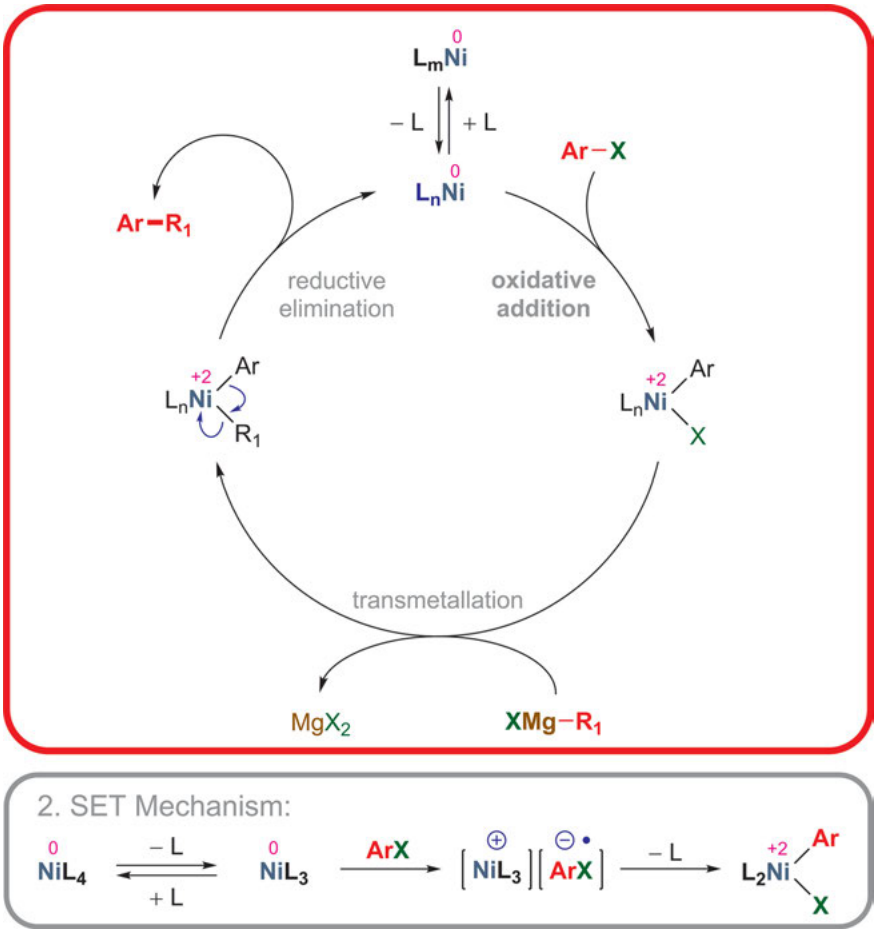


Fig. 53.2: The **Ni**-catalyzed ***Kumada*** *cross coupling* mechanism.[166]

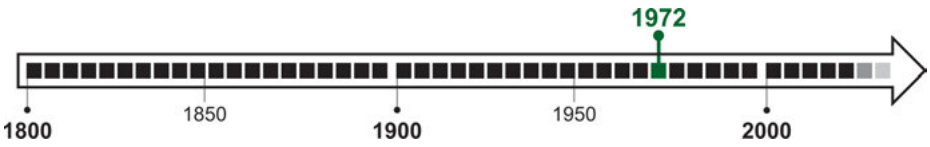


Fig. 53.3: The discovery of the ***Kumada*** *cross coupling*.[167]

166 The ***Kumada*** *cross coupling* can be ***Ni****-catalyzed*. Note, a possible example of a (2) *SET oxidative addition* step to a **Ni**-complex (not necessarily at play in the example shown) [2a].

167 The reaction was likely first described around 1972 [53].

54 Ley–Griffith Oxidation

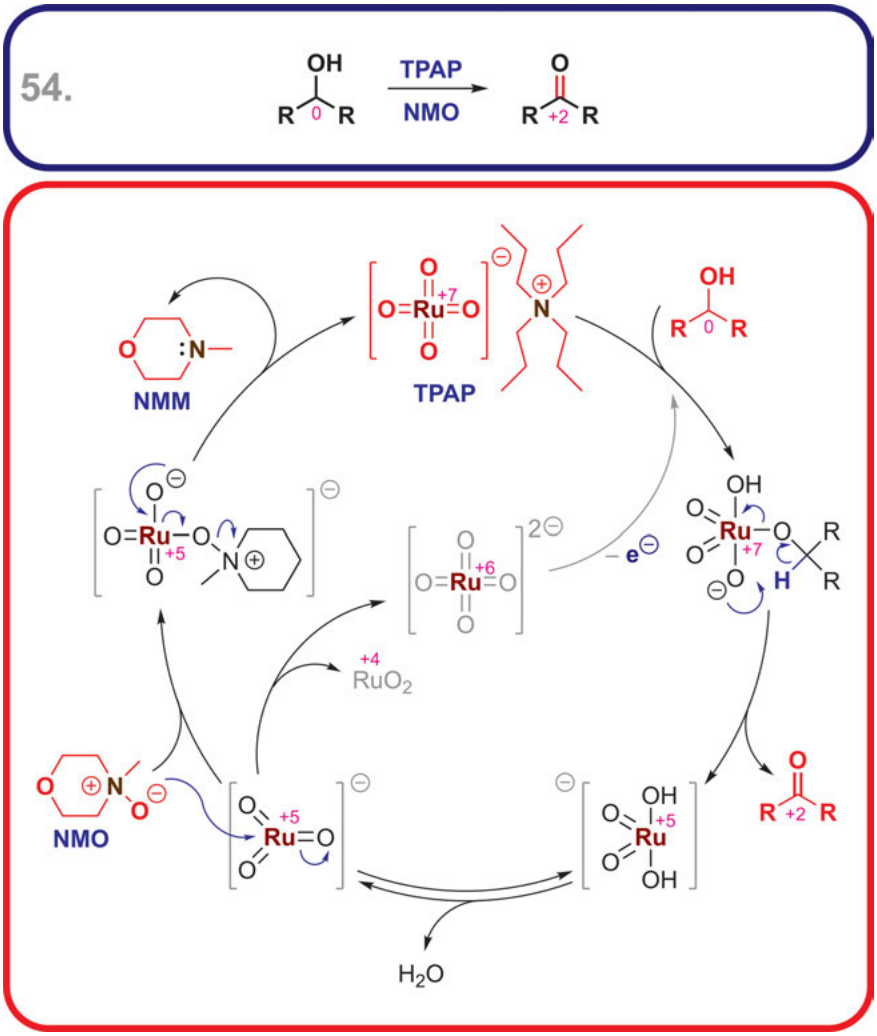


Fig. 54.1: The ***Ley–Griffith*** *oxidation* mechanism.[168]

168 The ***Ley–Griffith*** *oxidation* is based on the use of a named reagent: the ***Ley–Griffith*** *reagent* (**TPAP**) [54a].

https://doi.org/10.1515/9783110608373-054

Fig. 54.2: Reactions related to the ***Ley–Griffith*** *oxidation*.[169]

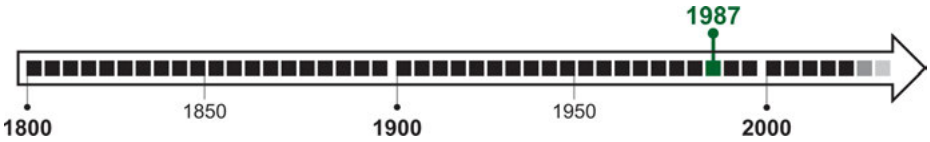


Fig. 54.3: The discovery of the ***Ley–Griffith*** *oxidation*.[170]

169 The ***Upjohn*** *dihydroxylation* (covered in Chapter 93) is related to the ***Ley–Griffith*** *oxidation*.
170 The reaction was likely first described around 1987 [54b].

55 Liebeskind–Srogl Cross Coupling

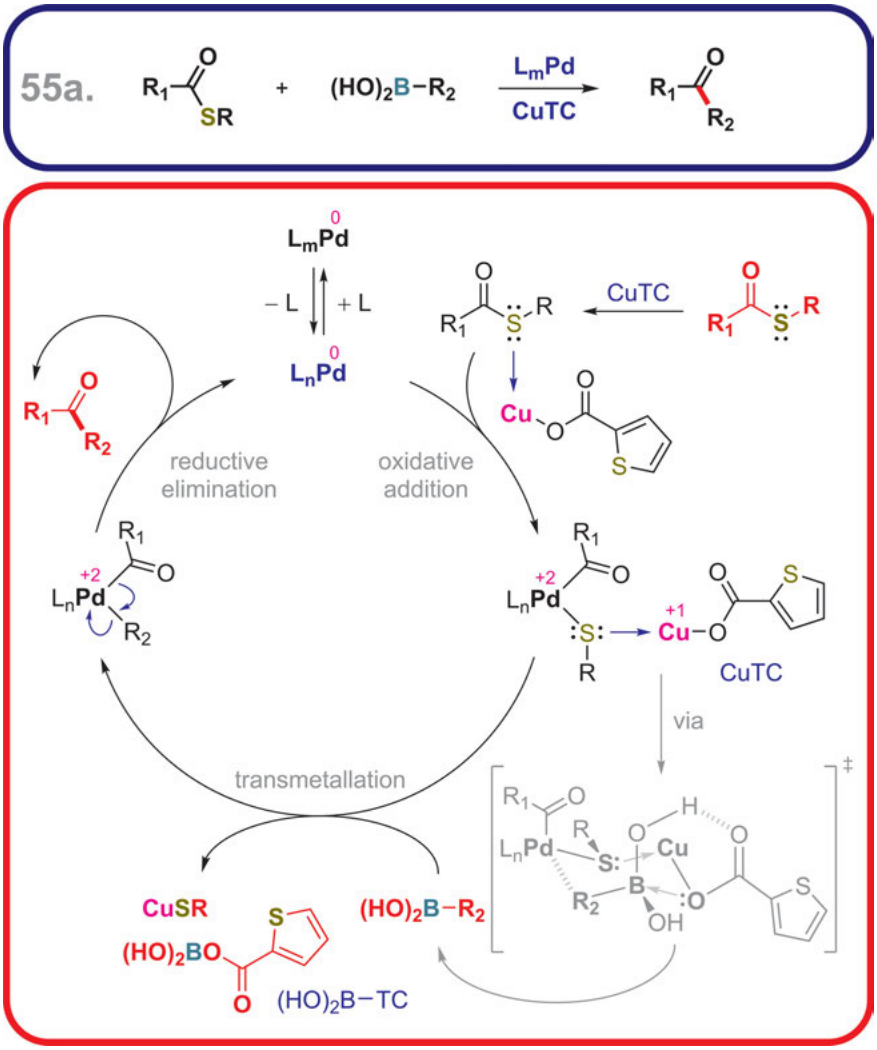


Fig. 55.1: The ***Liebeskind–Srogl*** *cross coupling* (thioesters) mechanism.[171]

171 The ***Liebeskind–Srogl*** *cross coupling* of *thioesters* is a type of ***Pd****-catalyzed cross coupling* reaction (C–C bond formation using *thioesters* and *boronic acids*). For teaching purposes, only a simplified general mechanism is shown.

https://doi.org/10.1515/9783110608373-055

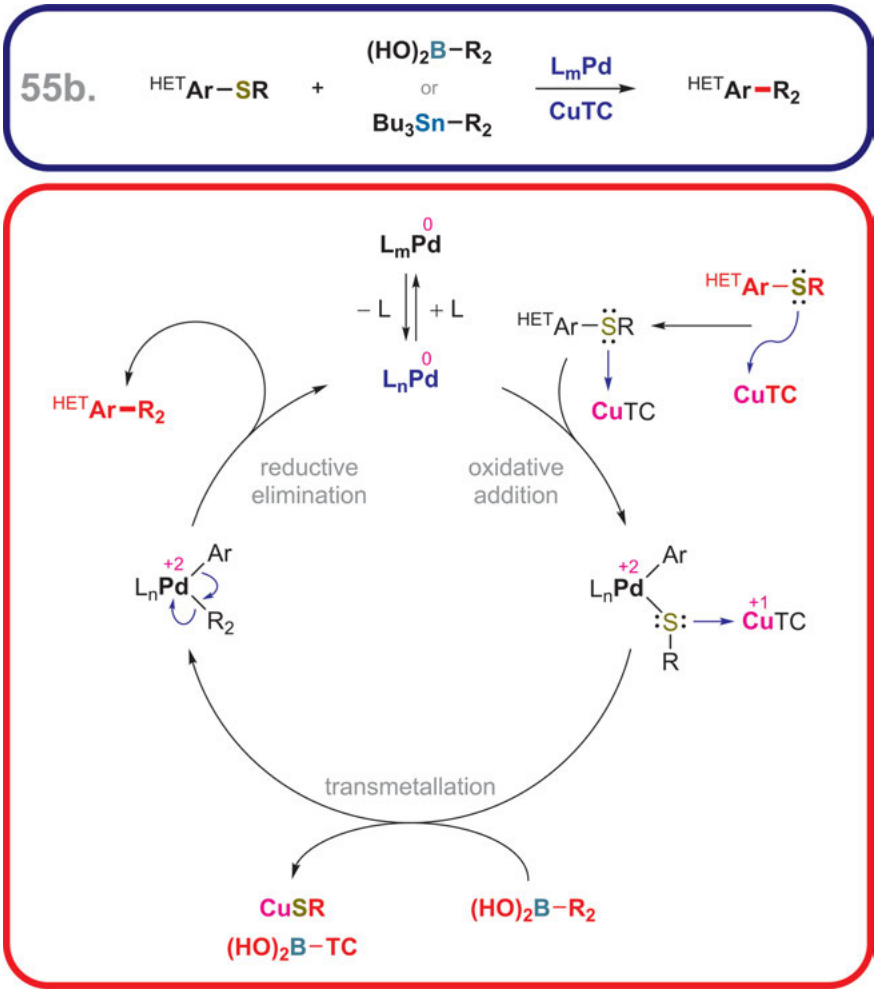


Fig. 55.2: The ***Liebeskind–Srogl*** *cross coupling* (thioethers) mechanism.[172]

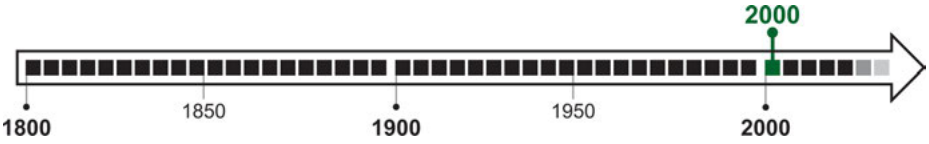


Fig. 55.3: The discovery of the ***Liebeskind–Srogl*** *cross coupling*.[173]

172 The ***Liebeskind–Srogl*** *cross coupling* of *thioethers* is a variation (C–C bond formation using *thioethers (ArSR)* and *boronic acids* or *organotin reagents = organostannanes*). For teaching purposes, only a simplified general mechanism is shown.

173 The reaction was likely first described around 2000 [55].

56 Mannich Reaction

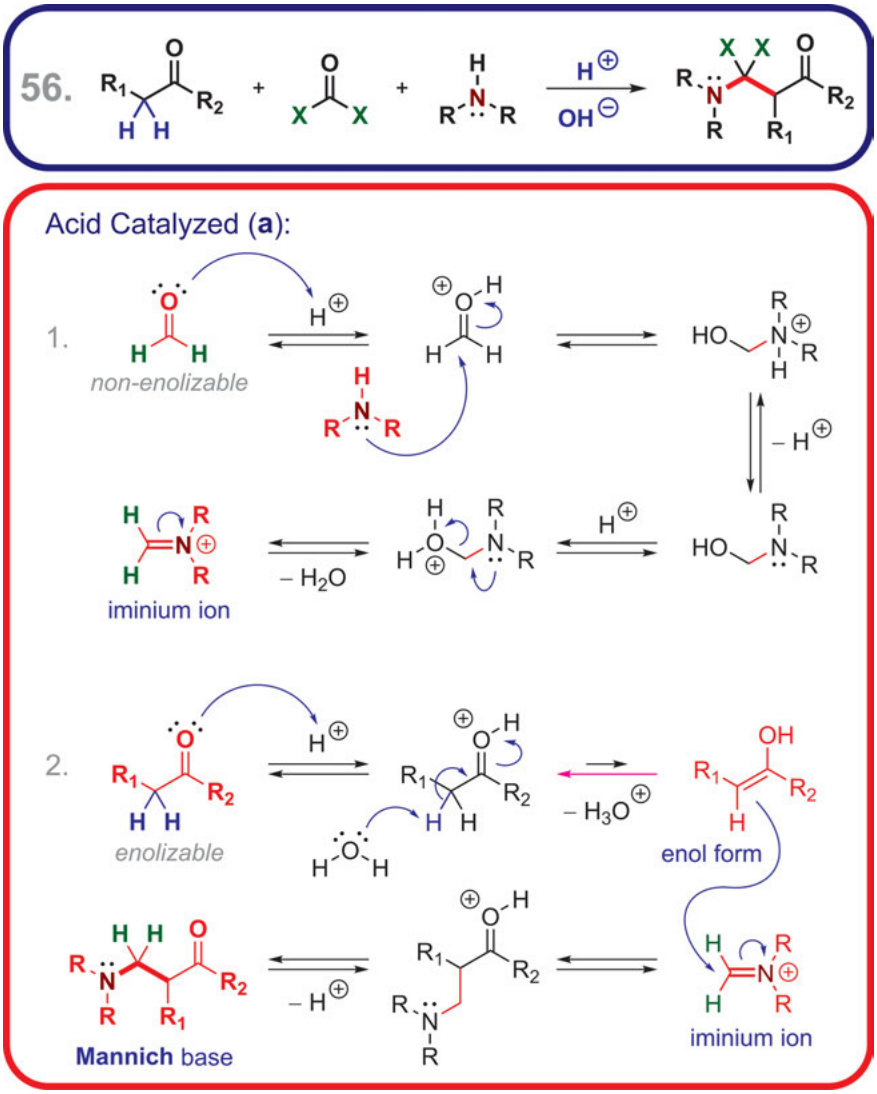


Fig. 56.1: The ***Mannich*** *reaction* mechanism (acid catalyzed).[174]

174 The ***Mannich*** *reaction* is also known as *the* ***Mannich*** *condensation.* This three-component reaction (3-CR) can be catalyzed in (a) acidic media (via an *iminium ion* intermediate). The final product (β–amino carbonyl) is also called a ***Mannich*** *base.*

https://doi.org/10.1515/9783110608373-056

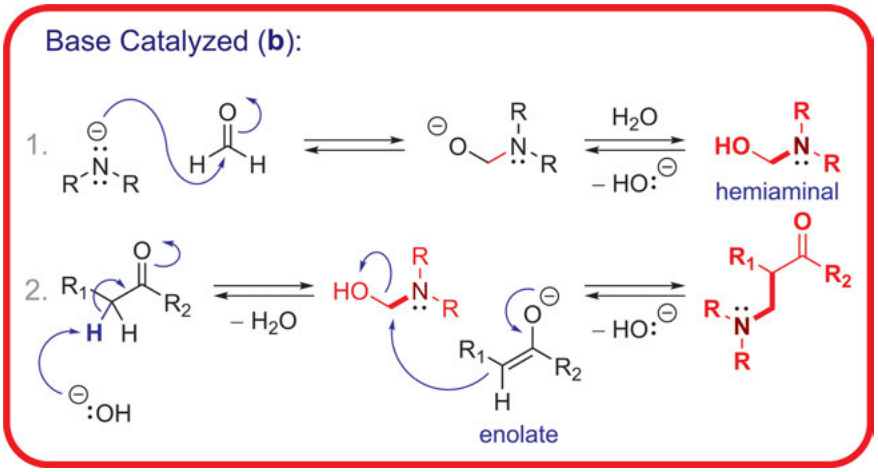


Fig. 56.2: The ***Mannich*** *reaction* mechanism (base catalyzed).[175]

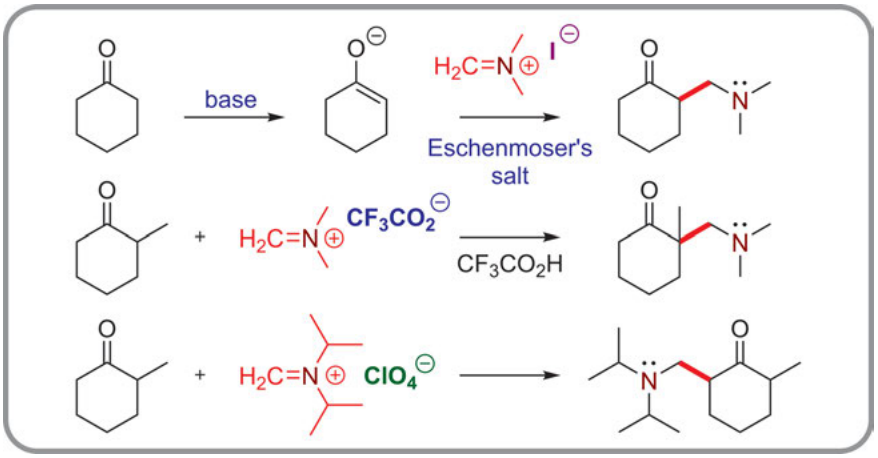


Fig. 56.3: Variations of the ***Mannich*** *reaction*.[176]

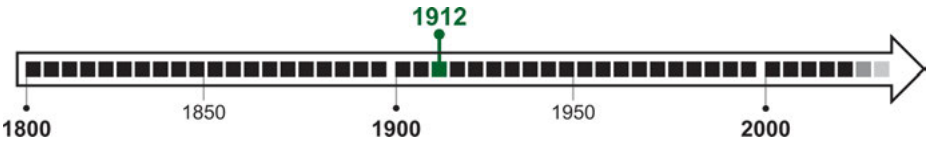


Fig. 56.4: The discovery of the ***Mannich*** *reaction*.[177]

175 The ***Mannich*** *reaction* can be also catalyzed in (b) basic media (via a *hemiaminal* intermediate).
176 There are several iterations of the ***Mannich*** *reaction* based on availability of the preformed iminium ions: ***Eschenmoser's*** *salts* or ***Böhme's*** *salts* (not shown here) [56a].
177 The reaction was likely first described around 1912 [56b].

57 McMurry Coupling

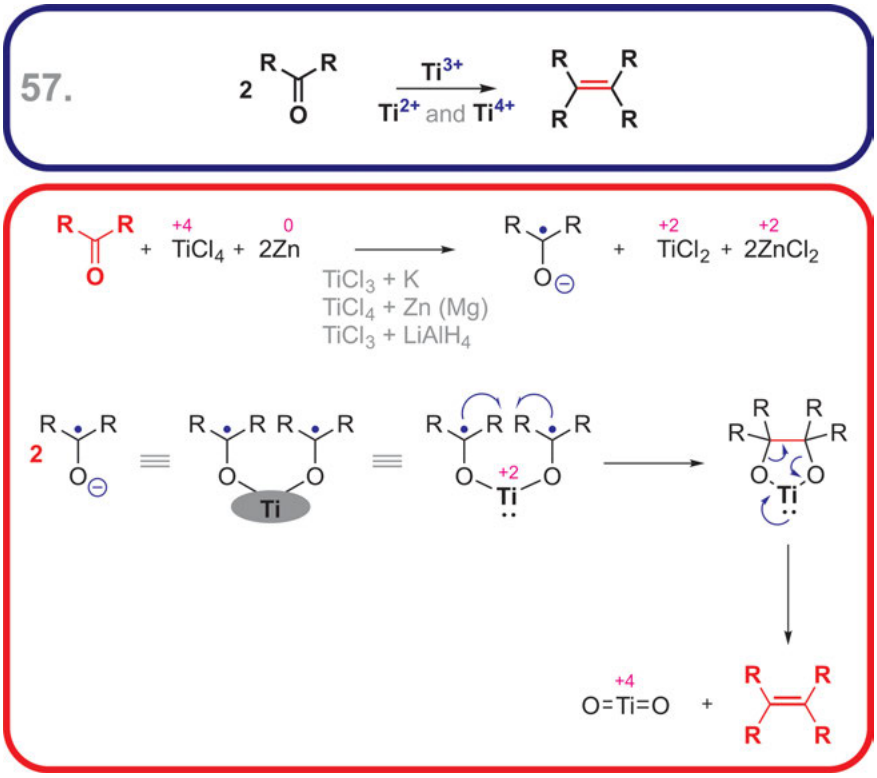


Fig. 57.1: The ***McMurry*** *coupling* mechanism.[178]

178 The ***McMurry*** *coupling* or the ***McMurry*** *reaction* mechanism is not fully understood. It is believed the *low-valent titanium* species play a major role: Ti (0) + Ti (II) + Ti (III).

https://doi.org/10.1515/9783110608373-057

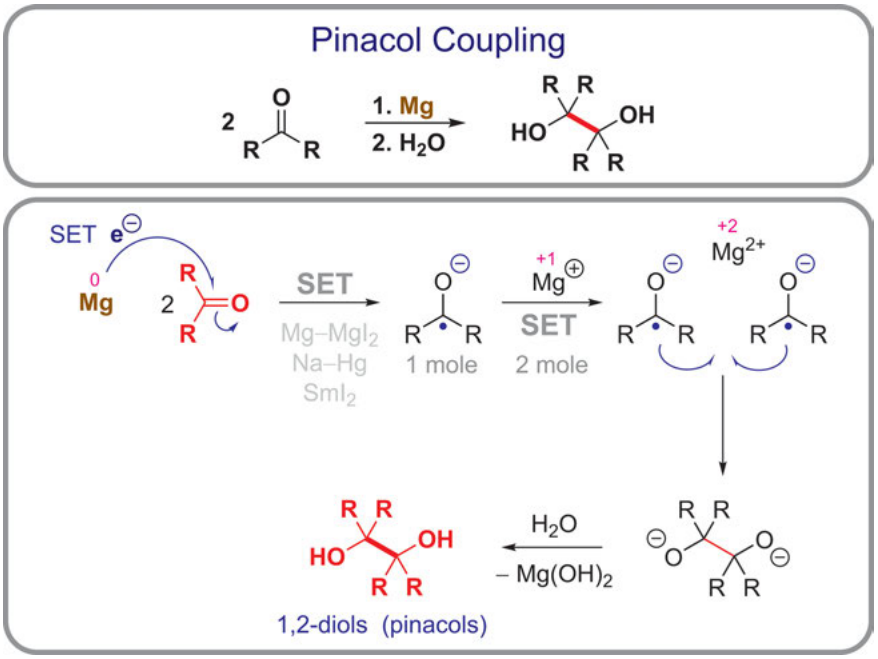


Fig. 57.2: The *pinacol coupling* mechanism.[179]

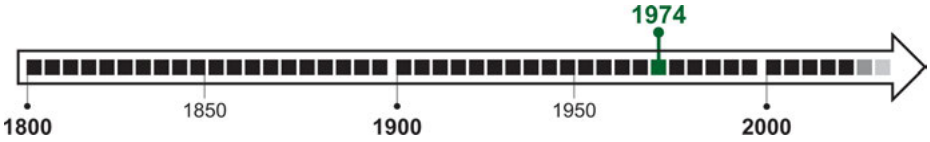


Fig. 57.3: The discovery of the ***McMurry*** *coupling*.[180]

179 The *pinacol coupling* undergoes a **single electron transfer** (SET) mechanism [57a, 57b]. This reaction is related to the ***McMurry*** *coupling* and the *acyloin condensation* (covered in Chapter 7). Please do not confuse the *pinacol coupling* with the *pinacol-pinacolone rearrangement* covered in Chapter 76.
180 The reaction was likely first described around 1974 [57c].

58 Meerwein–Ponndorf–Verley Reduction

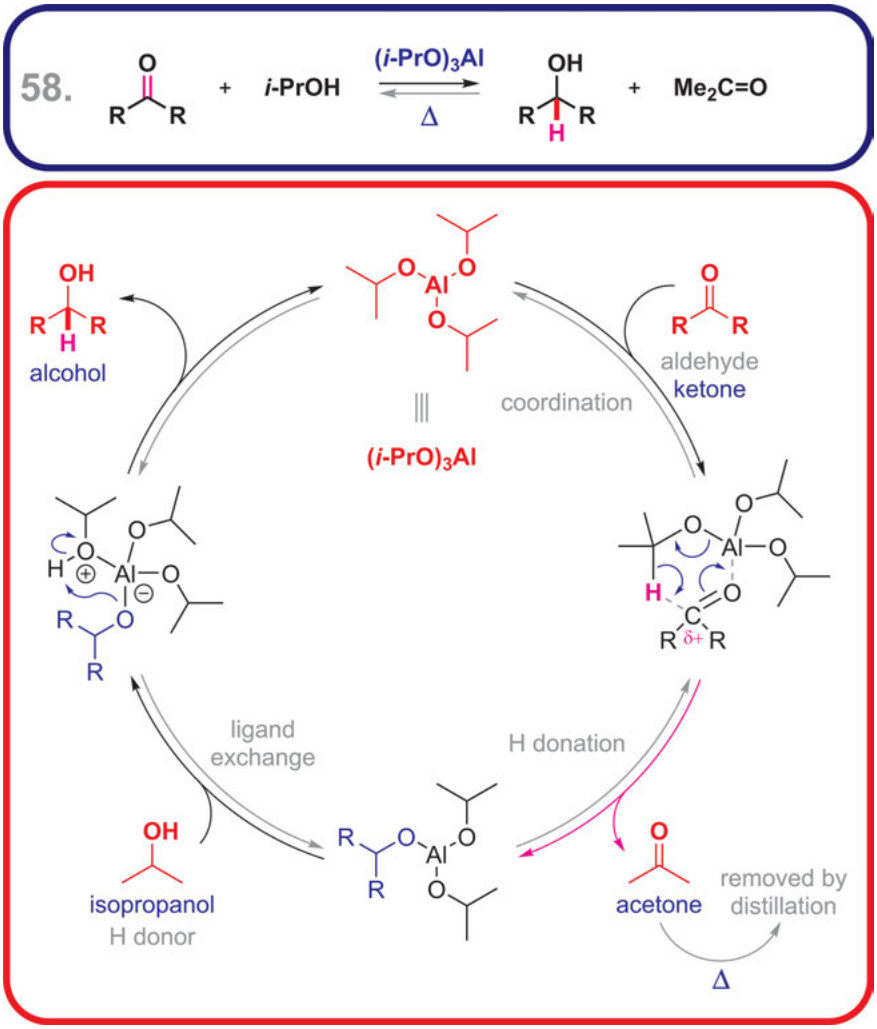


Fig. 58.1: The ***Meerwein–Ponndorf–Verley*** *reaction* mechanism.[181]

181 The ***Meerwein–Ponndorf–Verley*** *(MPV) reduction* is reversible. The reversed oxidation is called the ***Oppenauer*** *oxidation*. The equilibrium can be shifted towards reduction by removing formed *acetone* from the reaction mixture (via distillation).

https://doi.org/10.1515/9783110608373-058

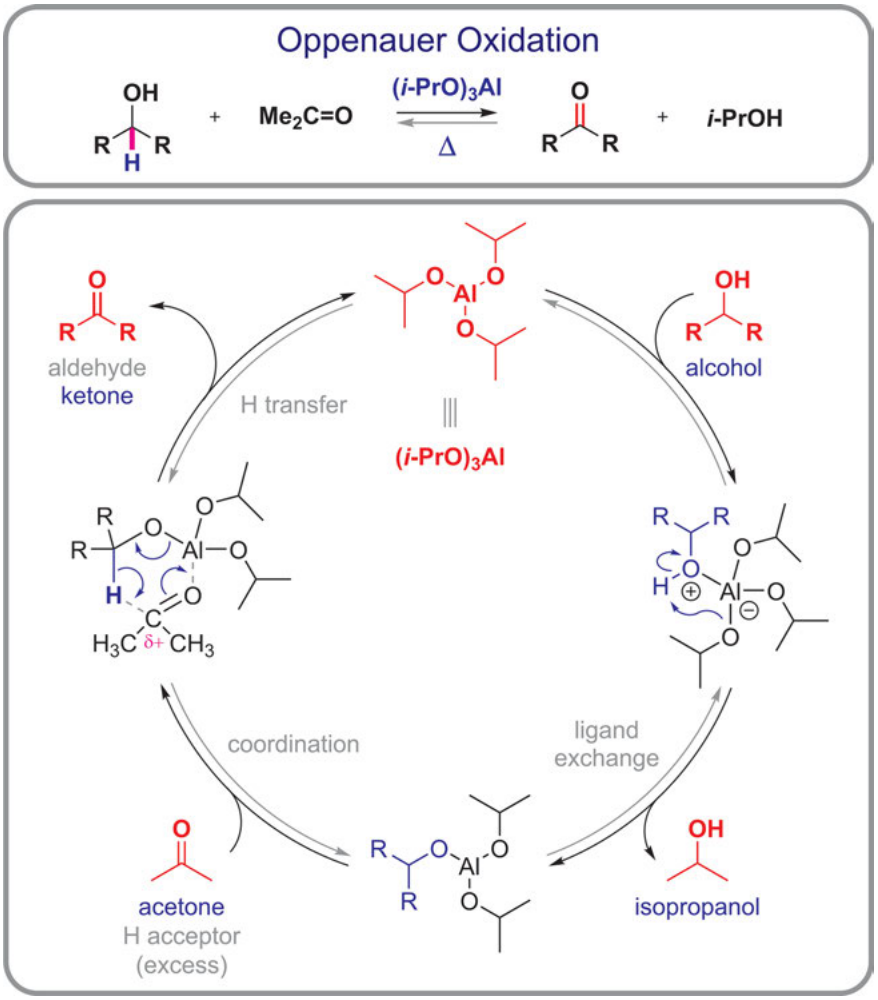


Fig. 58.2: The ***Oppenauer*** *oxidation* mechanism.[182]

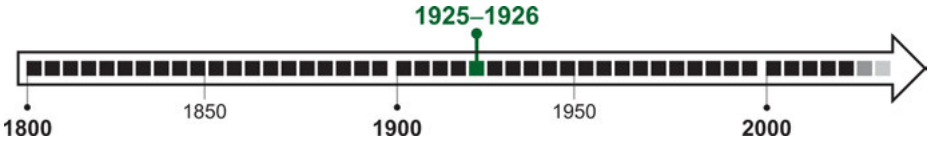


Fig. 58.3: The discovery of the ***Meerwein–Ponndorf–Verley*** *reaction*.[183]

182 The ***Oppenauer*** *oxidation* is a reversed process of the ***MPV*** *reduction* (see Chapter 69).

183 The reaction was likely first described around 1925 by Meerwein and Verley [58a, 58b], and then in 1926 by Ponndorf [58c].

59 Michael Addition

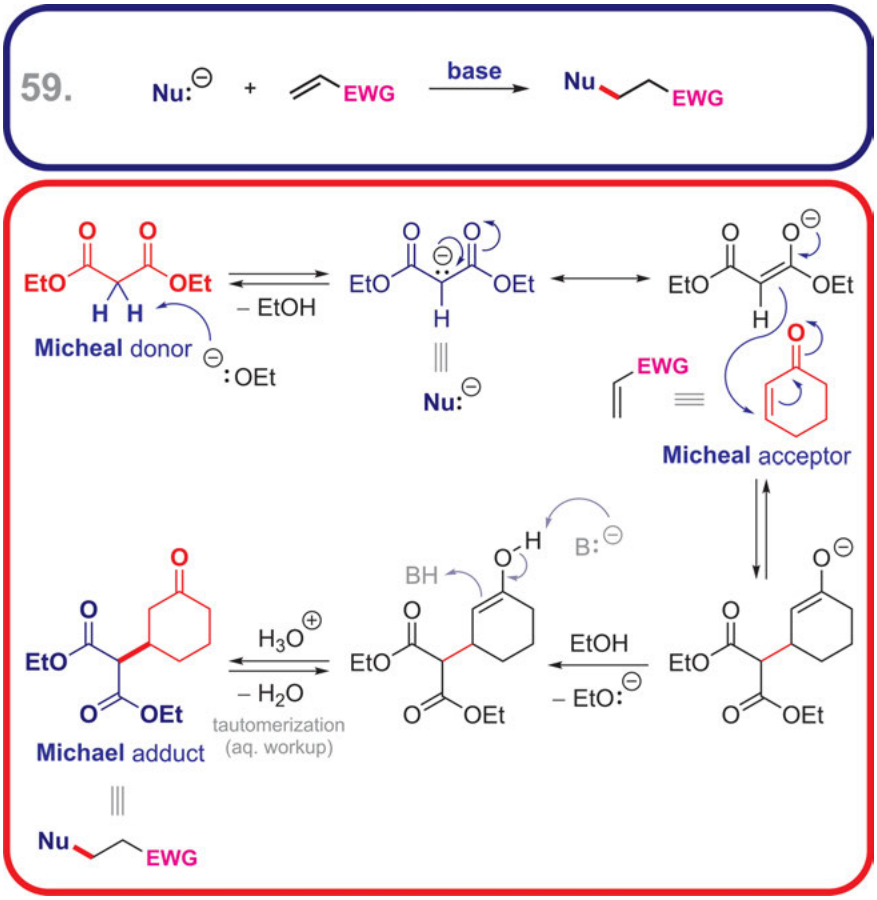


Fig. 59.1: The ***Michael*** *addition* mechanism.[184]

184 The ***Michael*** *addition* or the ***Michael*** *conjugate addition* is also simply called *the* ***Michael*** *reaction*. The products are known as ***Michael*** *adducts*. It is one of the most important reactions in organic chemistry.

https://doi.org/10.1515/9783110608373-059

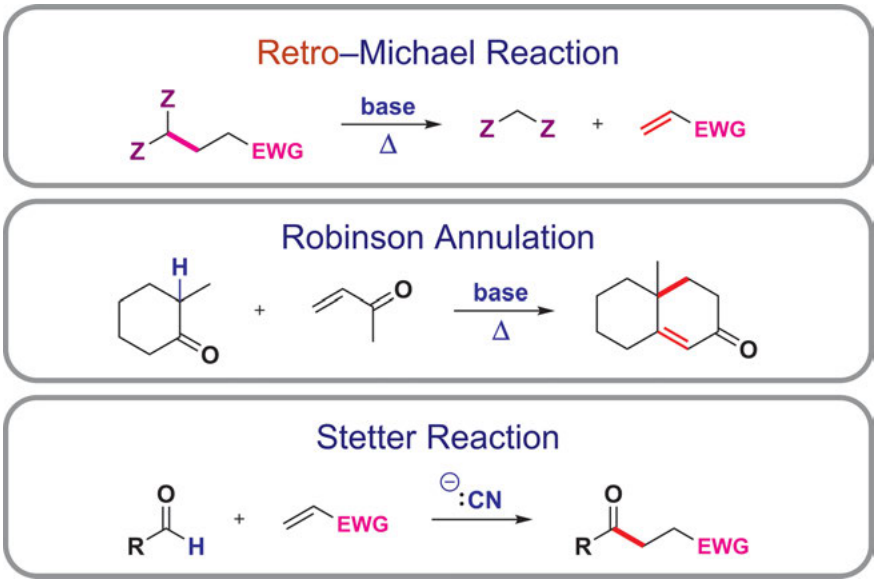


Fig. 59.2: Reactions related to the ***Michael*** *addition*.[185]

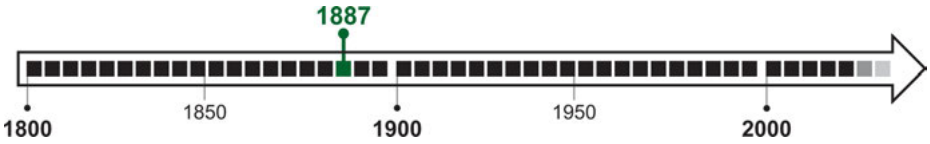


Fig. 59.3: The discovery of the ***Michael*** *addition*.[186]

185 There are variations of this reaction; for example, the *retro-**Michael** addition* and the ***Robinson*** *annulation* (covered in Chapter 83). Please note, the mechanism of the ***Stetter*** *reaction* (not shown) [59a] is related to both the ***Michael*** *addition* and to the *benzoin condensation* (covered in Chapter 15).
186 The reaction was likely first described around 1887 [59b].

60 Minisci Reaction

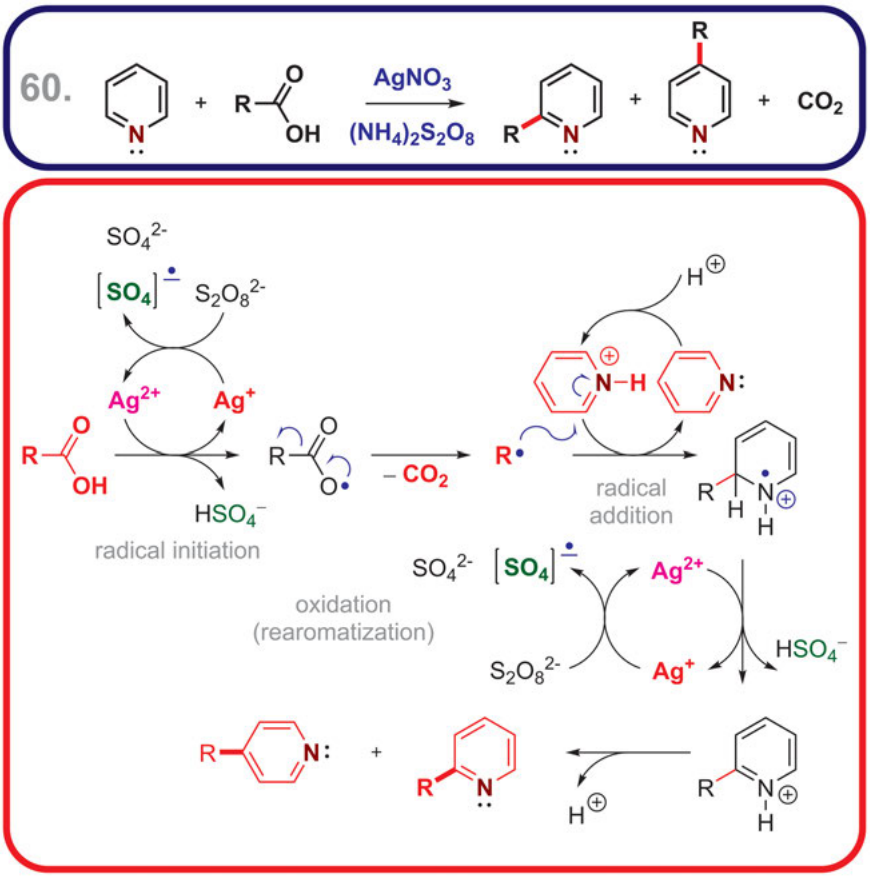


Fig. 60.1: The ***Minisci*** *reaction* mechanism.[187]

187 The ***Minisci*** *reaction* is a type of **free radical substitution** (not covered in this book). The closely related mechanistic examples are the $\mathbf{S_{RN}1}$ mechanism (covered in Chapter 5), the ***Barton*** *decarboxylation* (covered in Chapter 12), and the ***Wohl–Ziegler*** *reaction* (covered in Chapter 99).

https://doi.org/10.1515/9783110608373-060

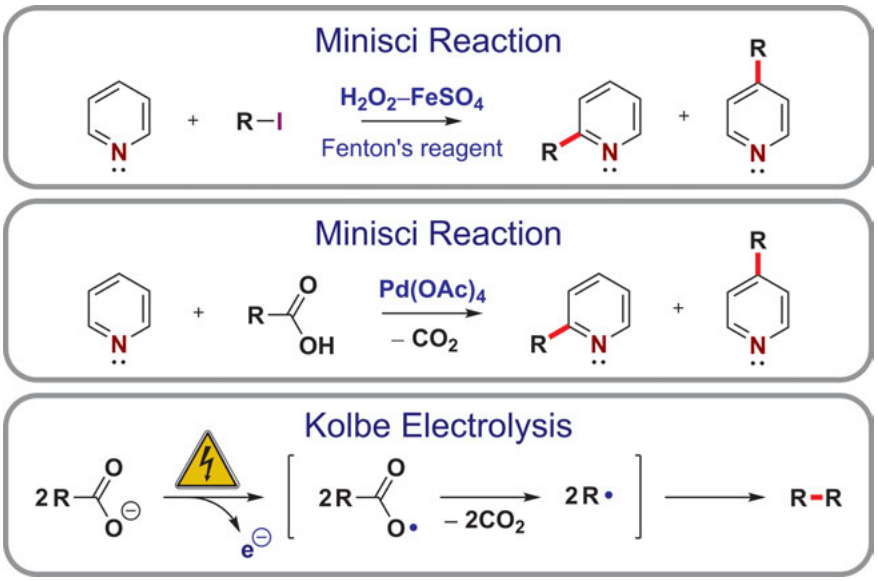


Fig. 60.2: Variations of the ***Minisci*** *reaction*.[188]

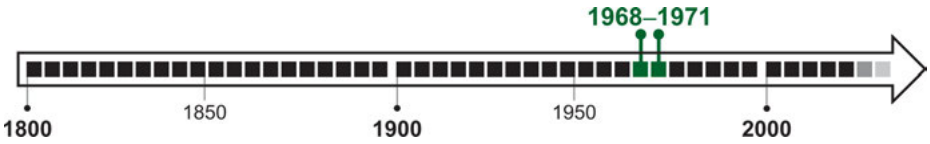


Fig. 60.3: The discovery of the ***Minisci*** *reaction*.[189]

188 There are several variations of the ***Minisci*** *reaction* depending on the free radical sources: ***Fenton's*** *reagent* [60a] and alkyl iodides; lead (IV) acetate [60b] and carboxylic acids. The ***Kolbe*** *electrolysis* or the ***Kolbe*** *reaction* is also related [60c].

189 The reaction was likely first described between 1968–1971 [60d, 60e].

61 Mitsunobu Reaction

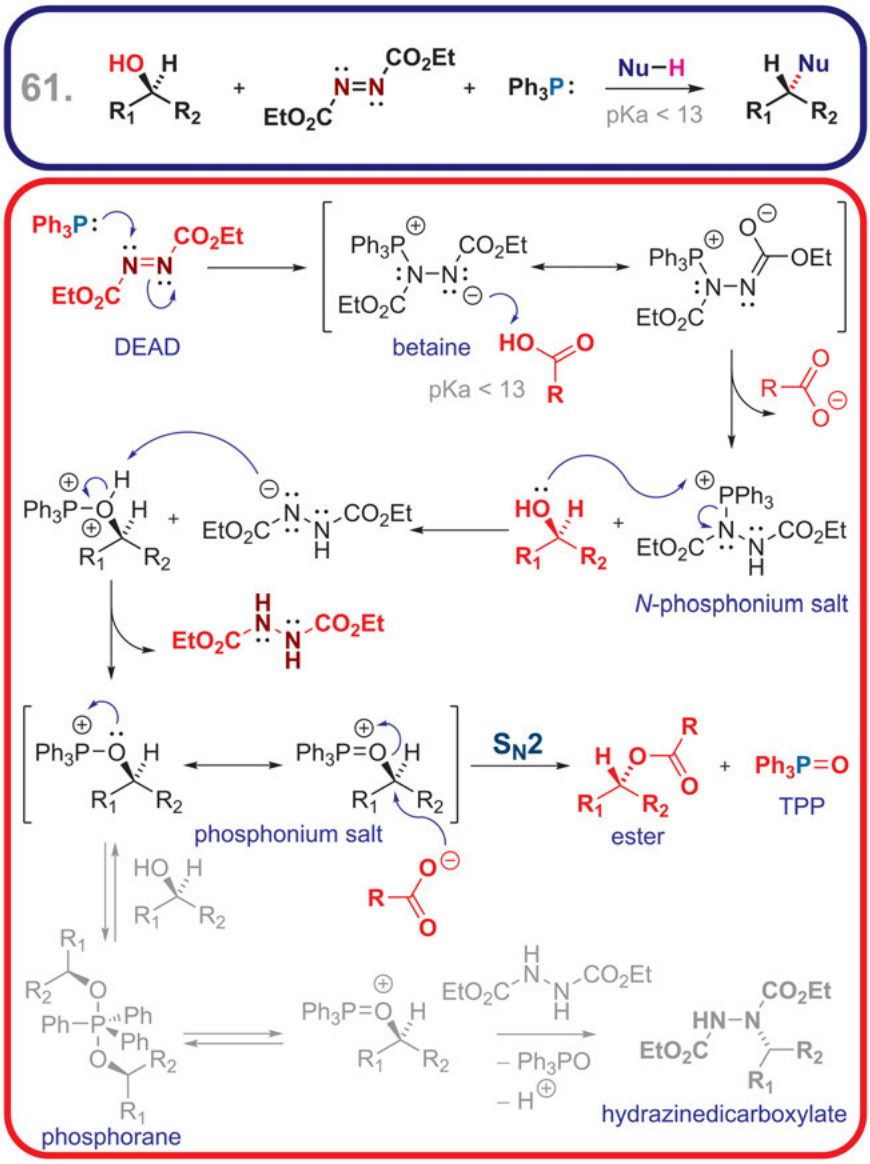


Fig. 61.1: The ***Mitsunobu*** *reaction* mechanism.[190]

190 The ***Mitsunobu*** *reaction* mechanism is complicated but related to the (aliphatic) **nucleophilic substitution** (S_N2) covered in Chapter 2. Note, the pK_a of the NuH acid should be generally < 13 [61a].

https://doi.org/10.1515/9783110608373-061

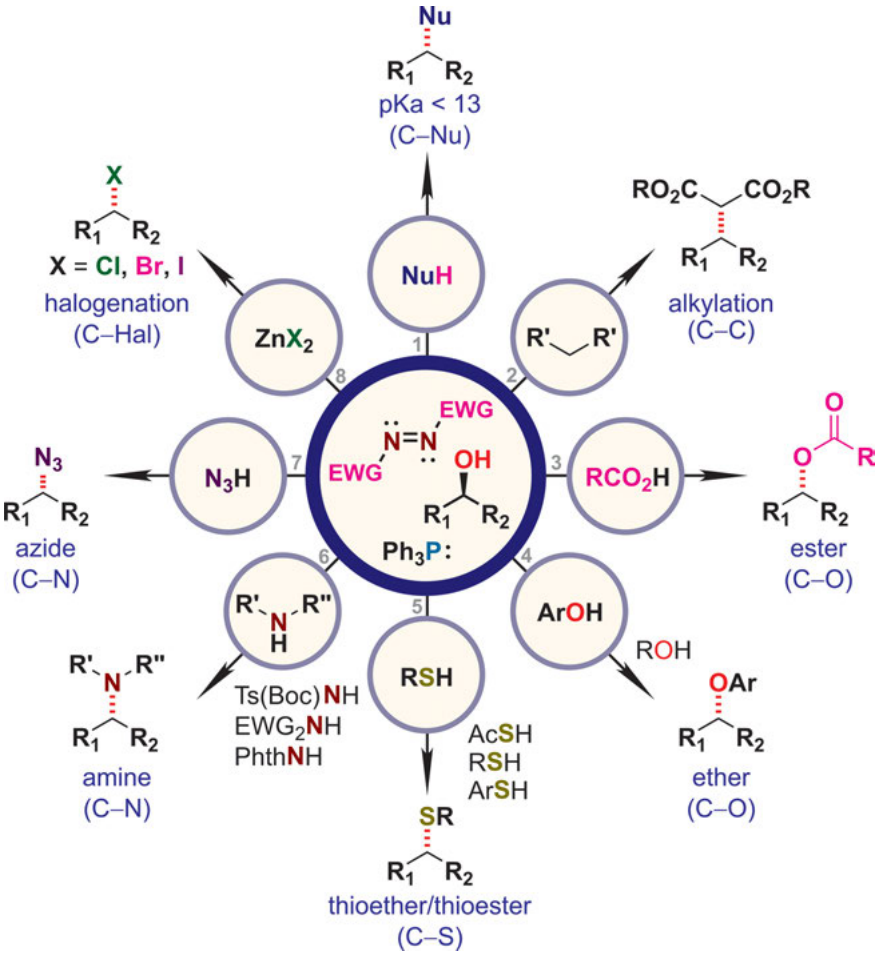


Fig. 61.2: Synthetic versatility of the ***Mitsunobu*** *reaction*.[191]

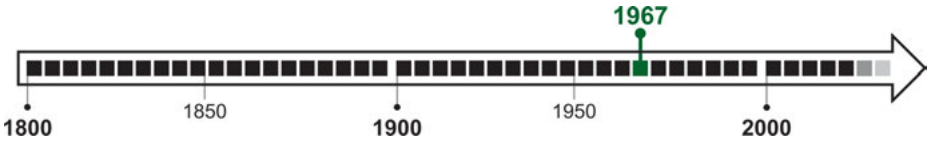


Fig. 61.3: The discovery of the ***Mitsunobu*** *reaction*.[192]

191 The ***Mitsunobu*** *reaction* has wide synthetic application and can convert alcohols into various products using different nucleophiles (Nu): 1. R–Nu, $pK_a < 13$; 2. alkylated products C–C; 3. esters C–O; 4. ethers C–O; 5. thioethers or thioesters C–S; 6. amines C–N; 7. azides C–N; 8. alkyl halides C–X; and others [61b, 61c].

192 The reaction was likely first described around 1967 [61d, 61e].

62 Miyaura Borylation

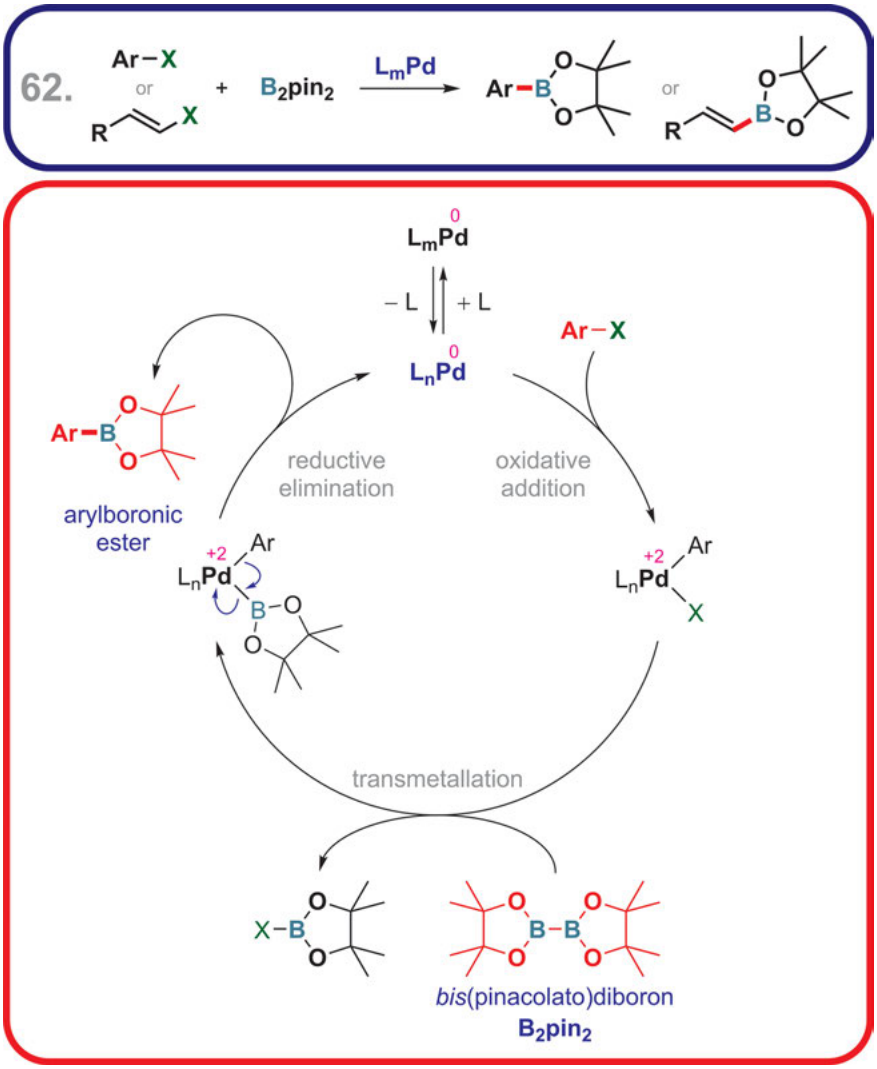


Fig. 62.1: The ***Miyaura*** *borylation* mechanism.[193]

193 The ***Miyaura*** *borylation* is a type of **Pd**-*catalyzed cross coupling* reaction (C–B bond formation using *aryl halides* and *bis(pinacolato)diboron* or $\mathbf{B_2pin_2}$ [62a]). For teaching purposes, a simplified and general mechanism is shown. The synthesized *boronic esters* (and their related *boronic acids*) are one of the most important reagents in synthetic organic and medicinal chemistry.

https://doi.org/10.1515/9783110608373-062

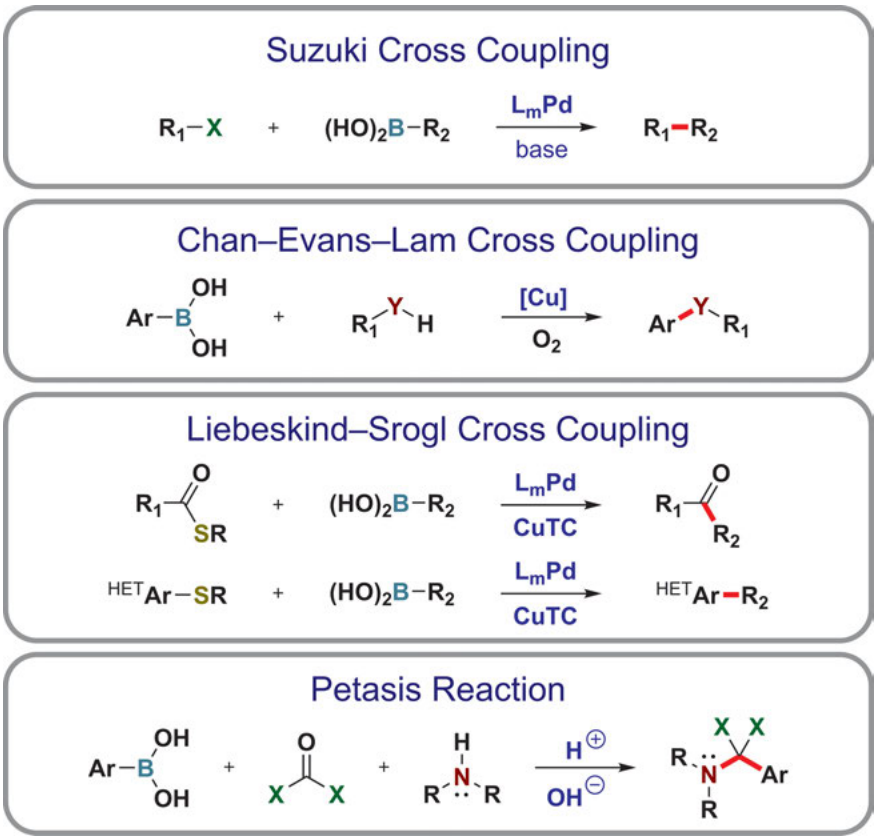


Fig. 62.2: Synthetic application of boronic esters and acids.[194]

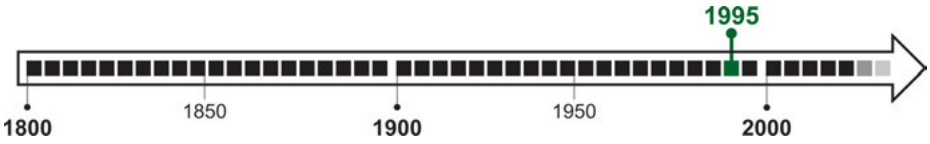


Fig. 62.3: The discovery of the ***Miyaura*** *borylation*.[195]

194 Many *key cross-coupling* reactions utilize *boronic esters* (and their related *boronic acids*): the ***Suzuki*** *cross coupling* (covered in Chapter 89), the ***Chan–Evans–Lam*** *cross coupling* (covered in Chapter 23), ***Liebeskind–Srogl*** *cross coupling* (covered in Chapter 55). The ***Petasis*** *reaction* is a mechanistically different three-component (3-CR) reaction, but it uses boronic acids as well [62b].

195 The reaction was likely first described around 1995 [62c].

63 Mukaiyama RedOx Hydration

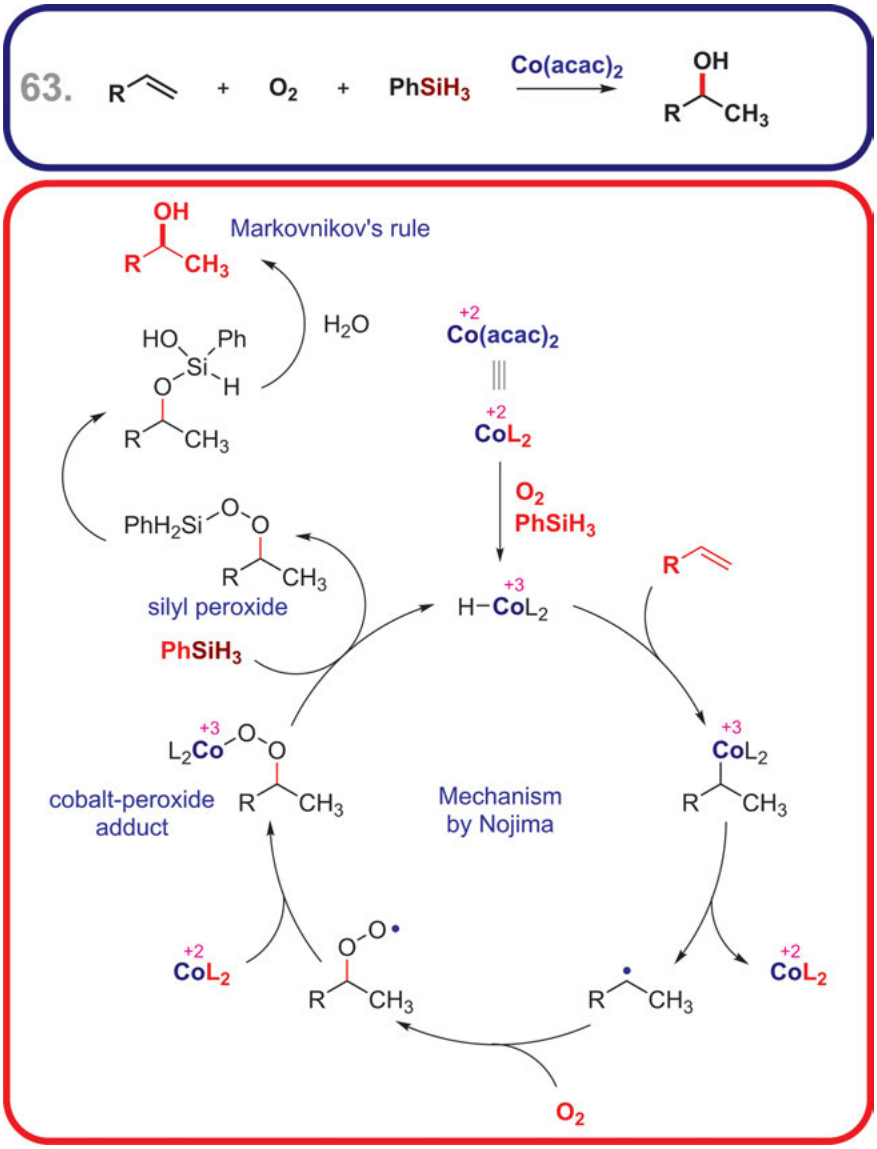


Fig. 63.1: The ***Mukaiyama*** *RedOx hydration* mechanism by **Nojima**.[196]

196 The revised ***Mukaiyama*** *RedOx hydration* mechanism is recently proposed by **Nojima** [63a].

https://doi.org/10.1515/9783110608373-063

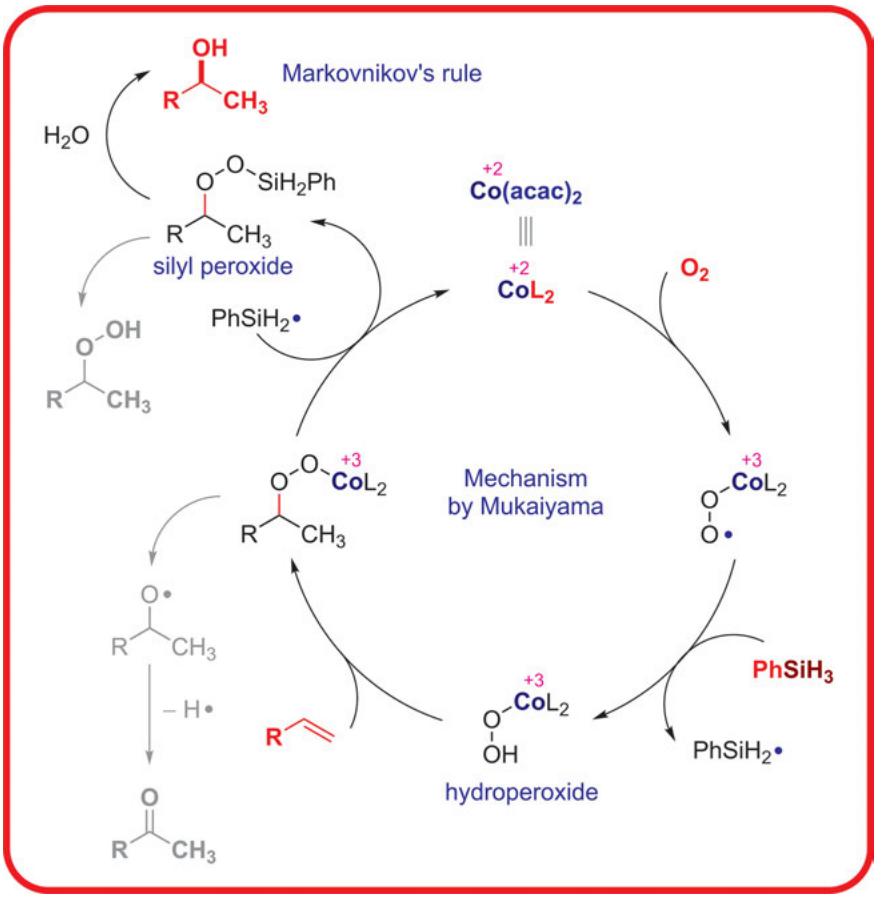


Fig. 63.2: The ***Mukaiyama*** *oxidation-reduction hydration* mechanism by **Mukaiyama**.[197]

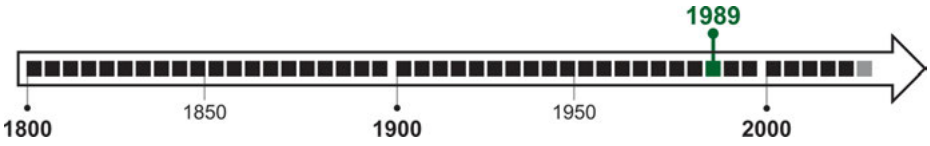


Fig. 63.3: The discovery of the ***Mukaiyama*** *oxidation-reduction hydration*.[198]

197 The original ***Mukaiyama*** *oxidation-reduction hydration* mechanism by **Mukaiyama** [63b, 63c, 63d]. The ***Mukaiyama*** *oxidation-reduction hydration* should not be confused with the ***Mukaiyama*** *aldol addition reaction* (not shown here). The reaction follows *Markovnikov's rule*. The ***Mukaiyama*** *oxidation-reduction hydration* is a safe alternative to the *oxymercuration-reduction reaction* (Chapter 20 and 52).

198 The reaction was likely first described around 1989 [63b, 63c, 63d].

64 Nazarov Cyclization

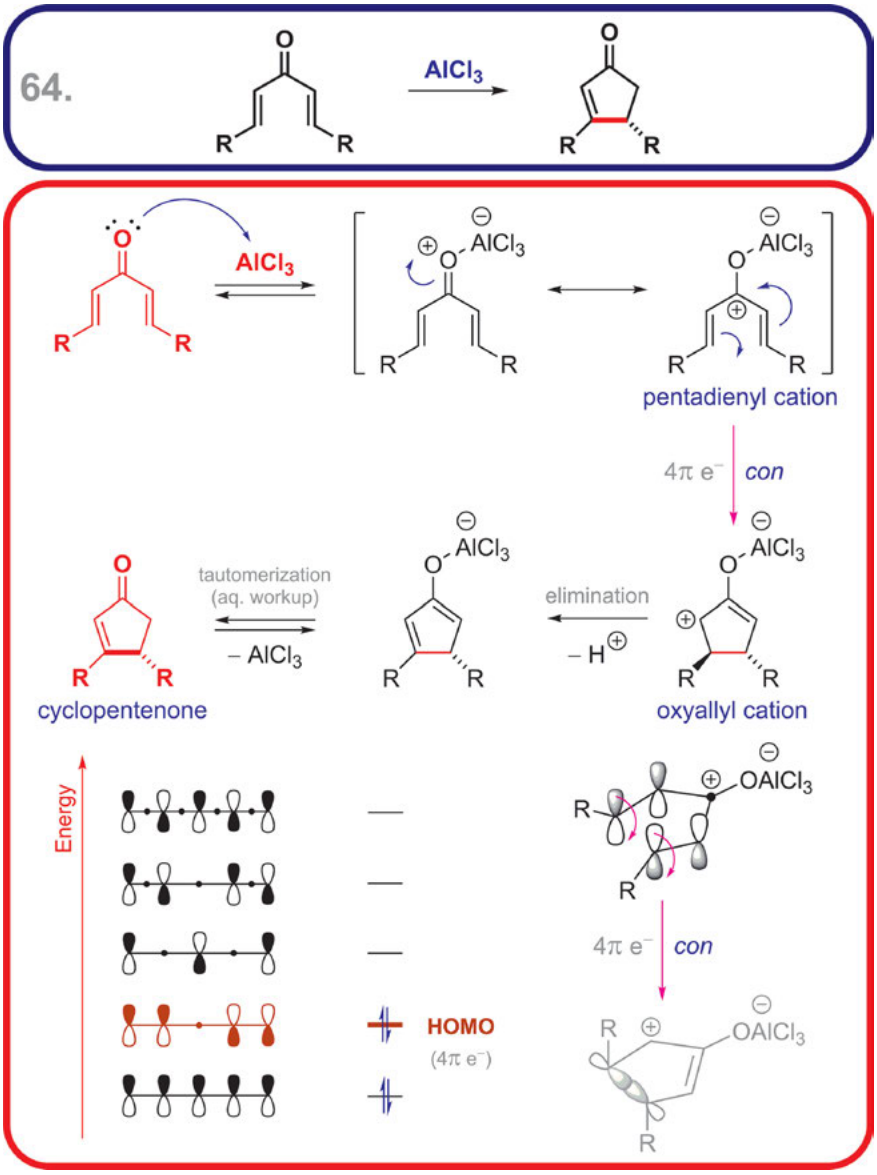


Fig. 64.1: The ***Nazarov*** *cyclization* mechanism.[199]

199 The ***Nazarov*** *cyclization reaction* is a pericyclic reaction with a concerted mechanism. This is an example of a [4π] ***con****rotatory electrocyclization*.

https://doi.org/10.1515/9783110608373-064

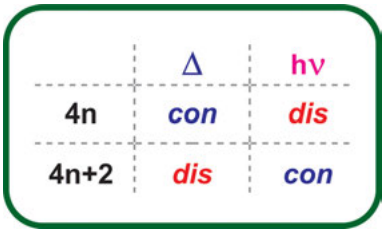


Fig. 64.2: The ***Woodward–Hoffmann*** *rules* (the pericyclic selection rules).[200]

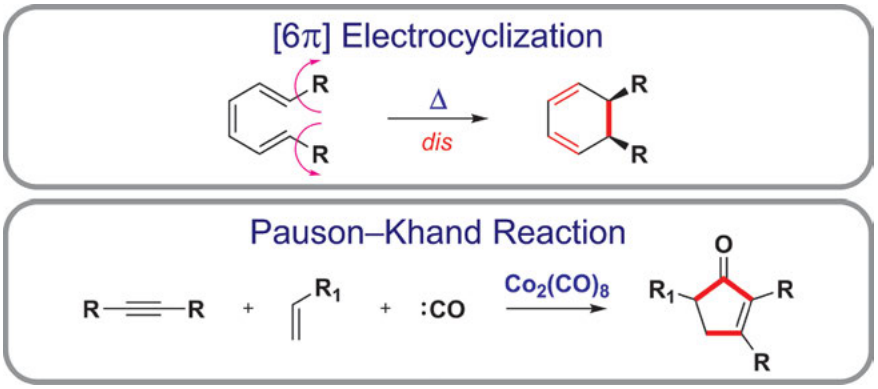


Fig. 64.3: Reactions related to the ***Nazarov*** *cyclization*.[201]

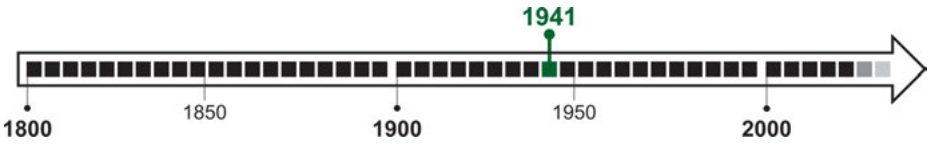


Fig. 64.4: The discovery of the ***Nazarov*** *cyclization*.[202]

200 The ***Woodward–Hoffmann*** *rules* (the pericyclic selection rules) [64a, 64b] for the *electrocyclization reactions*. Please note, the ***Nazarov*** *cyclization* is a ***con****rotatory* process (**4n** = 4π), which is allowed at the ground state = under thermal conditions or control (Δ). An example of [6π] *electrocyclization* below should be a ***dis****rotatory* process (**4n+2** = 6π), which is allowed at the ground state (Δ). The outcome at the excited state = under photochemical conditions or control (hν) should be reverse [64c].

201 There are numerous examples of other [4n] *electrocyclic* and [4n+2] *electrocyclic reactions*. The ***Pauson–Khand*** *reaction* (see Chapter 73) undergoes a different mechanism, but it also yields *cyclopentenones*.

202 The reaction was likely first described around 1941 [64d, 64e], see also [64f, 64g].

65 Nef Reaction

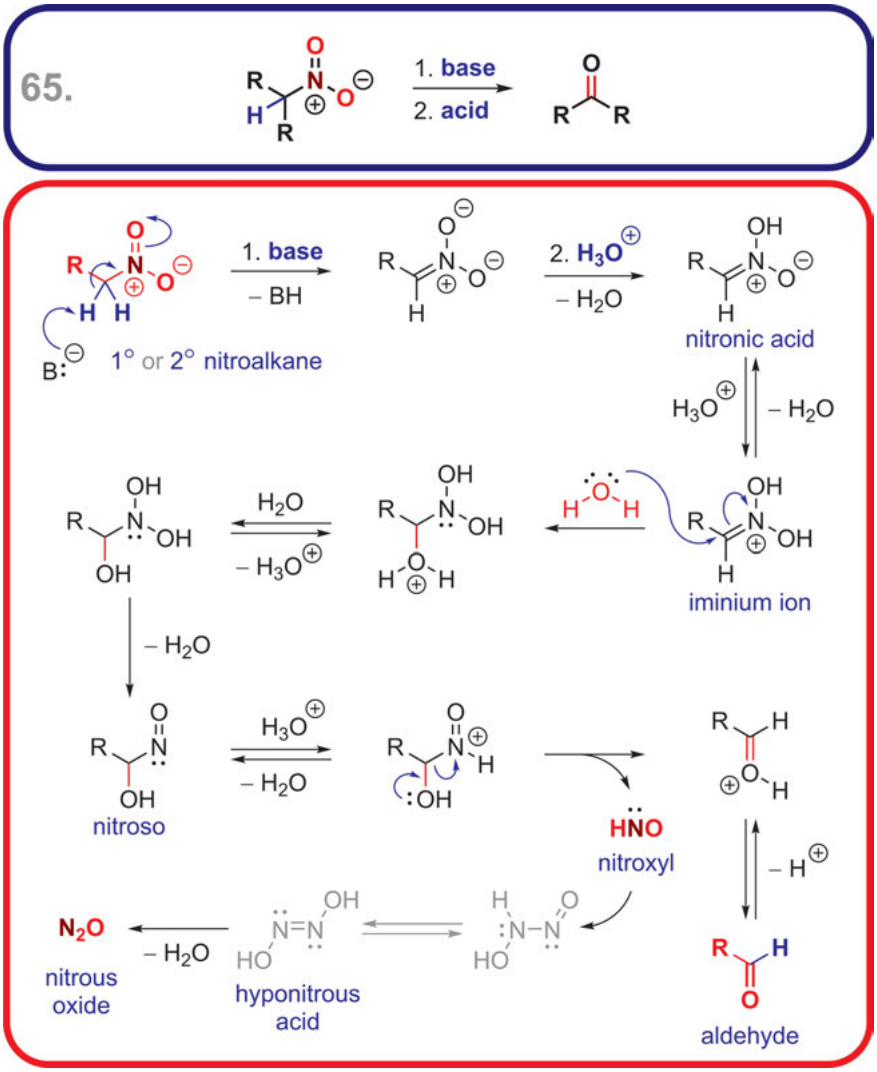


Fig. 65.1: The ***Nef*** *reaction* mechanism (base-acid-catalyzed).[203]

203 The classic ***Nef*** *reaction* is catalyzed by an acid and yields *aldehydes* and *ketones*. A base is needed to convert a primary (1°) or secondary (2°) *nitroalkane* into its conjugate base *(nitronic acid)*. The tertiary (3°) nitroalkanes do not react.

https://doi.org/10.1515/9783110608373-065

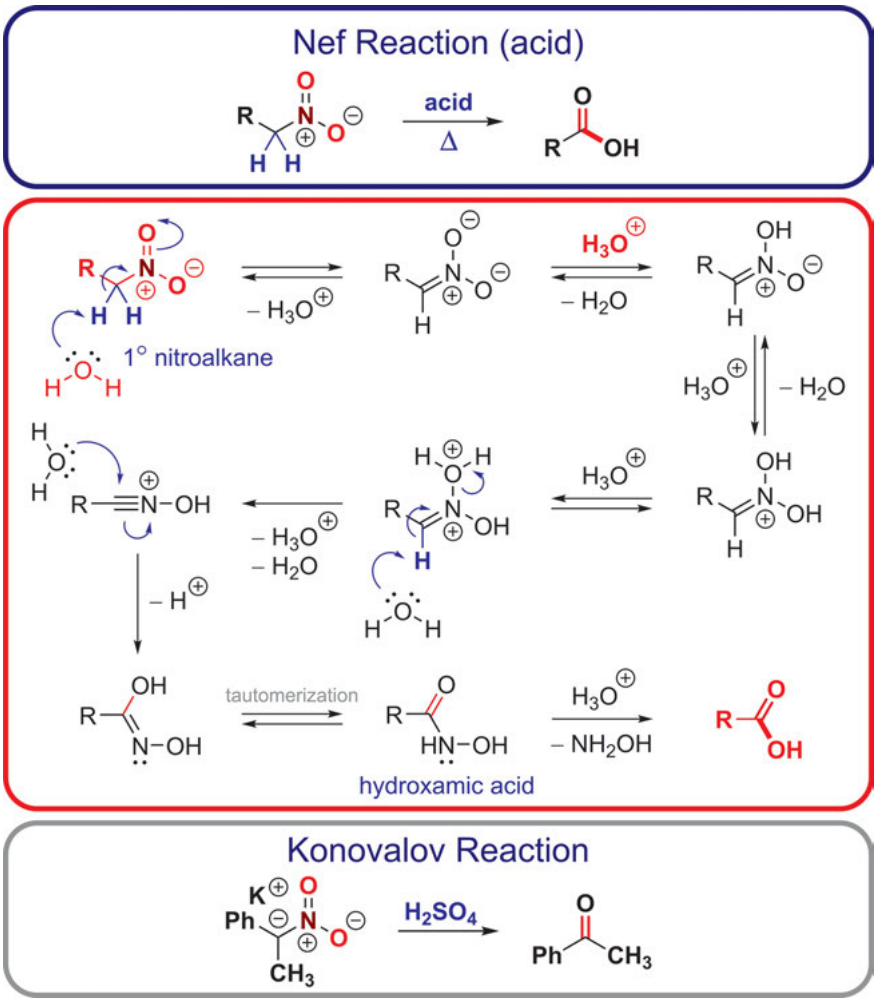


Fig. 65.2: The ***Nef*** *reaction* mechanism (acid-catalyzed).[204]

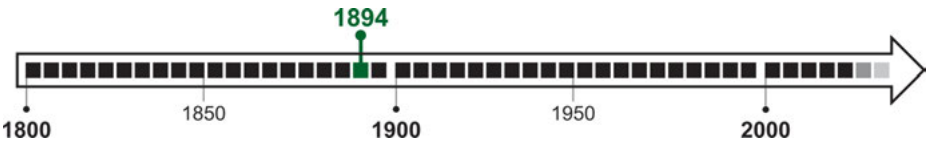


Fig. 65.3: The discovery of the ***Nef*** *reaction*.[205]

204 The mechanism of the ***Nef*** *reaction* can change and go through a *hydroxamic acid* intermediate if a strong acid (exclusively) is used with a primary (1°) *nitroalkane*. In this case, a *carboxylic acid* is formed [1] and [65a]. Please note, the reaction was likely first reported by Konovalov [65b].

205 The reaction was likely first described around 1894 [65c, 65d].

66 Negishi Cross Coupling

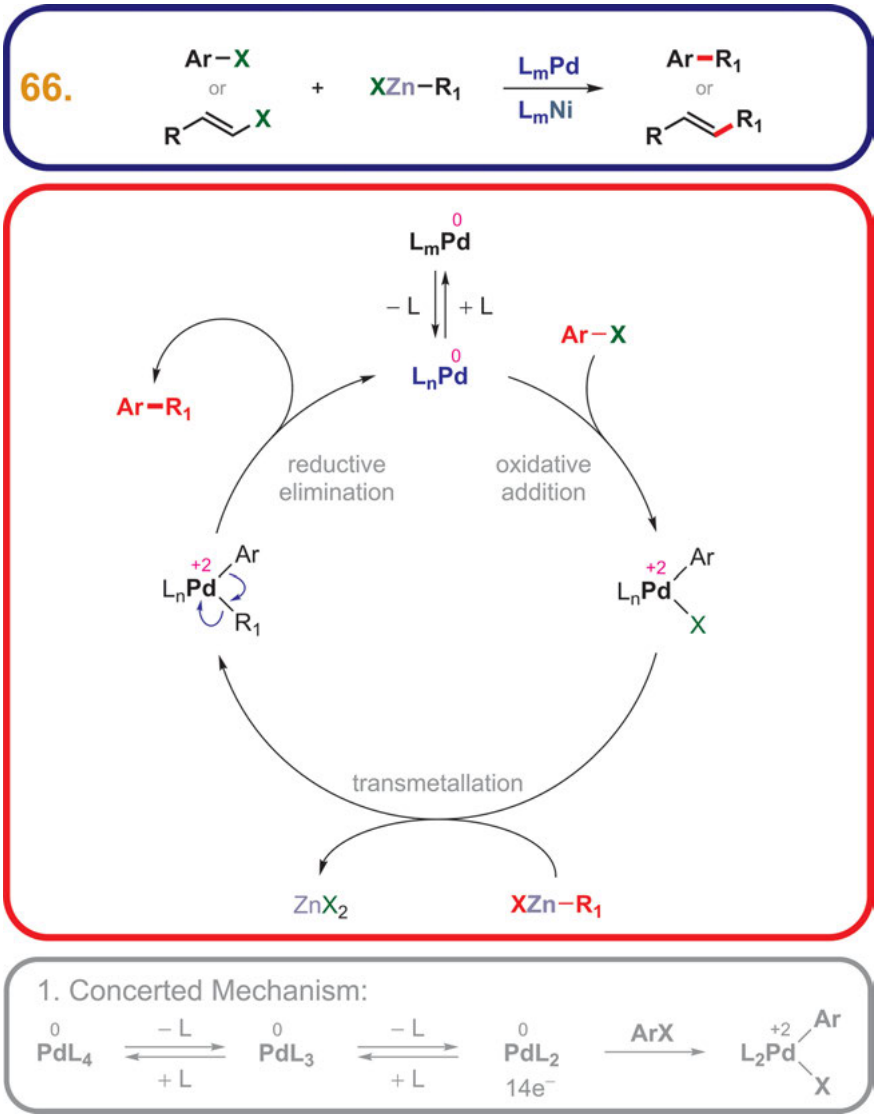


Fig. 66.1: The **Pd**-catalyzed ***Negishi*** *cross coupling* mechanism.[206]

206 The ***Negishi*** *cross coupling* is a type of ***Pd****-catalyzed cross coupling* reaction (C–C bond formation using *aryl halides* and *organozinc compounds*). For teaching purposes, a simplified and general mechanism is shown. Note, (1) *concerted oxidative addition* step to a low-coordinate (14e⁻) **Pd**-complex is more complicated [2a].

https://doi.org/10.1515/9783110608373-066

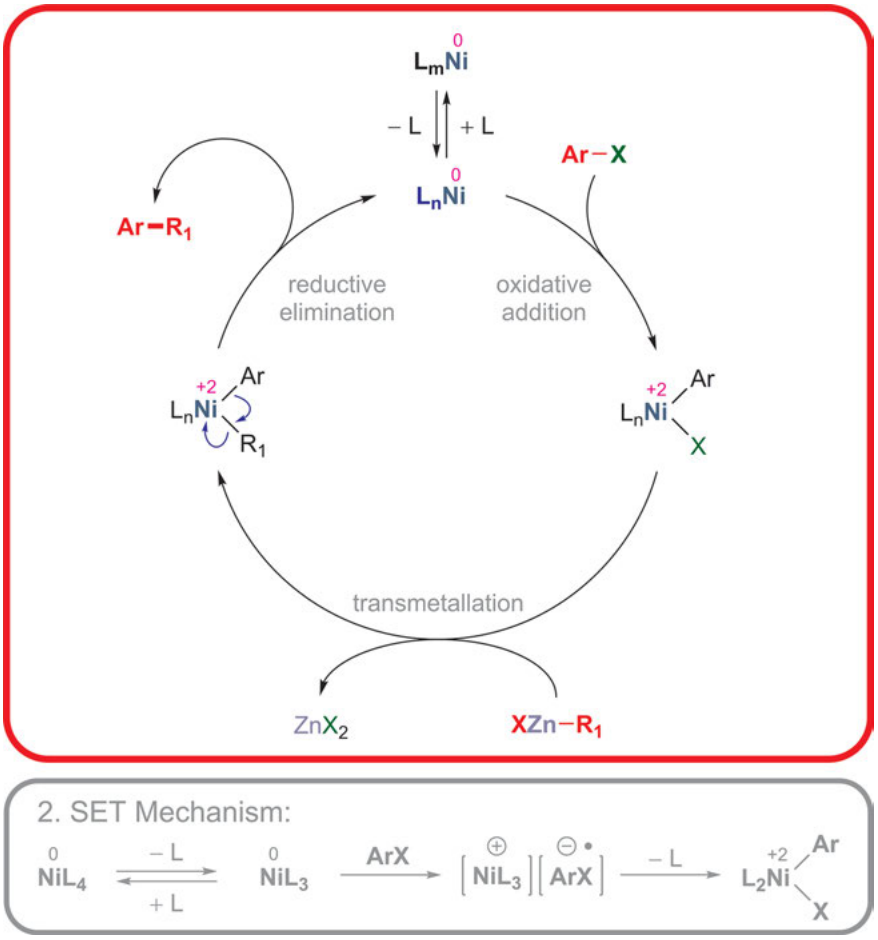


Fig. 66.2: The **Ni**-catalyzed ***Negishi*** *cross coupling* mechanism.[207]

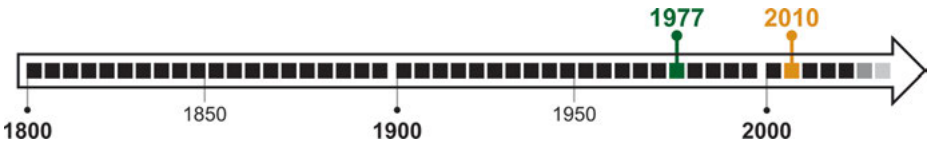


Fig. 66.3: The discovery of the ***Negishi*** *cross coupling*.[208]

207 The ***Negishi*** *cross coupling* can be ***Ni***-*catalyzed*. Note, a possible example of a (2) *SET oxidative addition* step to a **Ni**-complex (not necessarily at play in the example shown) [2a].

208 The reaction was likely first described around 1977 [66]. In **2010**, Ei-ichi Negishi (jointly with Richard F. Heck and Akira Suzuki) received the Nobel Prize in Chemistry for the development of **Pd**-catalyzed cross coupling reactions [46c].

67 Norrish Type I & II Reaction

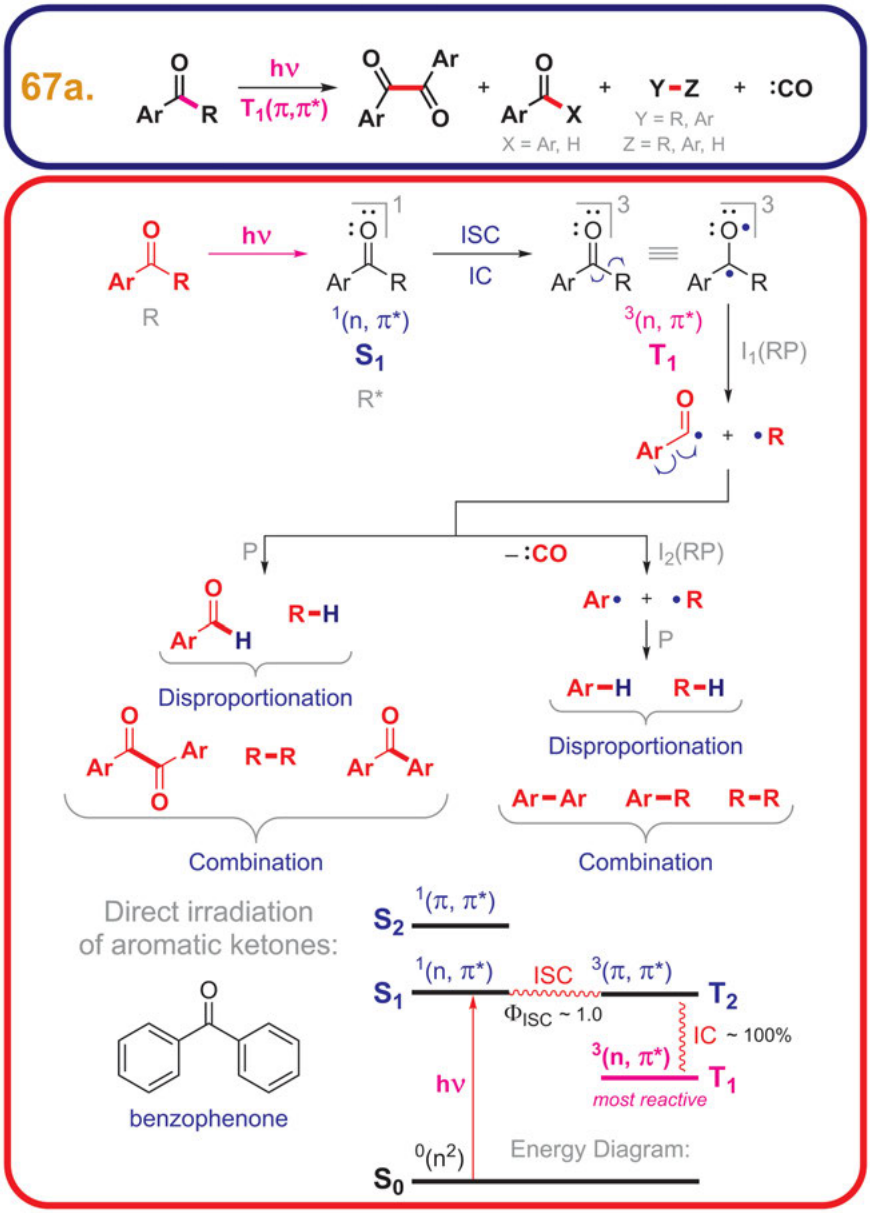


Fig. 67.1: The ***Norrish Type I*** *reaction* mechanism.[209]

209 The ***Norrish Type I*** *reaction* is a photochemical decomposition (**α–cleavage**) of *aldehydes* and

https://doi.org/10.1515/9783110608373-067

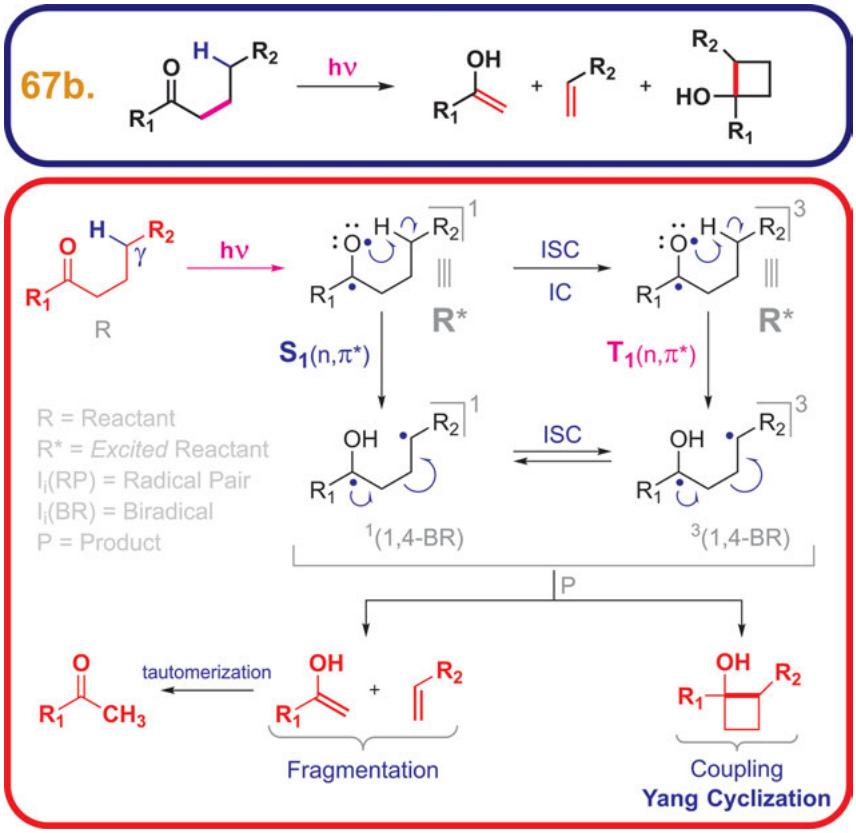


Fig. 67.2: The ***Norrish Type II*** *reaction* mechanism.[210]

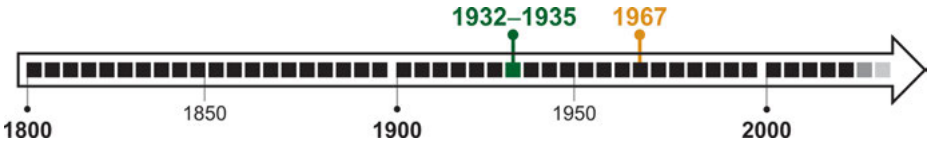


Fig. 67.3: The discovery of the ***Norrish*** *fragmentation*.[211]

ketones. The products may be formed because of initial *fragmentation* and subsequent *disproportionation* or *(re)combination* of formed radical species. Upon *direct irradiation* of aromatic ketones (i.e., benzophenone) the reaction usually occurs from the triplet excited state $\mathbf{T_1 = {}^3(n, \pi^*)}$ [2b].

210 The ***Norrish Type II*** *reaction* is a photochemical intramolecular **γ–H abstraction**. The products may be formed due to *fragmentation*, *(re)combination* or the ***Yang*** *cyclization* of 1,4-biradicals. The reaction may occur from the singlet $\mathbf{S_1 = {}^1(n, \pi^*)}$ or triplet excited state $\mathbf{T_1 = {}^3(n, \pi^*)}$ [2b].

211 The **Type I** and **II** reactions were likely first described between 1932–1935 [67a, 67b, 67c, 67d] or possibly earlier, see also [67e, 67f]. In **1967**, Ronald George Wreyford Norrish (jointly with Manfred Eigen and George Porter) received the Nobel Prize in Chemistry [67g].

68 Olefin (Alkene) Metathesis

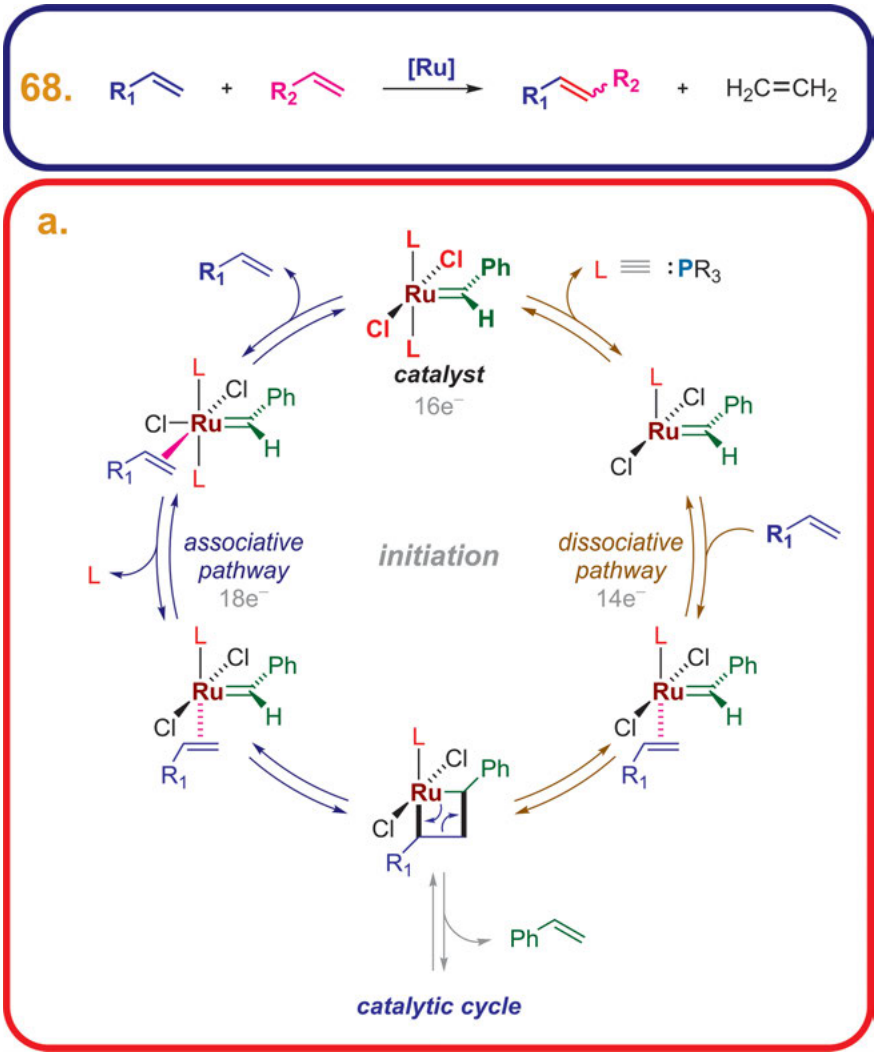


Fig. 68.1: The *olefin (alkene) metathesis* mechanism (initiation).[212]

212 The ***Ru**-catalyzed olefin (alkene) metathesis* mechanism starts with the stable *catalyst (16e⁻) initiation cycle (**a**)*: theoretically it can go either via a dissociative pathway (14e⁻), or an associative pathway (18e⁻), an interchange pathway is not shown here [68a].

https://doi.org/10.1515/9783110608373-068

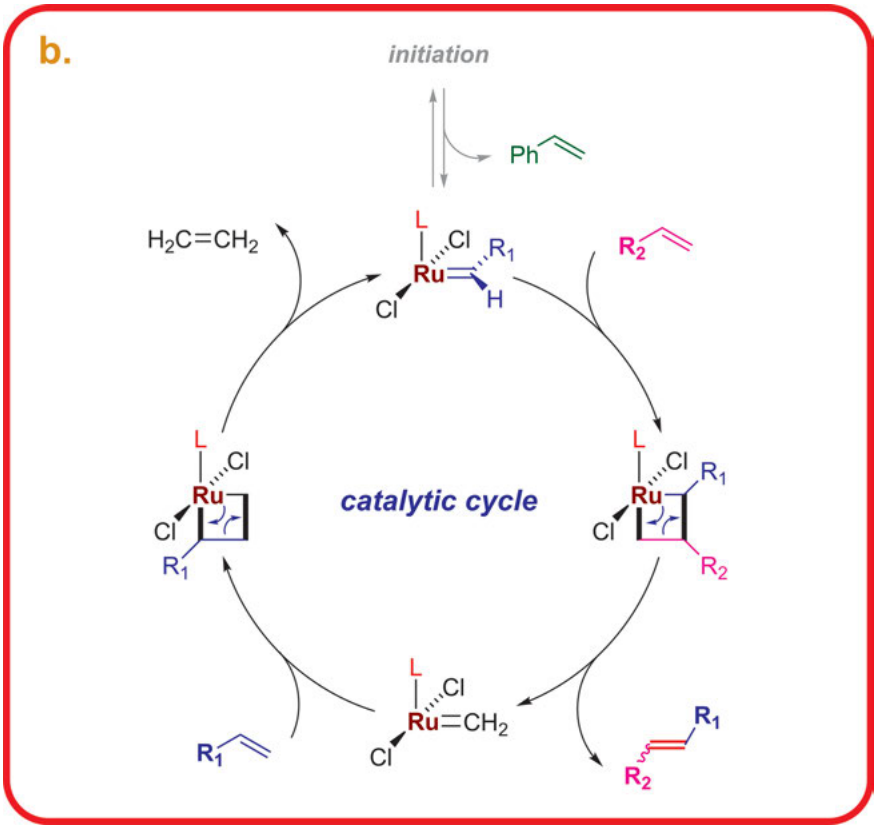


Fig. 68.2: The *olefin (alkene) metathesis* mechanism (catalytic cycle).[213]

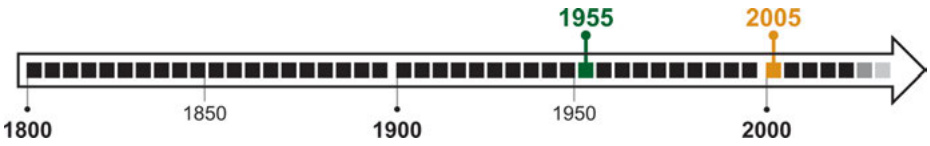


Fig. 68.3: The discovery of the *olefin metathesis*.[214]

213 After the loss of *styrene*, the *main catalytic cycle* (***b***) continues with the "active" catalyst. Please note, the mechanism is rather complex and varies significantly depending on the substrate and catalyst. For teaching purposes, a simplified and general example is shown.

214 The reaction was likely first described around 1955 [68b, 68c]. In **2005**, Yves Chauvin, Robert H. Grubbs and Richard R. Schrock received the Nobel Prize in Chemistry for the development of the *metathesis* transformations [68d].

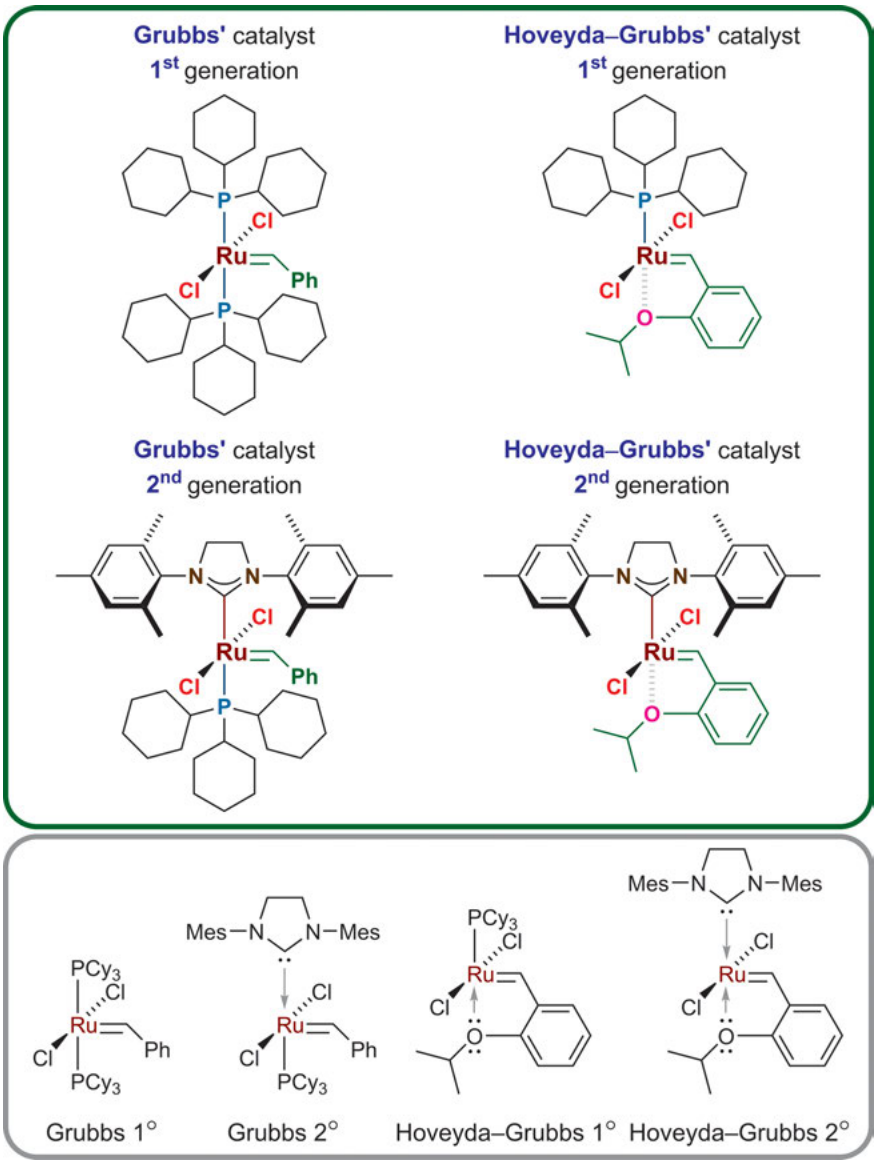


Fig. 68.4: The main *olefin (alkene) metathesis* catalysts.[215]

215 The most common catalysts used in the ***Ru**-catalyzed olefin (alkene) metathesis* are ***Grubbs'** catalysts* (1st and 2nd generation) [68e, 68f] and ***Hoveyda–Grubbs'** catalysts* (1st and 2nd generation) [68g].

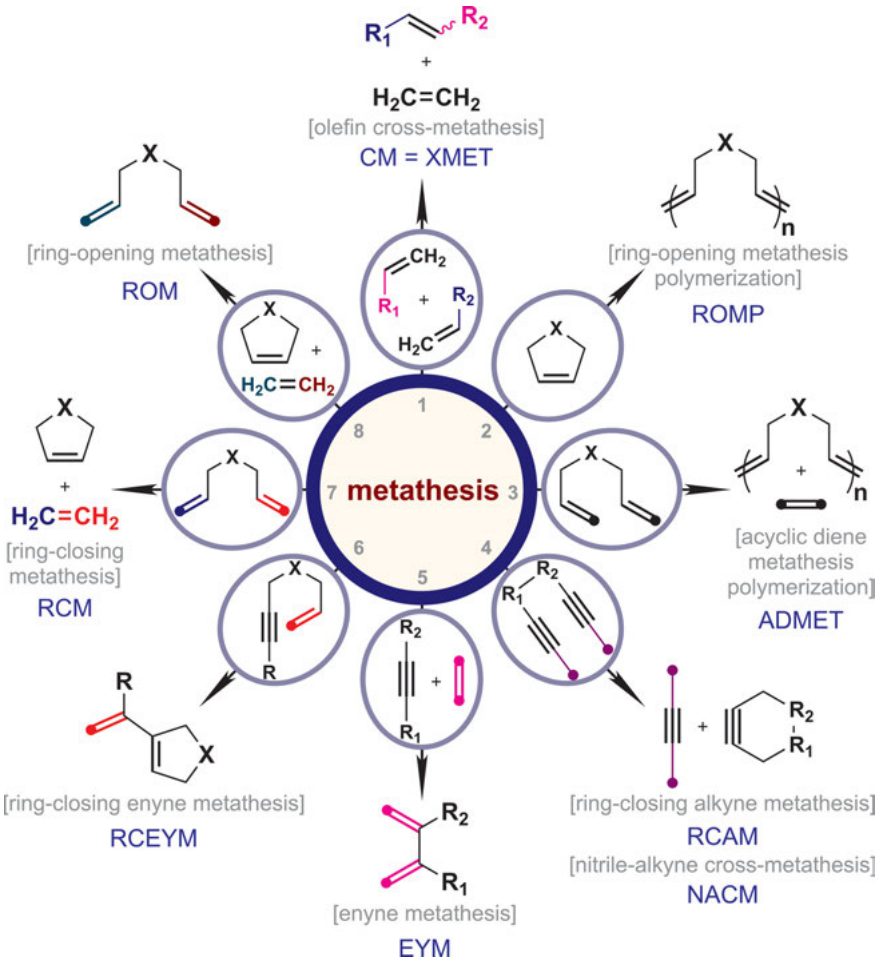


Fig. 68.5: Classification of *metathesis* reactions.[216]

216 The metathesis reactions can be classified as: 1. CM = XMET (olefin cross-metathesis); 2. ROMP (ring-opening metathesis polymerization); 3. ADMET (acyclic diene metathesis polymerization); 4. RCAM (ring-closing alkyne metathesis) and NACM (nitrile-alkyne cross-metathesis); 5. EYM (enyne metathesis); 6. RCEYM (ring-closing enyne metathesis); 7. **RCM** (ring-closing metathesis); 8. ROM (ring-opening metathesis).

69 Oppenauer Oxidation

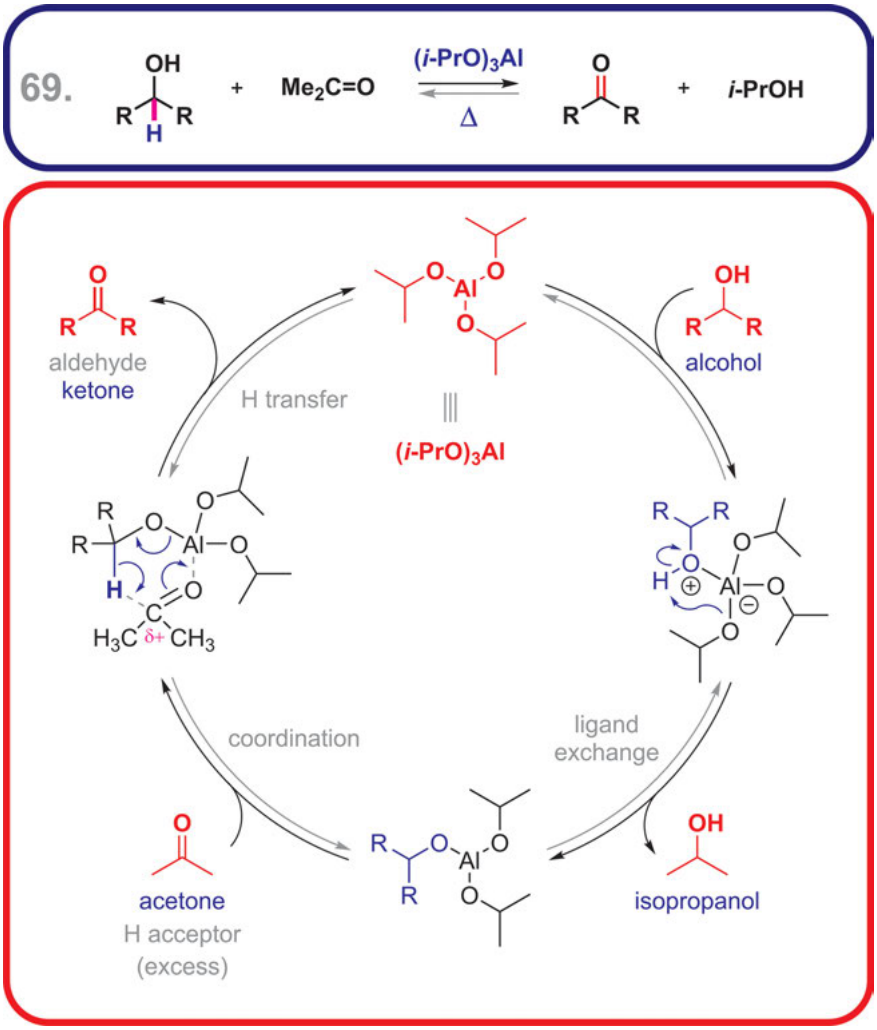


Fig. 69.1: The ***Oppenauer*** *oxidation* mechanism.[217]

217 The ***Oppenauer*** *oxidation* is reversible. The reversed reduction is called the ***Meerwein–Ponndorf–Verley*** *(MPV) reduction*. The equilibrium can be shifted towards oxidation by adding the excess of *acetone*.

https://doi.org/10.1515/9783110608373-069

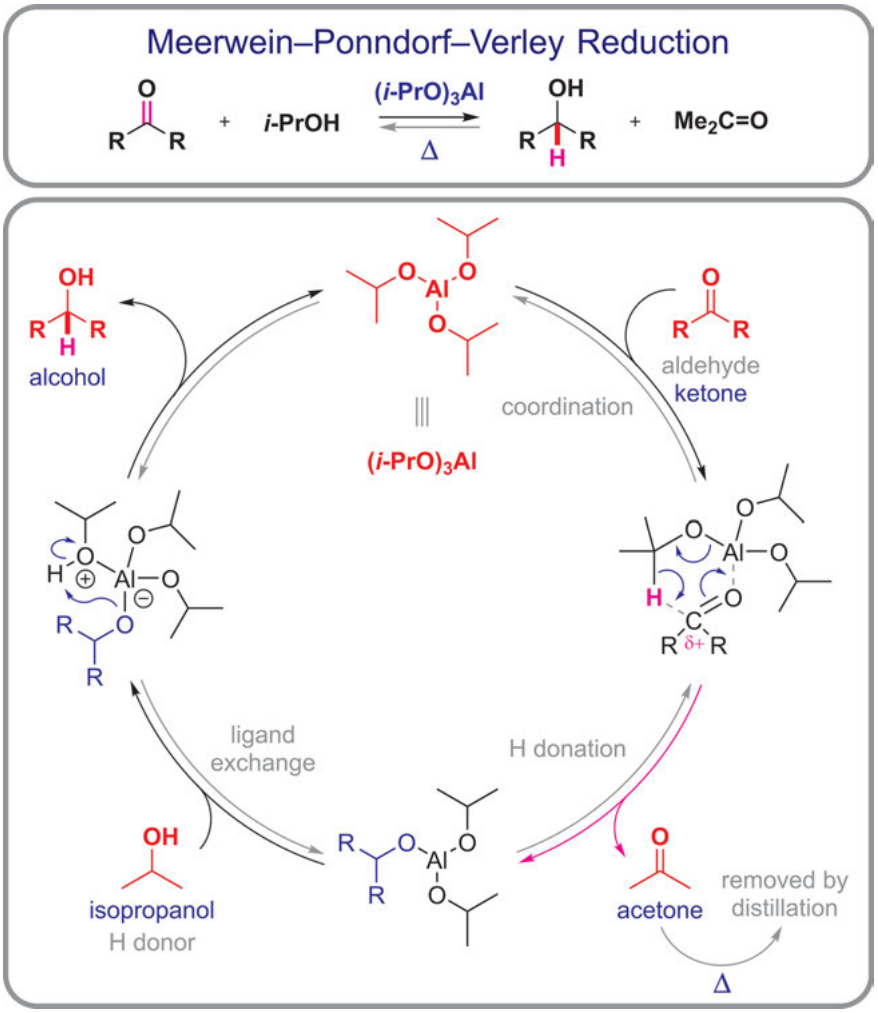


Fig. 69.2: The ***Meerwein–Ponndorf–Verley*** *reaction* mechanism.[218]

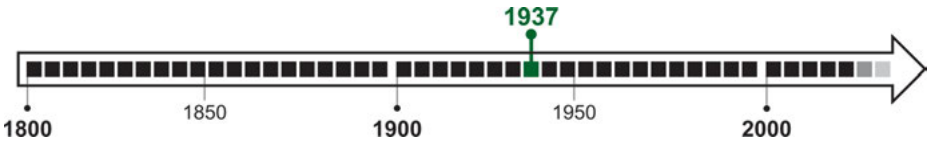


Fig. 69.3: The discovery of the ***Oppenauer*** *oxidation*.[219]

218 The ***Meerwein–Ponndorf–Verley*** *reduction* is a reversed process of the ***Oppenauer*** *oxidation*. It is also covered in Chapter 58.

219 The reaction was likely first described around 1937 [69].

70 Ozonolysis

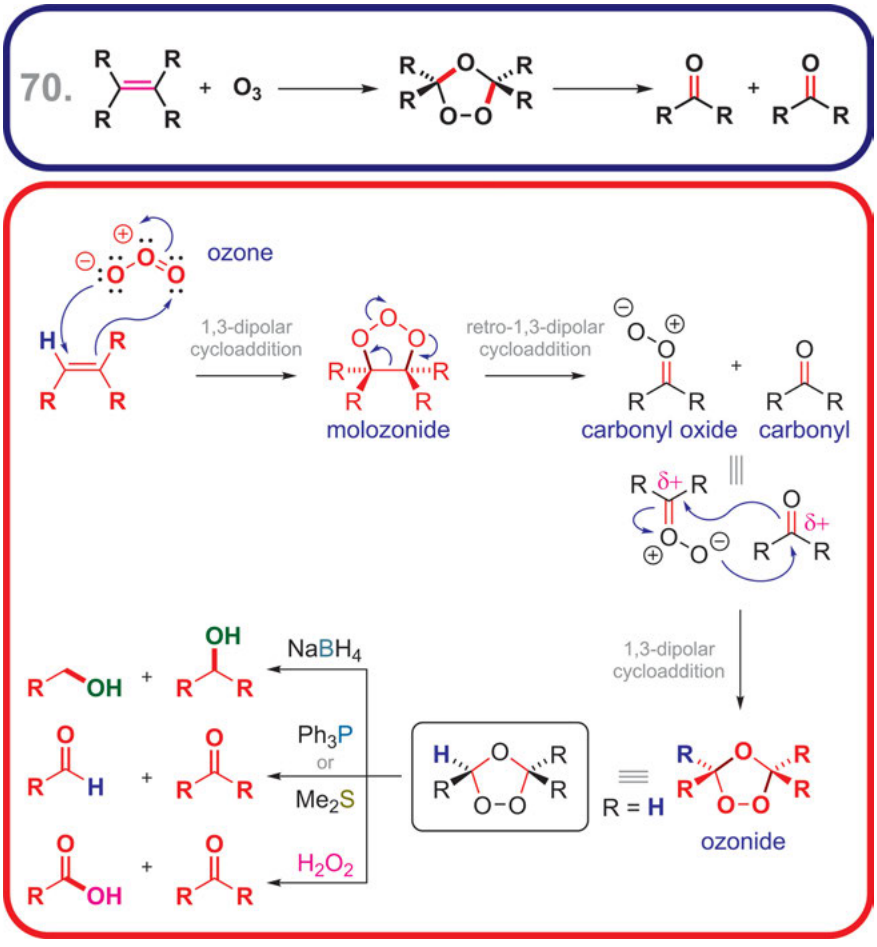


Fig. 70.1: The *ozonolysis* mechanism (the ***Criegee*** mechanism).[220]

220 The *ozonolysis* mechanism was first proposed by Criegee [70a, 70b, 70c], thus it is often called the ***Criegee*** *mechanism* (it is different from *the* ***Criegee*** *oxidation* covered in Chapter 29). Formally, the first step of *ozonolysis* is a *1,3-dipolar cycloaddition reaction* or a (3+2)-*cycloadditon reaction*.

https://doi.org/10.1515/9783110608373-070

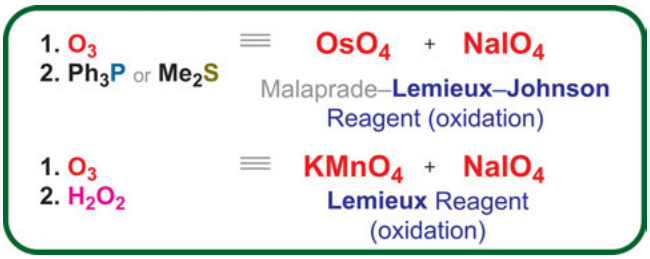


Fig. 70.2: Alternative to the *ozonolysis* reaction conditions.[221]

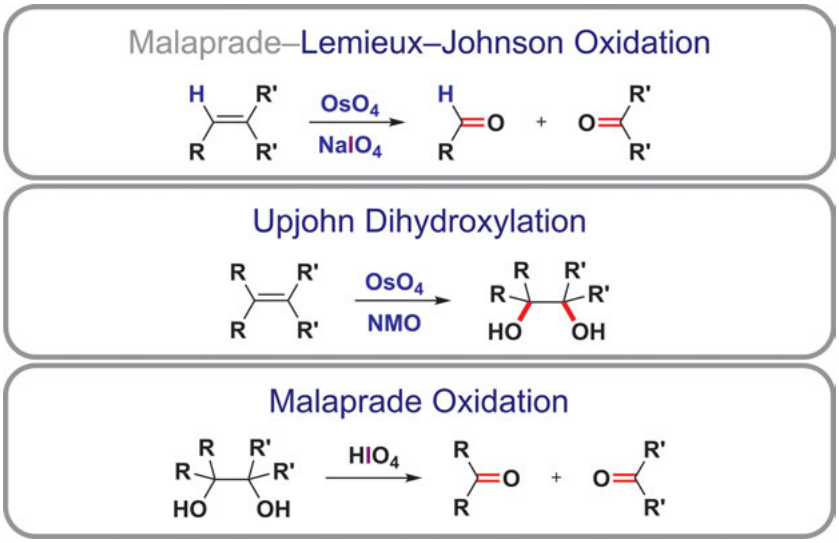


Fig. 70.3: Reactions related to the *ozonolysis*.[222]

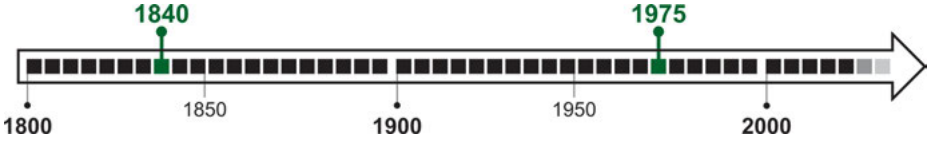


Fig. 70.4: The discovery of the *ozonolysis*.[223]

---

221 The *Malaprade–**Lemieux–Johnson** reagent* [70d] is an alternative to the use of *ozone* [70e], followed by Ph_3P or Me_2S to form *aldehydes* and *ketones*. The ***Lemieux*** reagent [70f] is an alternative to the use of *ozone*, followed by H_2O_2, to form *carboxylic acids* and *ketones*.

222 The *Malaprade–**Lemieux–Johnson** reaction (oxidation)* is an alternative to the *ozonolysis reaction* under Ph_3P or Me_2S conditions. The ***Upjohn** dihydroxylation* (covered in Chapter 93) followed by the ***Malaprade** oxidation* (covered in Chapter 29) can be also used as an alternative to *ozonolysis*.

223 The reaction was likely first described around 1840 [70g], the mechanism was proposed around 1975 [70b, 70c].

71 Paal–Knorr Syntheses

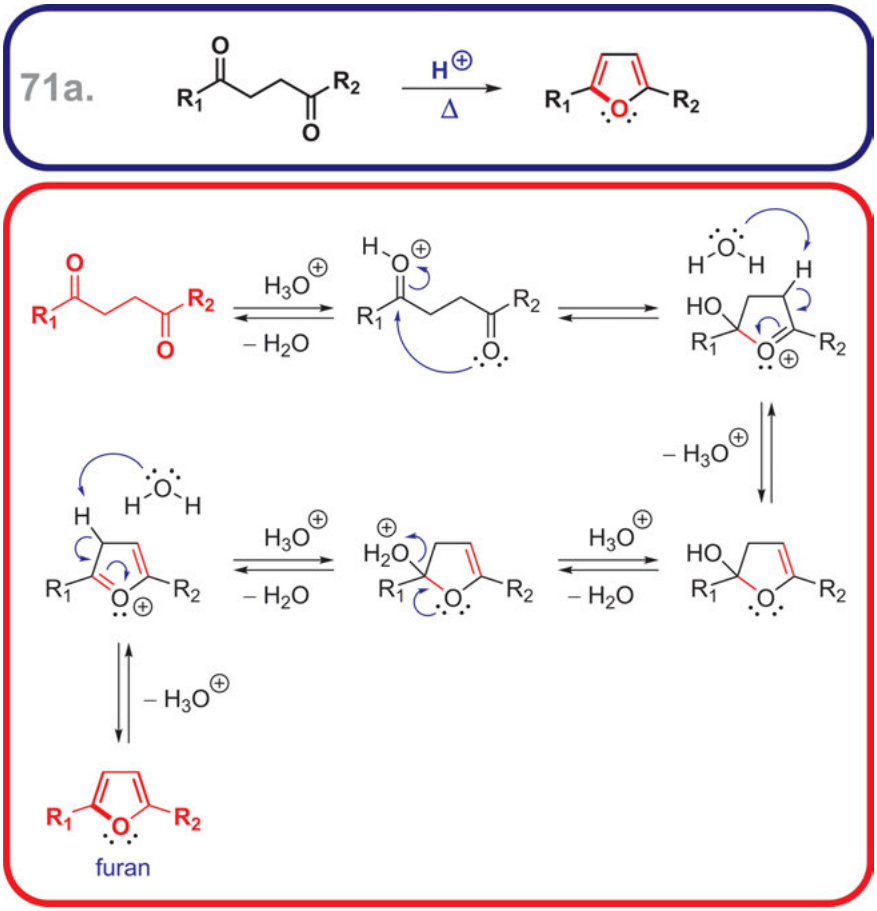


Fig. 71.1: The ***Paal–Knorr*** *furan synthesis* mechanism.[224]

224 The ***Paal–Knorr*** *synthesis* is a reaction that was initially proposed for the synthesis of *furans* and *pyrroles*: the ***Paal–Knorr*** *furan synthesis*.

https://doi.org/10.1515/9783110608373-071

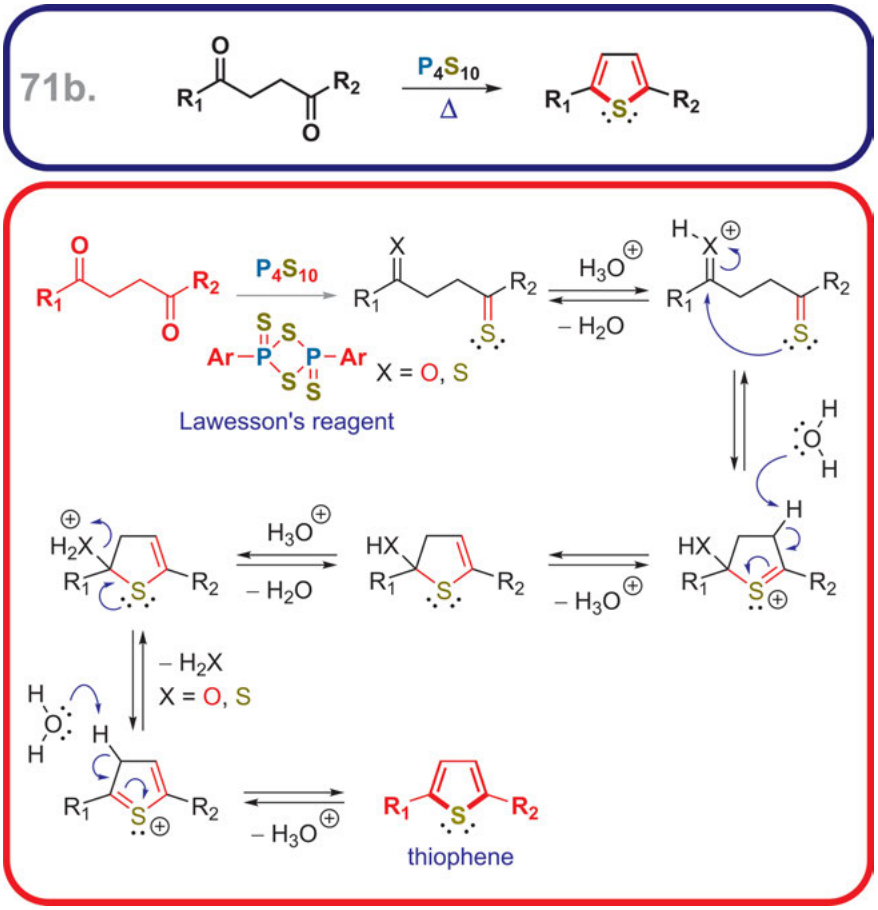


Fig. 71.2: The ***Paal–Knorr*** *thiophene synthesis* mechanism.[225]

225 The ***Paal–Knorr*** *thiophene synthesis* was adopted for the preparation of *thiophenes*, for example by using ***Lawesson's*** *reagent* [71a].

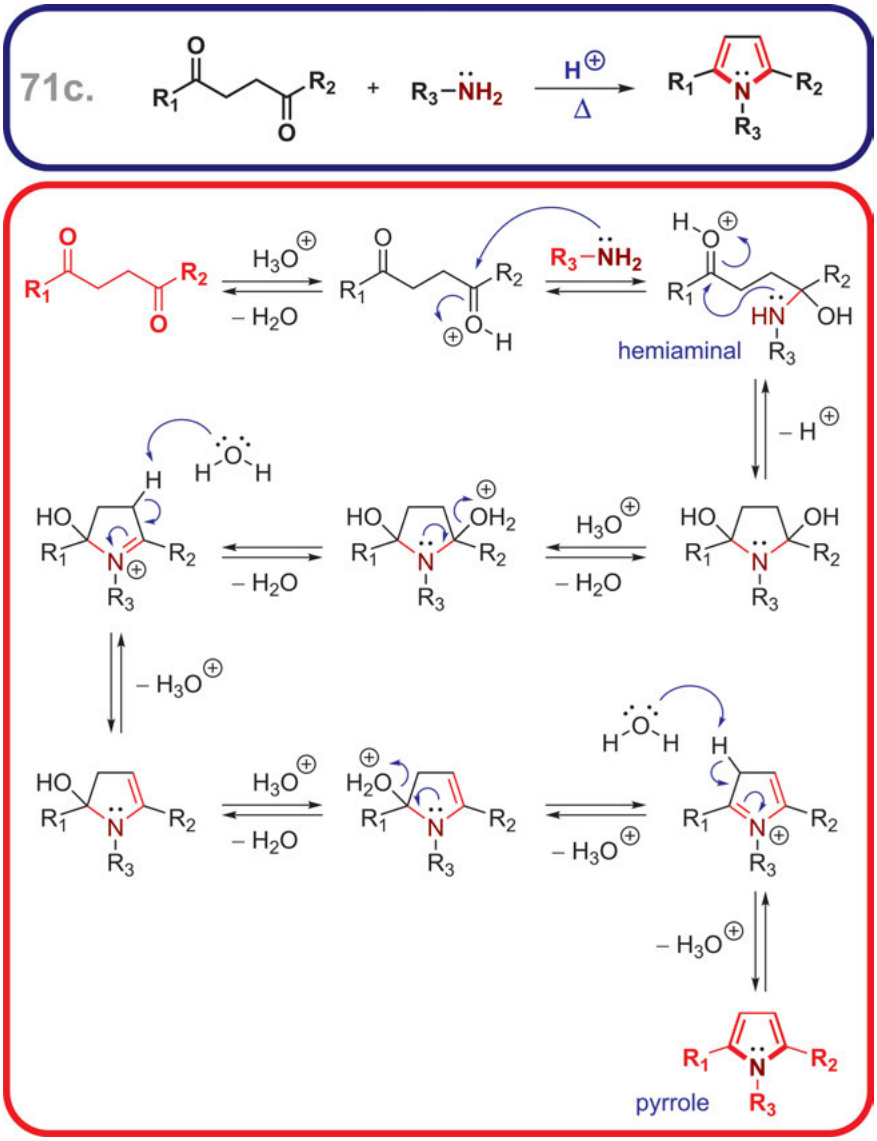


Fig. 71.3: The ***Paal–Knorr*** *pyrrole synthesis* mechanism.[226]

226 The ***Paal–Knorr*** *pyrrole synthesis* is a reaction that was initially proposed for the synthesis of *pyrroles*. It should not be confused with the ***Knorr*** *pyrrole synthesis* (not shown).

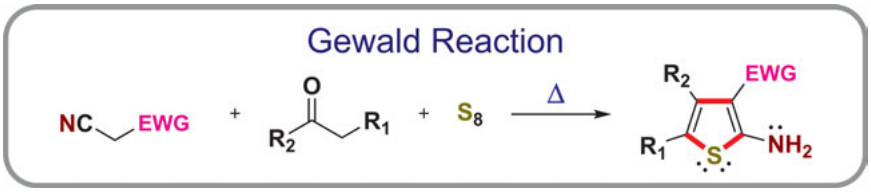


Fig. 71.4: Reactions related to the ***Paal–Knorr*** *thiophene synthesis*.[227]

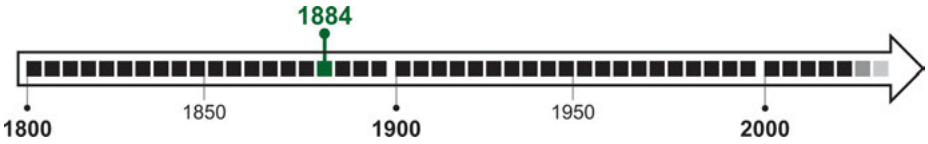


Fig. 71.5: The discovery of the ***Paal–Knorr*** *syntheses*.[228]

227 Thiophenes (2-aminothiophenes) can be prepared via the ***Gewald*** *condensation* (see Chapter 41).
228 The reaction was likely first described around 1884 [71b, 71c].

72 Paternò–Büchi Reaction

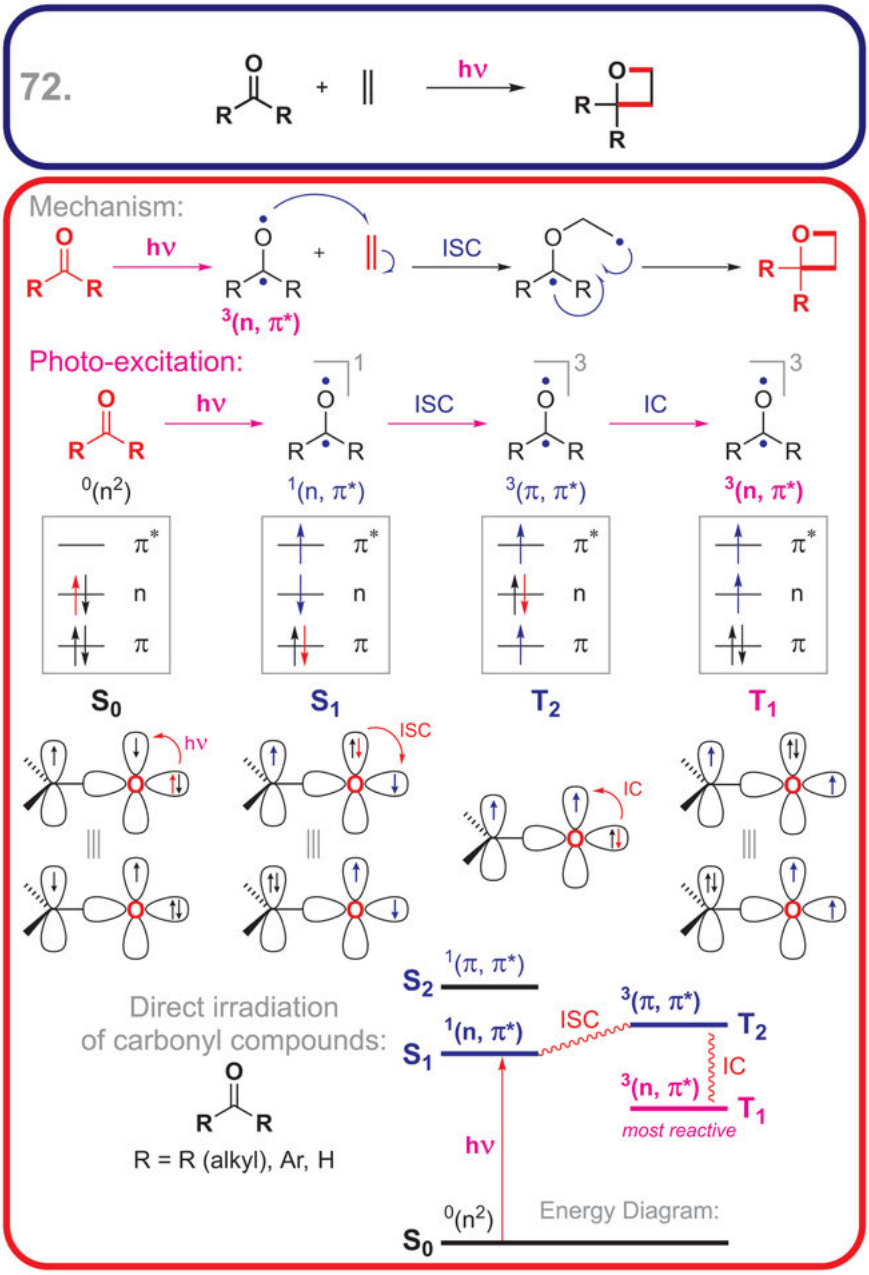


Fig. 72.1: The ***Paternò–Büchi*** *reaction* mechanism.[229]

https://doi.org/10.1515/9783110608373-072

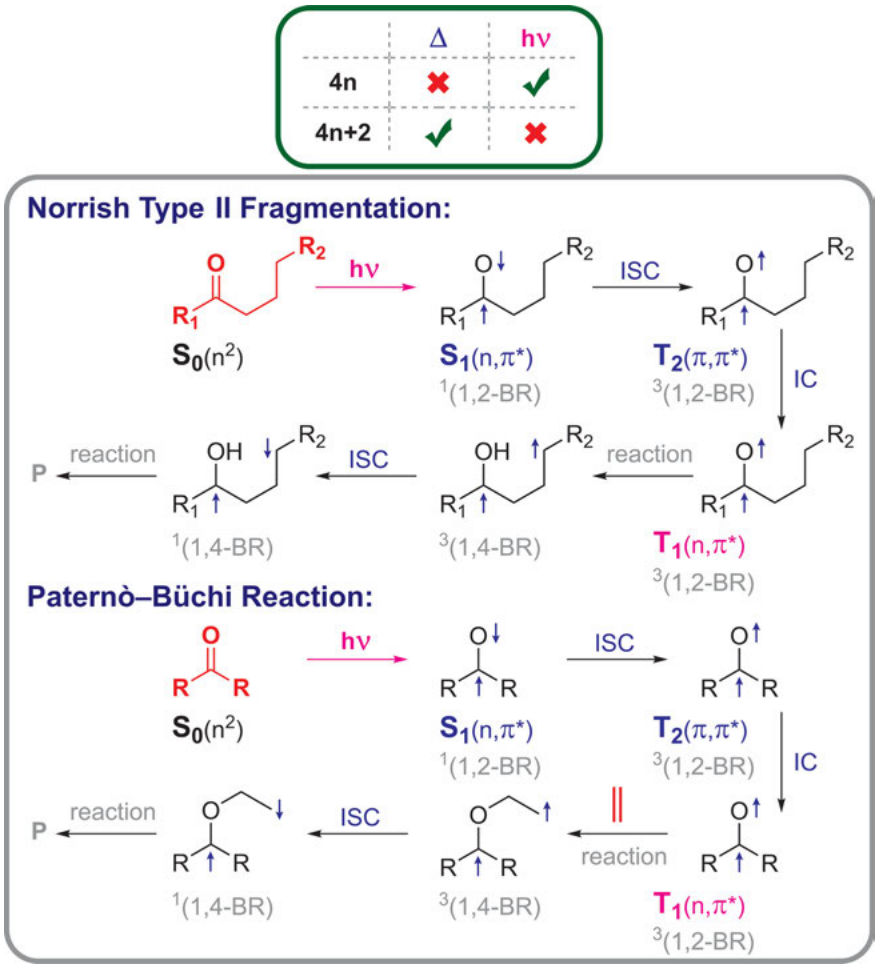


Fig. 72.2: The ***Norrish Type II*** *reaction* vs the ***Paternò–Büchi*** *reaction* mechanism.[230]

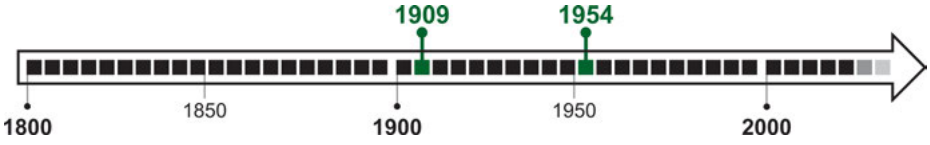


Fig. 72.3: The discovery of the ***Paternò–Büchi*** *reaction*.[231]

---

229 The ***Paternò–Büchi*** *reaction* is a photochemical **[2_π+2_π]** or **[2+2]**-*cycloaddition reaction*. The ***Woodward–Hoffmann*** *rules* [64a, 64b, 64c]: this reaction (**4n** = 4π) is not allowed at the ground state = under thermal conditions (Δ) but allowed at the excited state = under photochemical conditions (hν) [2b].

230 Compare the mechanistic similarities between the ***Norrish Type II*** *reaction* (covered in Chapter 67) and the ***Paternò–Büchi*** *cycloaddition reaction* [2b].

231 The reaction was likely described by Paternò around 1909 [72a] and by Büchi in 1954 [72b].

73 Pauson–Khand Reaction

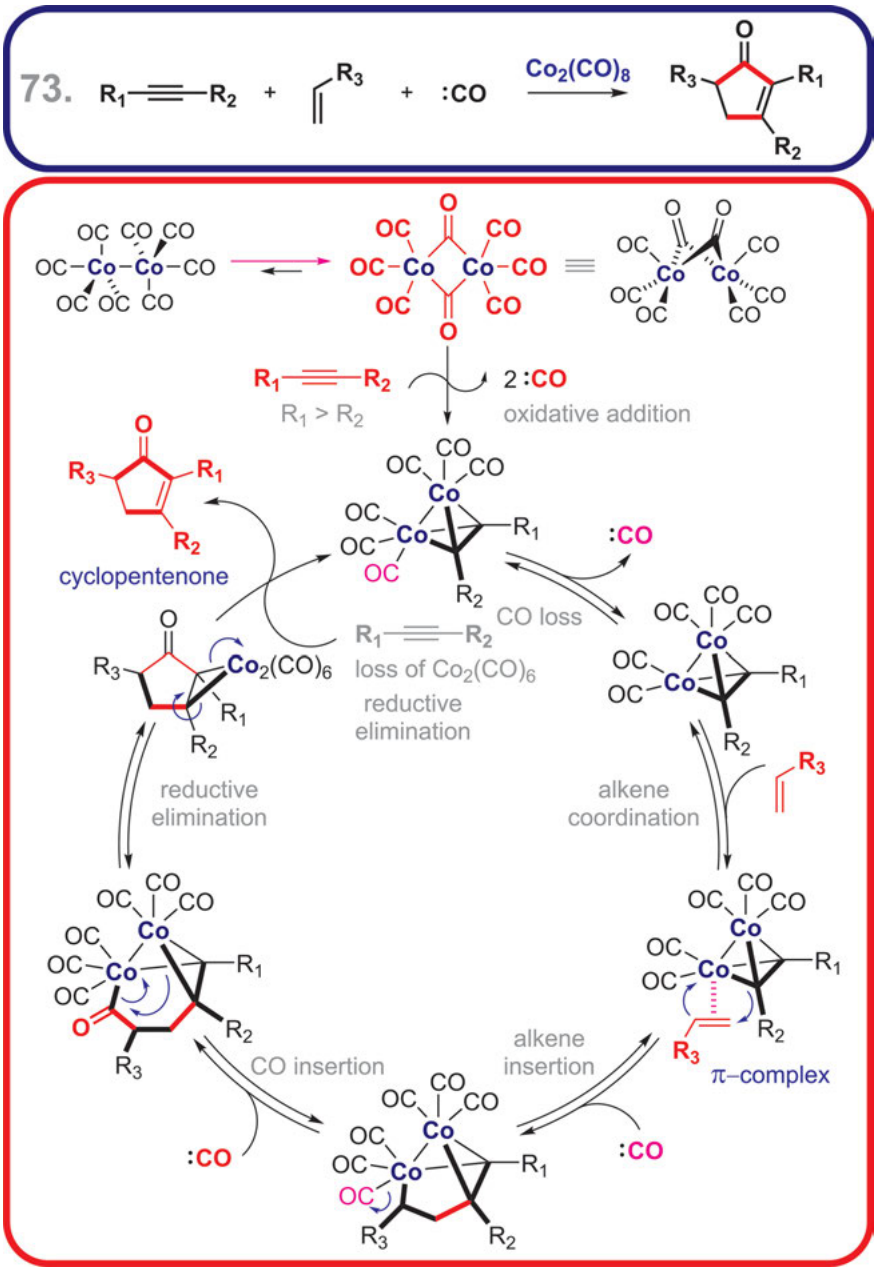


Fig. 73.1: The ***Pauson–Khand*** *reaction* mechanism.[232]

https://doi.org/10.1515/9783110608373-073

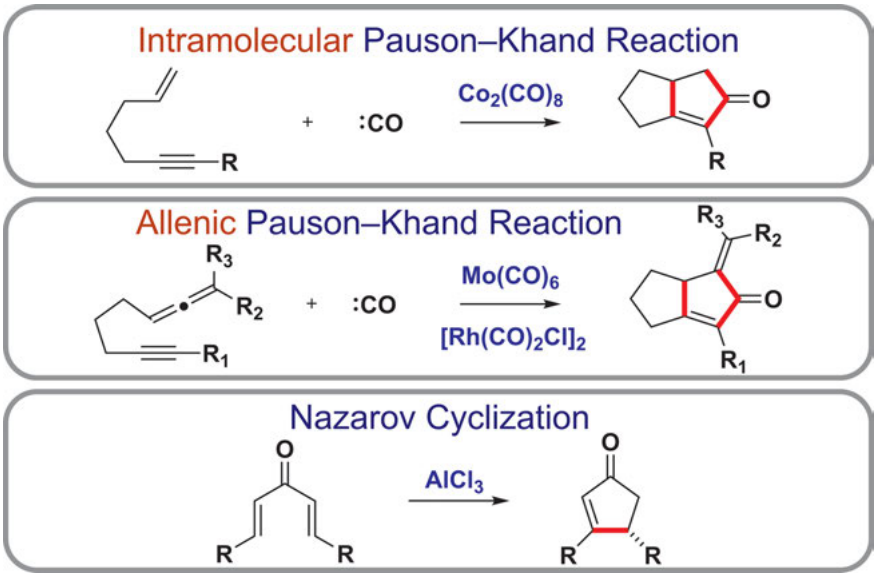


Fig. 73.2: Variations of the ***Pauson–Khand*** *reaction*.[233]

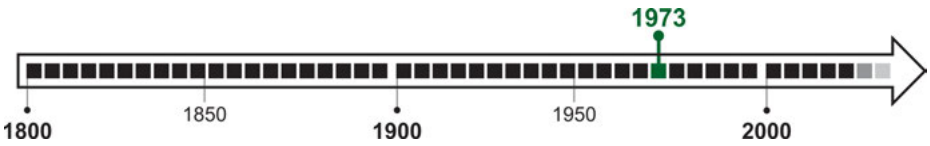


Fig. 73.3: The discovery of the ***Pauson–Khand*** *reaction*.[234]

232 The ***Pauson–Khand*** *reaction* is a ***Co****-catalyzed* (2+2+1)*-cycloaddition reaction.*

233 There are several variations of this reaction: the *intramolecular* ***Pauson–Khand*** *reaction*, the *allenic* ***Pauson–Khand*** *reaction*, and others (not shown) [73a]. Other metals can catalyze it: **Mo**, **Rh**, *etc*. The ***Nazarov*** *cyclization* undergoes a different [4π] ***con****rotatory electrocyclization* mechanism (Chapter 64), but it also yields *cyclopentenones*.

234 The reaction was likely first described around 1973 [73b, 73c, 73d].

74 Peptide (Amide) Coupling

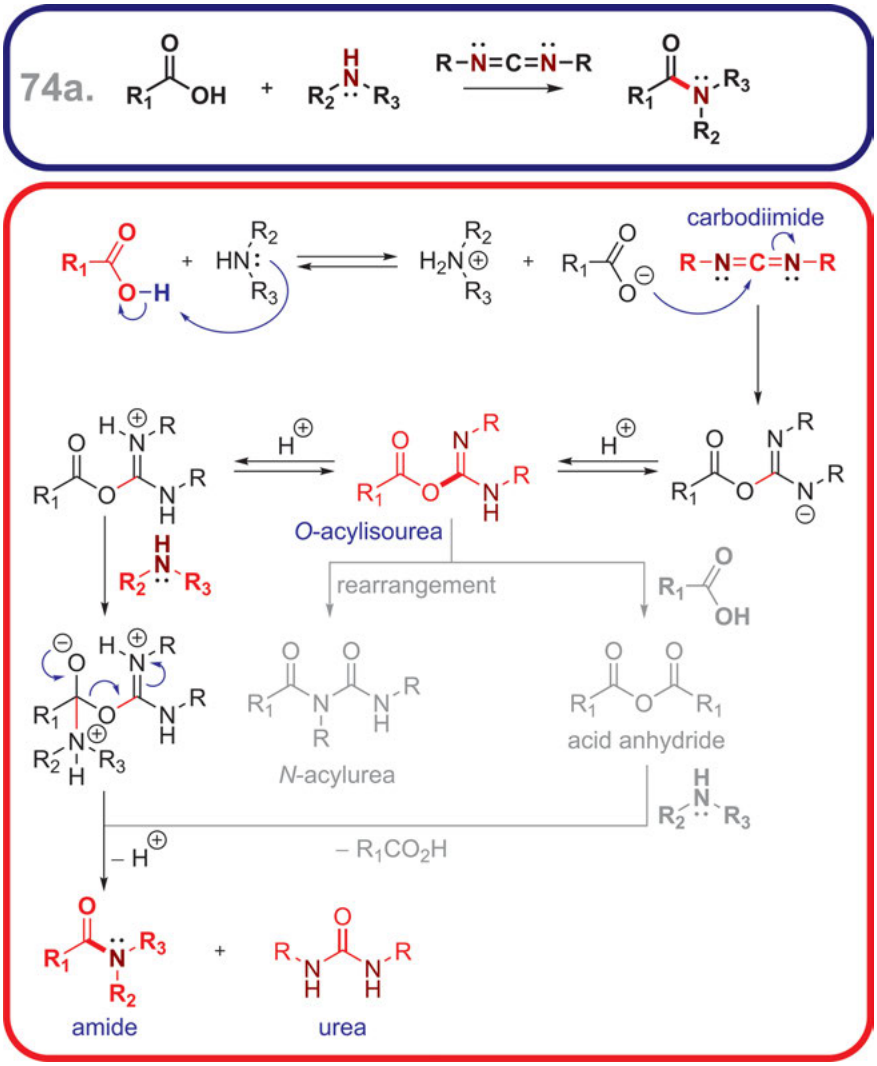


Fig. 74.1: The *peptide (amide) coupling* (DCC) mechanism.[235]

235 The *peptide (amide) coupling* mechanism based on the use of *carbodiimide* coupling reagents (DCC) [74a, 74b].

https://doi.org/10.1515/9783110608373-074

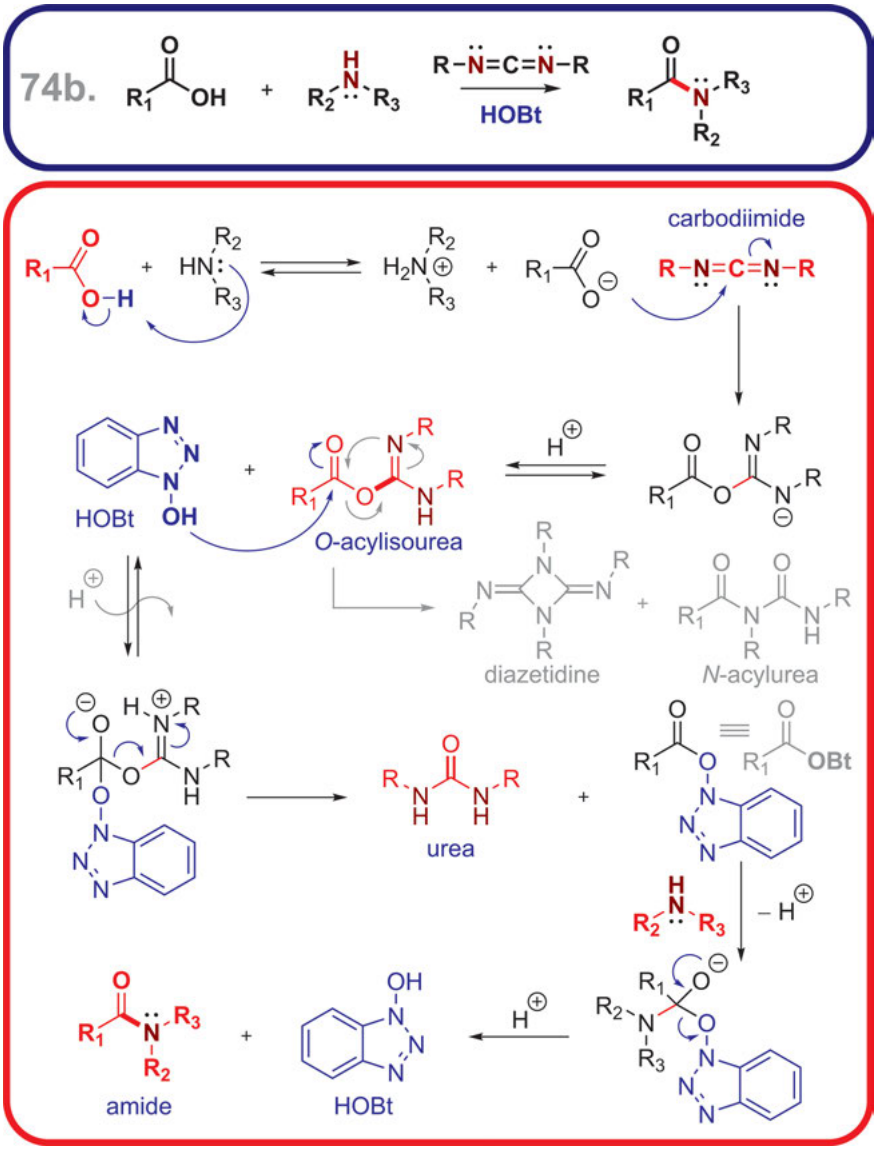


Fig. 74.2: The *peptide (amide) coupling* (DCC + HOBt) mechanism.[236]

236 The *peptide (amide) coupling* mechanism based on the use of *carbodiimide* coupling reagents and *additives* (DCC and HOBt) [74a, 74b].

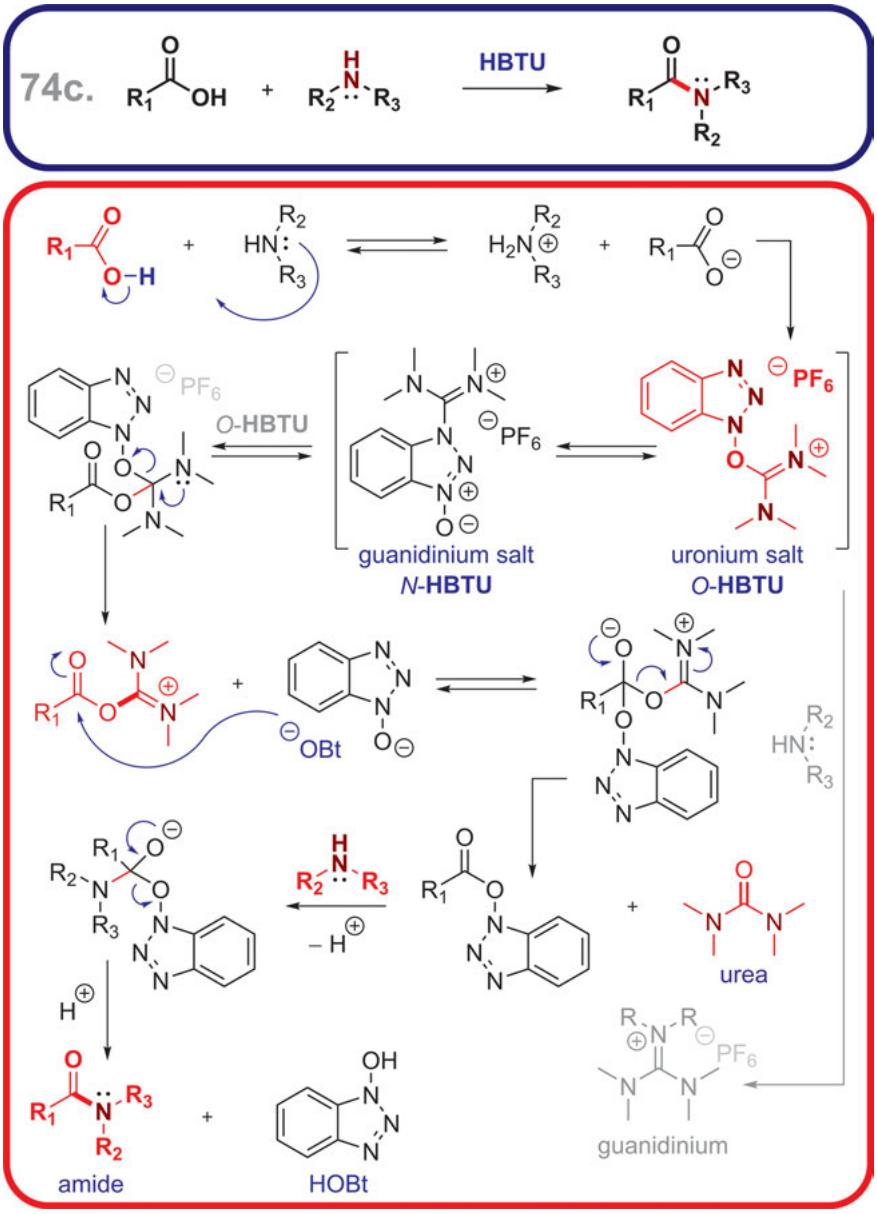


Fig. 74.3: The *peptide (amide) coupling* (HBTU) mechanism.[237]

237 The *peptide (amide) coupling* mechanism based on the use of *benzotriazole = guanidinium/uronium salts* coupling reagents (HBTU) [74c].

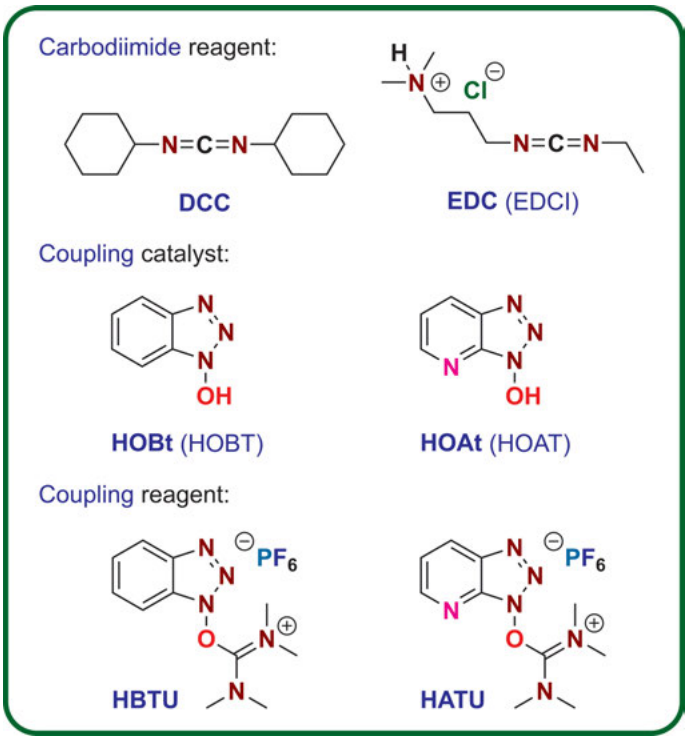


Fig. 74.4: The main *peptide (amide) coupling* reagents and catalysts.[238]

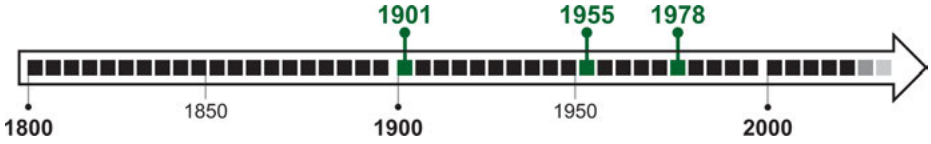


Fig. 74.5: The discovery of the *peptide (amide) coupling*.[239]

238 The most common reagents used in the *peptide (amide) coupling* or the *peptide synthesis* are the ***carbodiimide*** *reagents* (DCC [74d], EDC [74e], and many other); ***guanidinium/uronium salts*** (HBTU [74f], HATU [74g]; and many more like *phosphonium salts* PyBOP [74h]). The most common additives (catalysts) used in the *peptide synthesis* are HOBt [74i] and HOAt, among others.

239 A. The *peptide (amide) coupling* reaction was likely first described around 1901 [74j]. B. DCC coupling reagent was likely first described around 1955 [74k]. C. HBTU coupling reagent was likely first described around 1978 [74l].

75 Pictet–Spengler Reaction

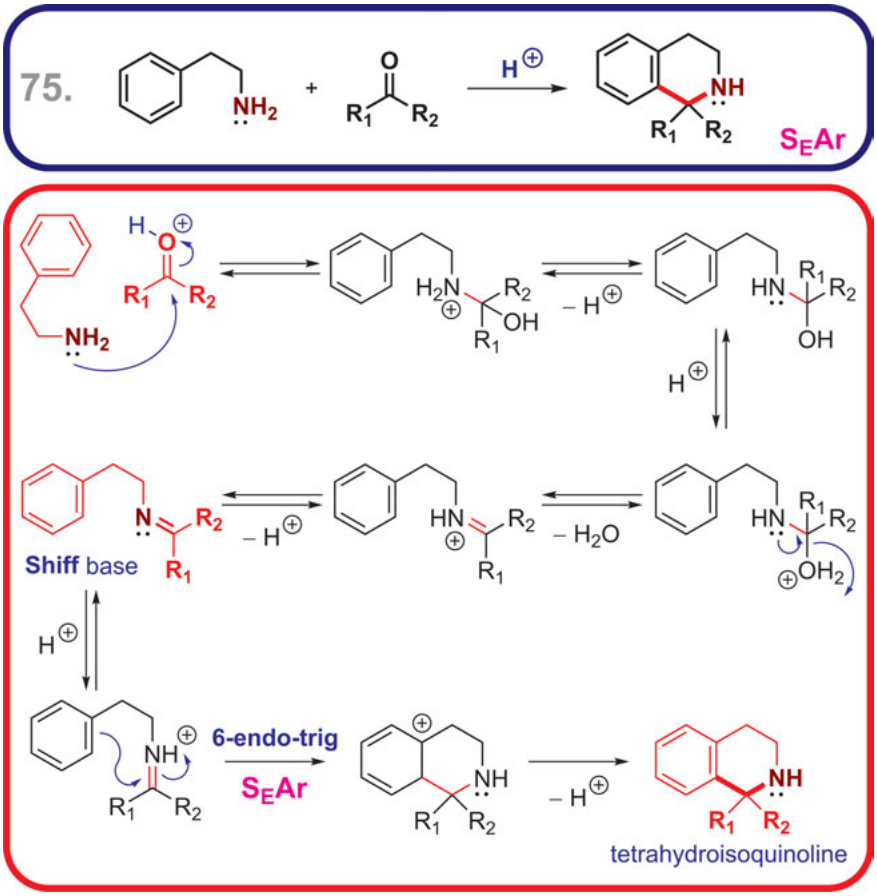


Fig. 75.1: The ***Pictet–Spengler*** *reaction* mechanism.[240]

240 The ***Pictet–Spengler*** *reaction* or the ***Pictet–Spengler*** *condensation* mechanism is a combination of the ***Mannich*** *condensation* = the *imine condensation (the* ***Shiff*** *base)* (see Chapter 56) and the **aromatic electrophilic substitution** (the ***arenium ion*** mechanism or **S_EAr**, which was covered in Chapter 3).

https://doi.org/10.1515/9783110608373-075

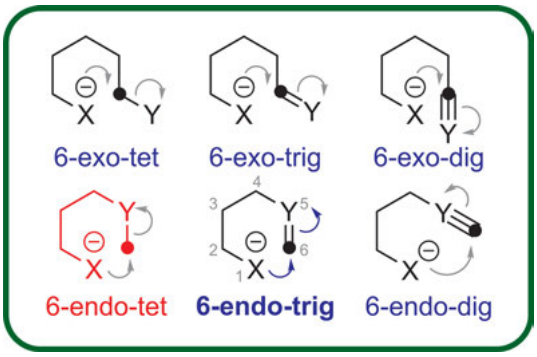


Fig. 75.2: ***Baldwin's*** *rules*.[241]

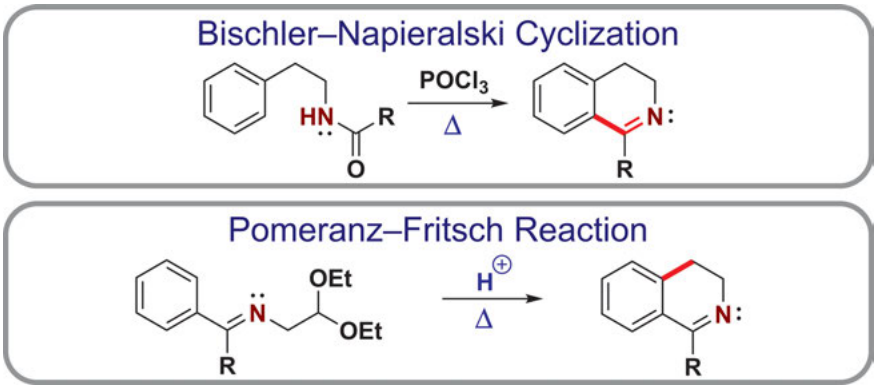


Fig. 75.3: Reactions related to the ***Pictet–Spengler*** *reaction*.[242]

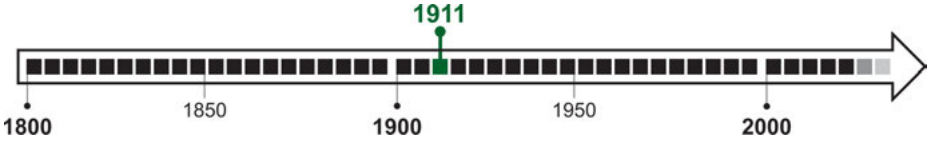


Fig. 75.4: The discovery of the ***Pictet–Spengler*** *reaction*.[243]

---

241 The cyclization (S_EAr) step is allowed according to *Baldwin's rules*: **6-endo-trig** [75a].

242 Several named reactions are related to the ***Pictet–Spengler*** *reaction*: the ***Bischler–Napieralski*** *cyclization* (Chapter 19), and closely related the ***Pomeranz–Fritsch*** *reaction* [19a, 19b]. Both reactions yield *isoquinolines*.

243 The reaction was likely first described around 1911 [75b].

76 Pinacol–Pinacolone Rearrangement

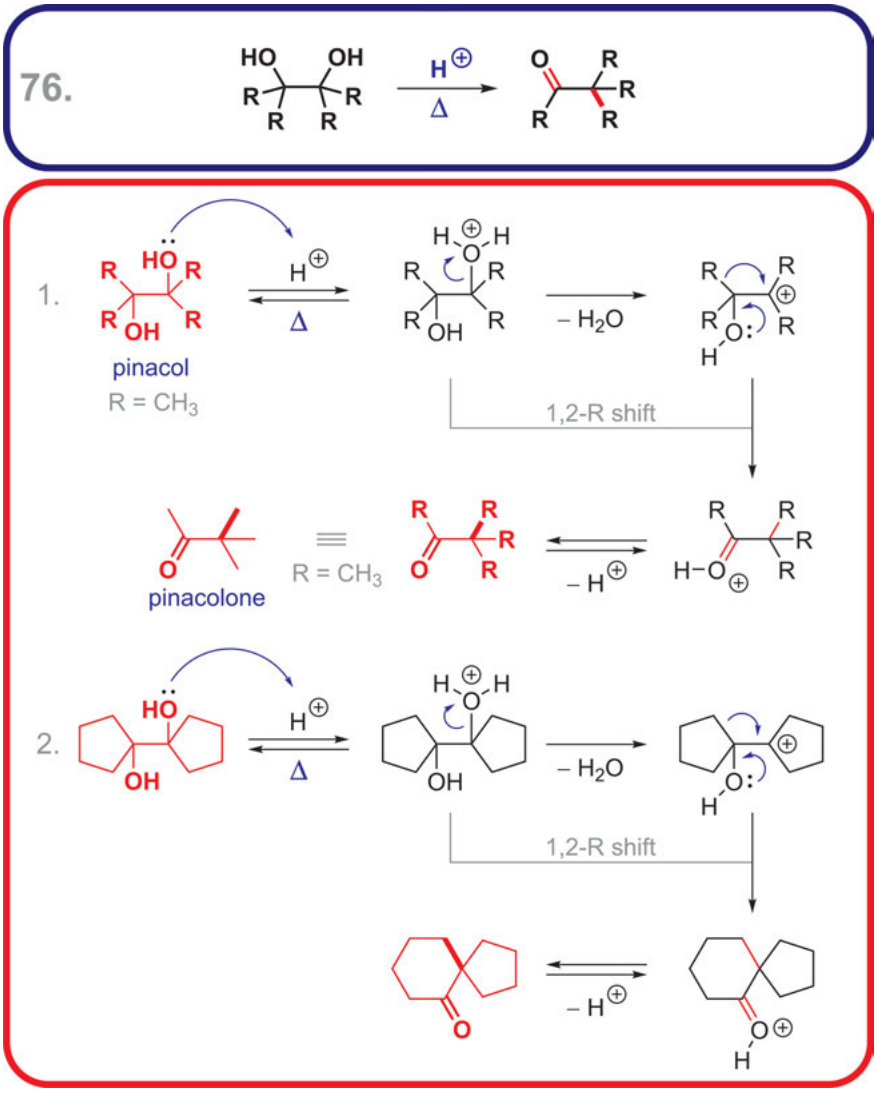


Fig. 76.1: The *pinacol-pinacolone rearrangement* mechanism.[244]

244 The *pinacol-pinacolone rearrangement* or simply the *pinacol rearrangement* mechanism is distantly related to the ***Wagner–Meerwein*** *rearrangement* covered in Chapter 96. The *pinacol-pinacolone rearrangement* should not be confused with the *pinacol coupling* covered in Chapter 57. Please also note: *2,3-dimethylbutane-2,3-diol* is called ***pinacol*** and *3,3-dimethyl-2-butanone* is called ***pinacolone***.

https://doi.org/10.1515/9783110608373-076

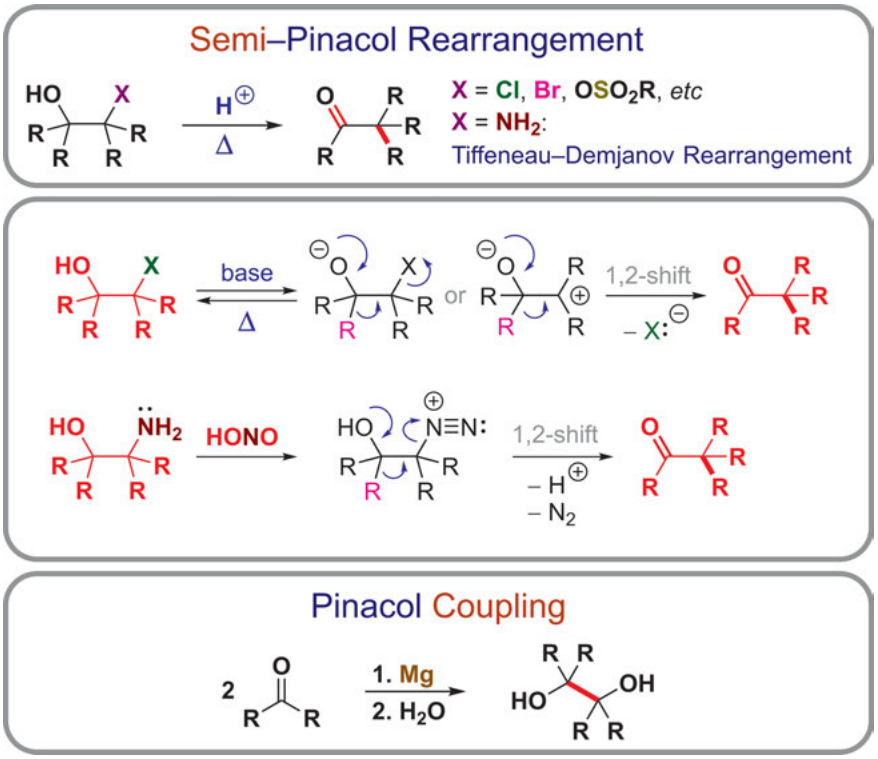


Fig. 76.2: The *semi-pinacol rearrangement* mechanism.[245]

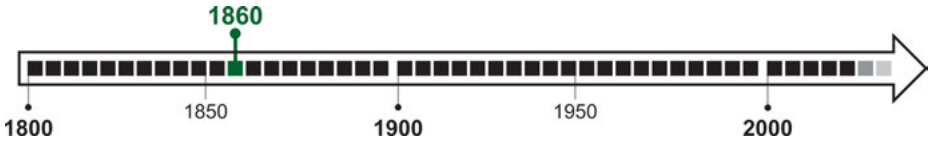


Fig. 76.3: The discovery of the *pinacol-pinacolone rearrangement*.[246]

245 The *semi-pinacol rearrangement* mechanism [1] is analogous to the *pinacol rearrangement*. It occurs in *α–substituted alcohols*. If X = NH_2, the reaction is called the ***Tiffeneau–Demjanov*** *rearrangement* [76a, 76b].

246 The reaction was likely first described around 1860 [76c].

77 Polonovski Reaction

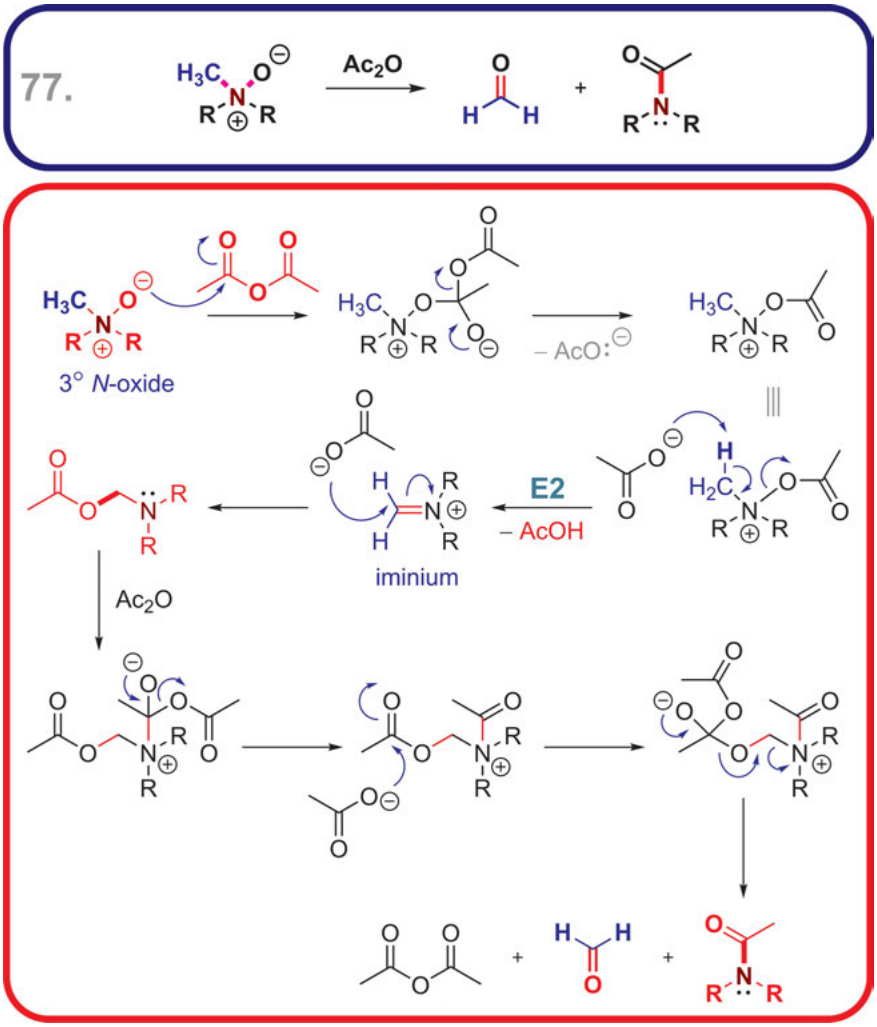


Fig. 77.1: The ***Polonovski*** *reaction* mechanism.[247]

247 The ***Polonovski*** *reaction* can be called the ***Polonovski*** *rearrangement*. The key intermediate is an *iminium ion* (see the ***Mannich*** *reaction* in Chapter 56).

https://doi.org/10.1515/9783110608373-077

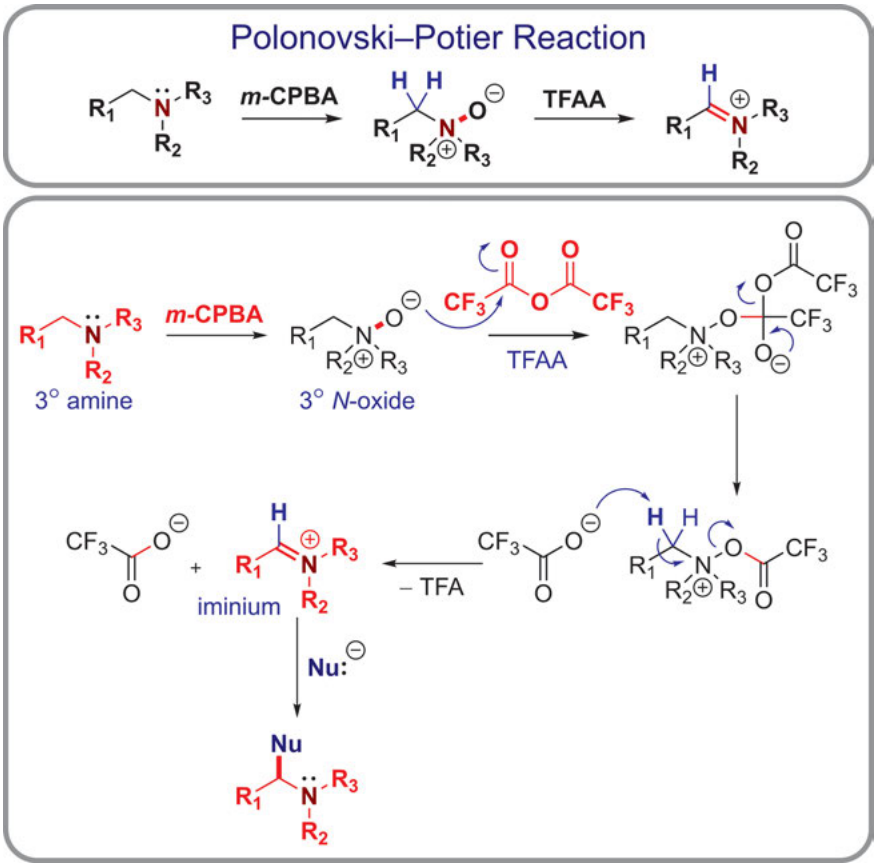


Fig. 77.2: The ***Polonovski–Potier*** *reaction* mechanism.[248]

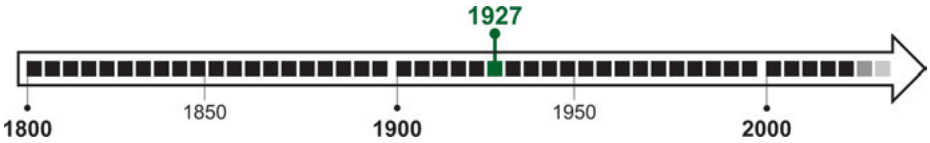


Fig. 77.3: The discovery of the ***Polonovski*** *reaction*.[249]

248 The ***Polonovski–Potier*** *reaction* is closely related [77a, 77b]. *Trifluoroacetic anhydride* (TFAA) is used instead of *acetic anhydride* and the *iminium ion* can be trapped with various nucleophiles.
249 The reaction was likely first described around 1927 [77c].

78 Prilezhaev Epoxidation

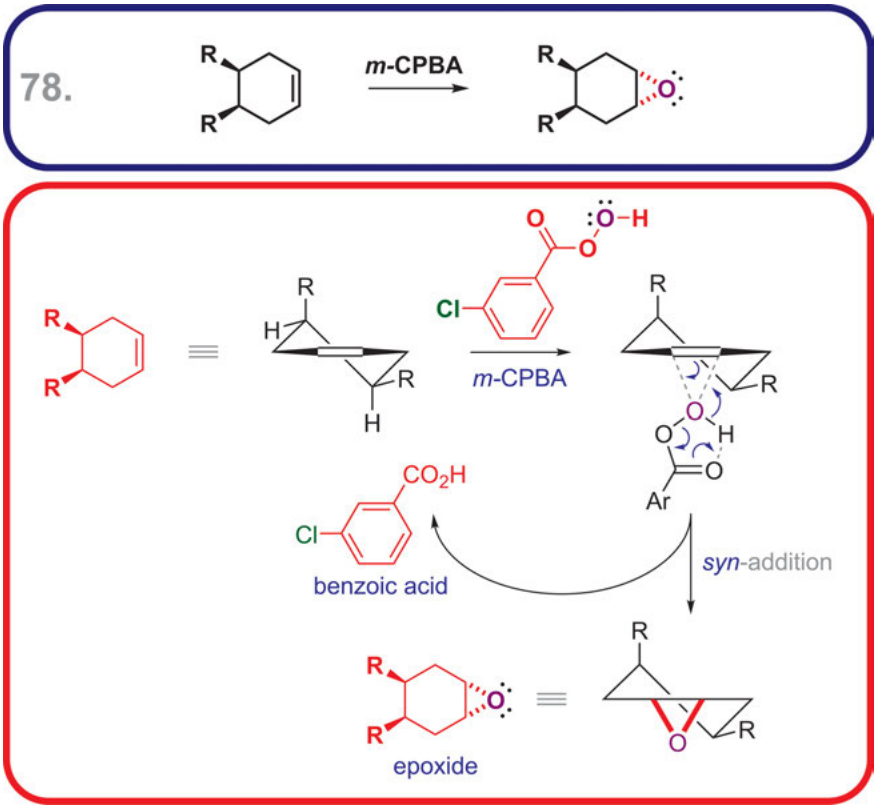


Fig. 78.1: The ***Prilezhaev*** *epoxidation* mechanism.[250]

250 The ***Prilezhaev*** *reaction* (in Russian Прилежаев) is a type of epoxidation, and it is often called the ***Prilezhaev*** *epoxidation*.

https://doi.org/10.1515/9783110608373-078

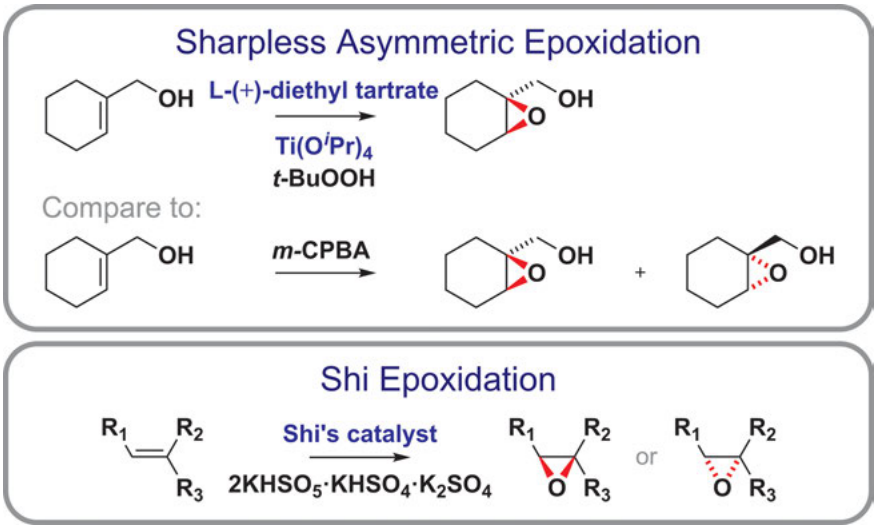


Fig. 78.2: Reactions related to the ***Prilezhaev*** *epoxidation*.[251]

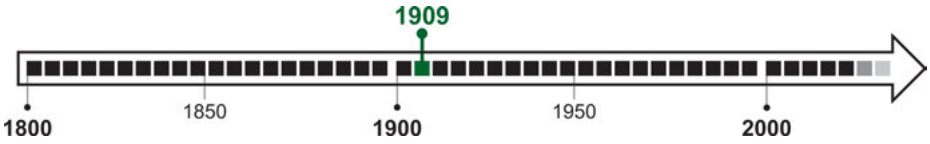


Fig. 78.3: The discovery of the ***Prilezhaev*** *epoxidation*.[252]

251 There are many ways to synthesize *epoxides*, such as: the ***Sharpless*** *asymmetric epoxidation* [78a] (compare to the ***Prilezhaev*** *epoxidation* where a mixture of enantiomers is formed); the ***Shi*** *asymmetric epoxidation* [78b], and many more other examples (not shown) [1].

252 The reaction was likely first described around 1909 [78c].

79 Prins Reaction

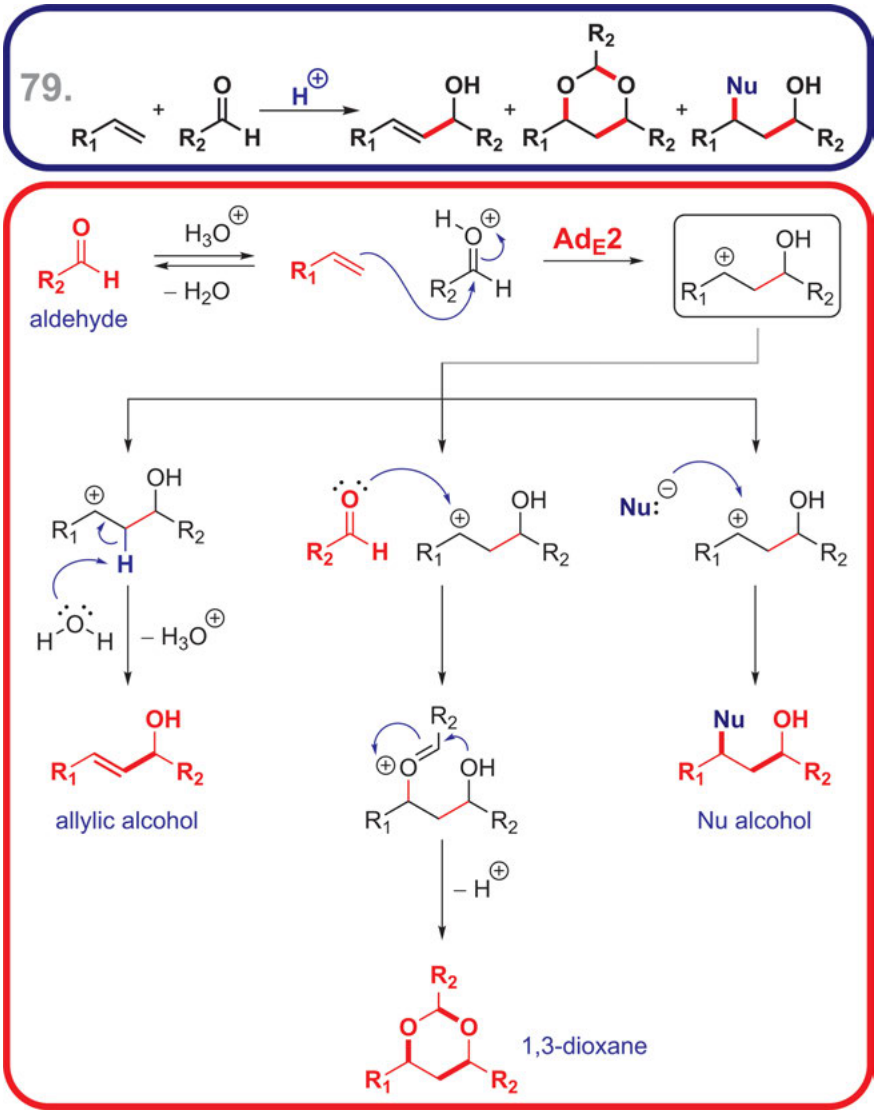


Fig. 79.1: The ***Prins** reaction* mechanism.[253]

253 The ***Prins** reaction* is a type of *condensation* with various possible products. Mechanistically (addition of a protonated *aldehyde* to an *alkene*), it is an example of the **electrophilic addition** covered in Chapter 1.

https://doi.org/10.1515/9783110608373-079

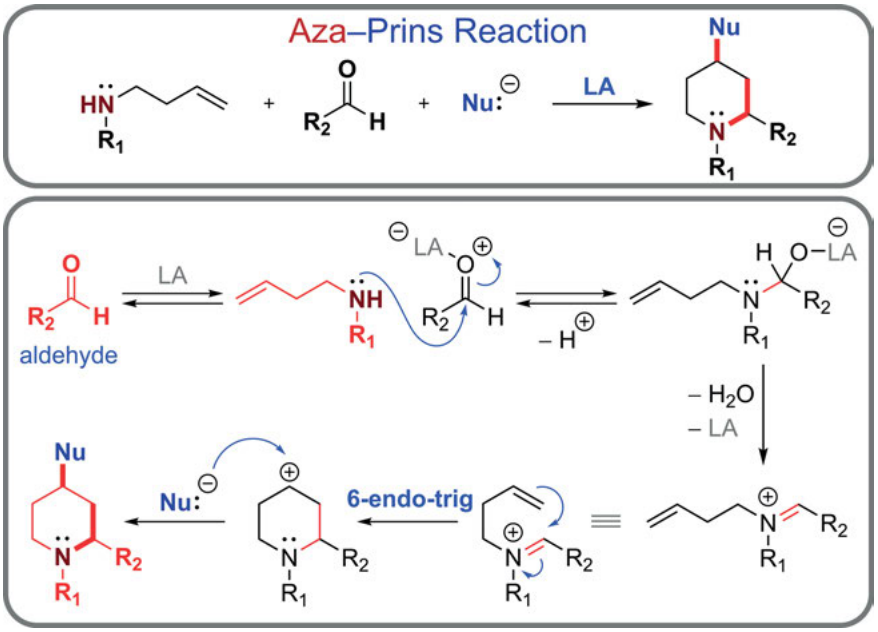


Fig. 79.2: The *aza-**Prins** reaction* mechanism.[254]

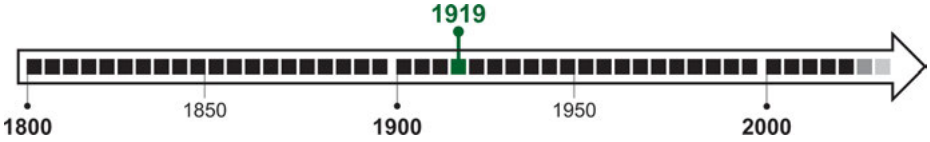


Fig. 79.3: The discovery of the ***Prins** reaction*.[255]

254 The *aza-**Prins** reaction* mechanism is related to the ***Prins** reaction* [79a, 79b]. It yields the *piperidine* core (see *Baldwin's rules* mentioned in Chapter 75: **6-endo-trig**). Other variations exist, for example the ***Prins**–pinacol reaction* (not shown here) [79c].

255 The reaction was likely first described around 1919 [79d, 79e].

80 Pummerer Rearrangement

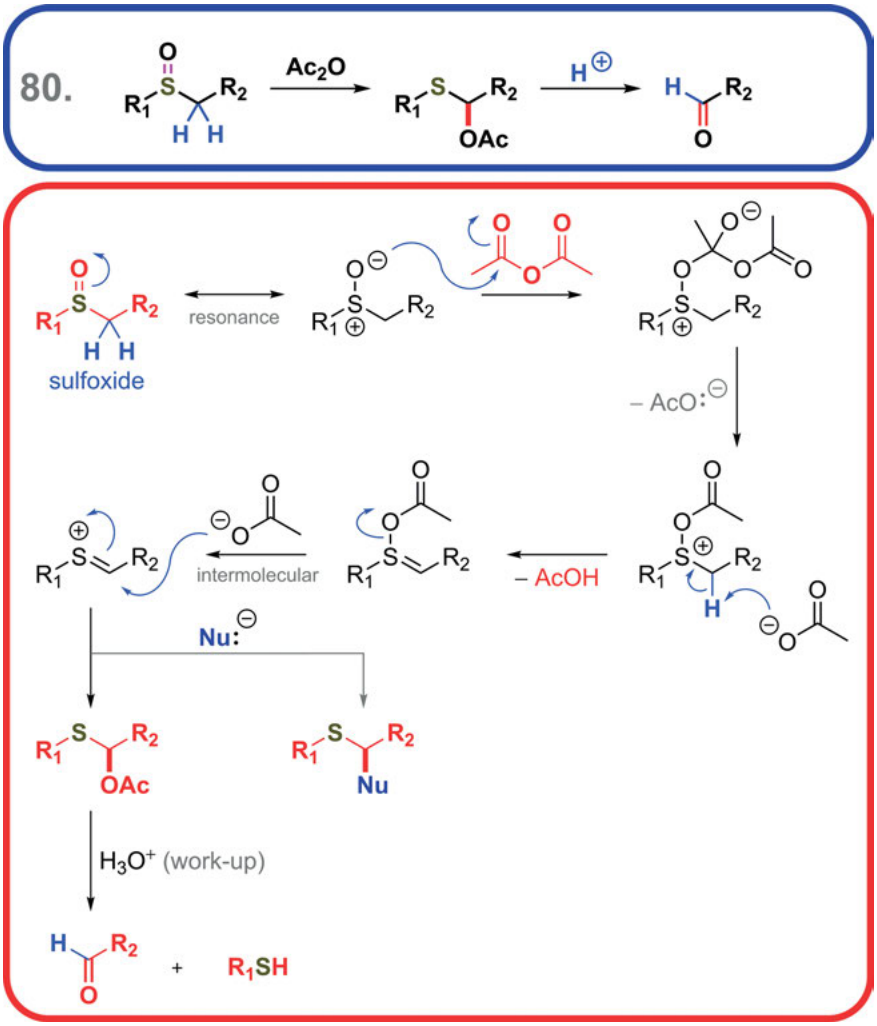


Fig. 80.1: The ***Pummerer*** *rearrangement* mechanism.[256]

256 The ***Pummerer*** *rearrangement* can be called the ***Pummerer*** *fragmentation*.

https://doi.org/10.1515/9783110608373-080

Fig. 80.2: Reactions related to the ***Pummerer*** *rearrangement*.[257]

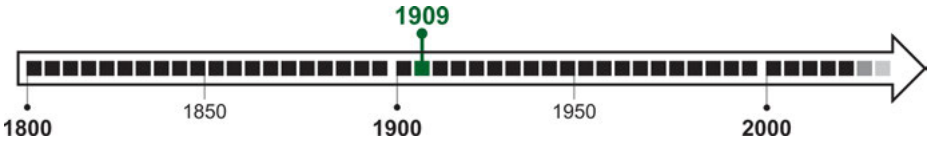


Fig. 80.3: The discovery of the ***Pummerer*** *rearrangement*.[258]

257 The ***Polonovski*** *reaction* mechanism (see Chapter 77) is related to the ***Pummerer*** *rearrangement*. An *amine oxide* (in the ***Polonovski*** *reaction*) plays similar role as a *sulfoxide* (in the ***Pummerer*** *rearrangement*).

258 The reaction was likely first described around 1909 [80].

81 Ramberg–Bäcklund Rearrangement

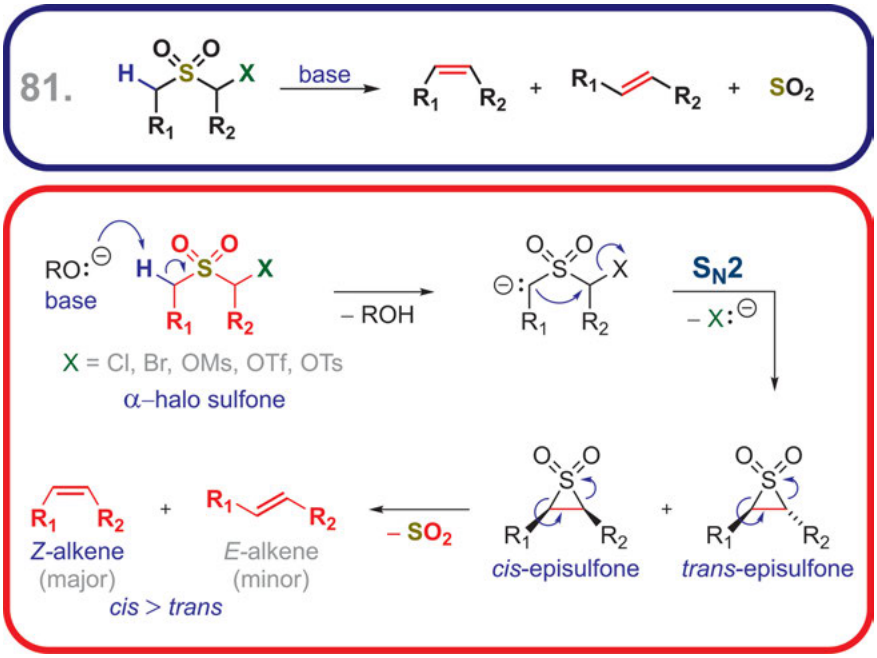


Fig. 81.1: The ***Ramberg–Bäcklund*** *rearrangement* mechanism.[259]

259 The ***Ramberg–Bäcklund*** *rearrangement* or the ***Ramberg–Bäcklund*** *reaction* mechanism is a combination of the bimolecular **nucleophilic substitution** (S_N2), covered in Chapter 2, and subsequent concerted **elimination** *(cheletropic elimination reaction)* [1a] and [81a].

https://doi.org/10.1515/9783110608373-081

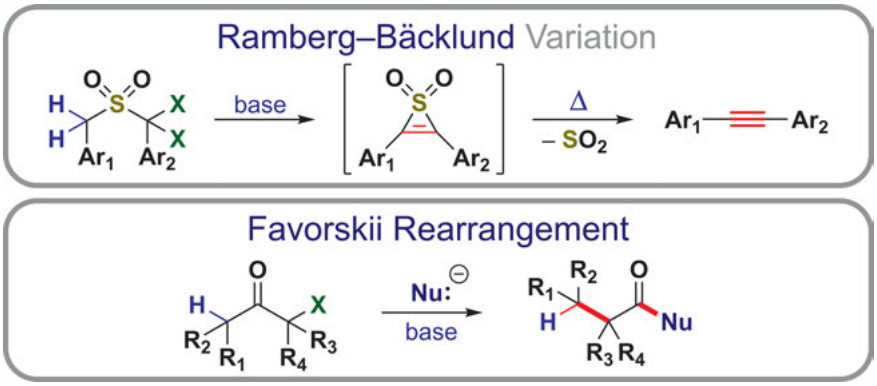


Fig. 81.2: Reactions related to the ***Ramberg–Bäcklund*** *rearrangement*.[260]

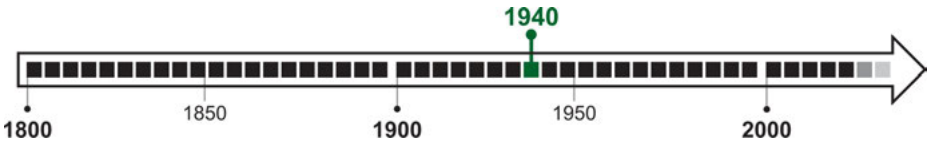


Fig. 81.3: The discovery of the ***Ramberg–Bäcklund*** *rearrangement*.[261]

260 There are several variations of the ***Ramberg–Bäcklund*** *rearrangement*; for example, the formation of *alkynes* instead of *alkenes* [81b] and [1a]. The **S_N2** step in the ***Favorskii*** *rearrangement* (covered in Chapter 37) is related to the ***Ramberg–Bäcklund*** *rearrangement*.

261 The reaction was likely first described around 1940 [81c].

82 Reformatsky Reaction

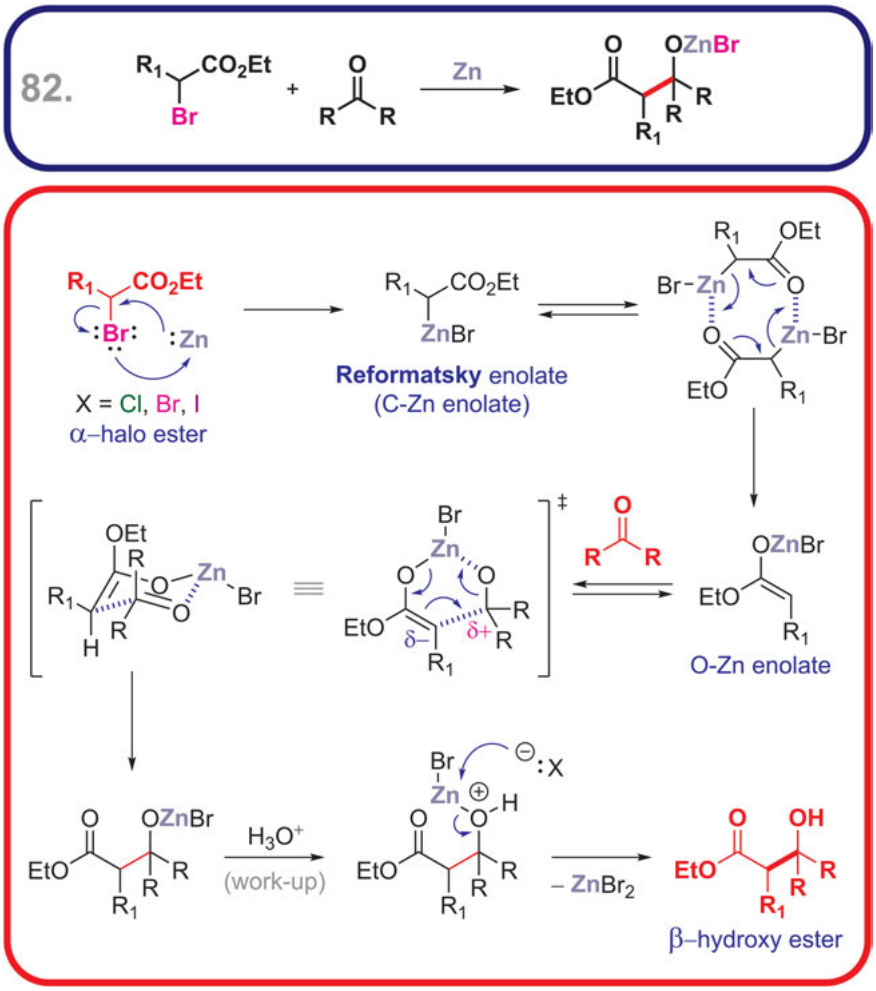


Fig. 82.1: The ***Reformatsky*** *reaction* mechanism.[262]

262 The ***Reformatsky*** *reaction (condensation)* (also spelled Reformatskii, and in Russian Сергей Николаевич Реформатский or С. Н. Реформатский) mechanistically is much like the *aldol condensation* reaction (see Chapter 83).

https://doi.org/10.1515/9783110608373-082

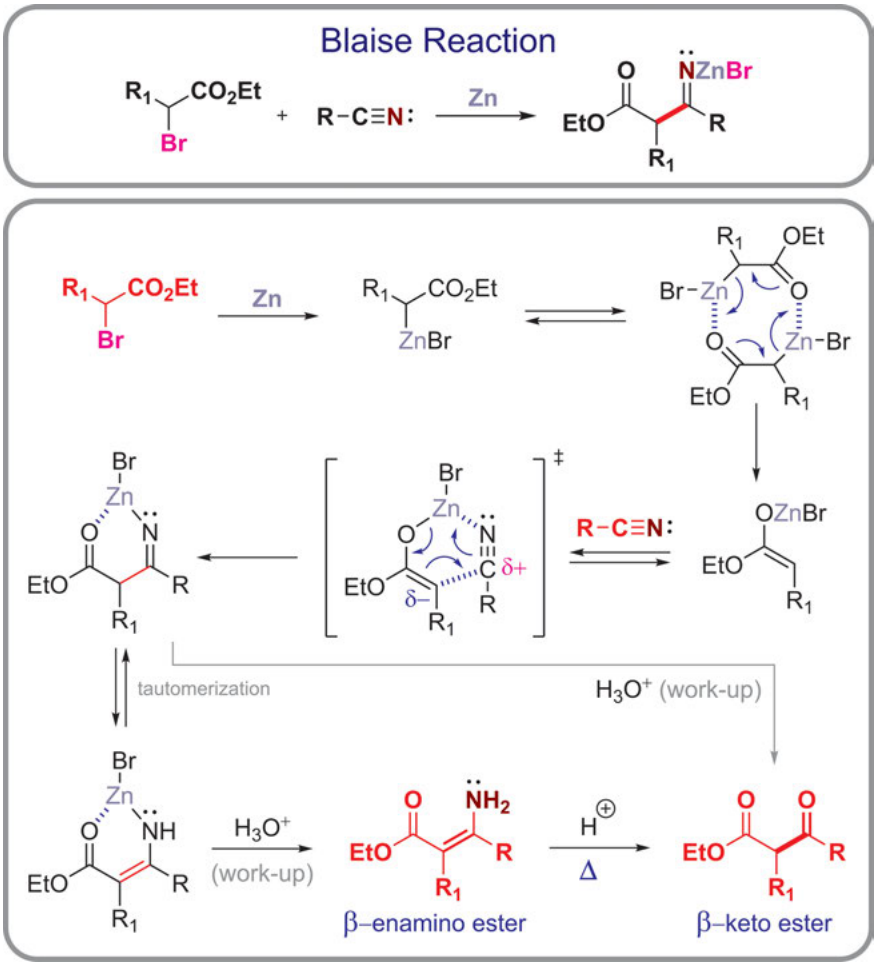


Fig. 82.2: The ***Blaise*** *reaction* mechanism.[263]

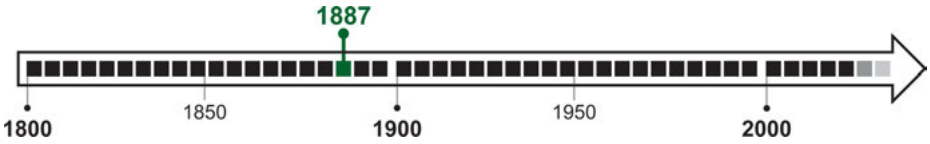


Fig. 82.3: The discovery of the ***Reformatsky*** *reaction*.[264]

263 The ***Blaise*** *reaction* is a variation of the ***Reformatsky*** *reaction* [82a, 82b]. In this case, the preformed ***Reformatsky*** *enolate (C-Zn or O-Zn enolate)* reacts with a *nitrile* instead of an *aldehyde* or *ketone*.

264 The reaction was likely first described around 1887 [82].

83 Robinson Annulation

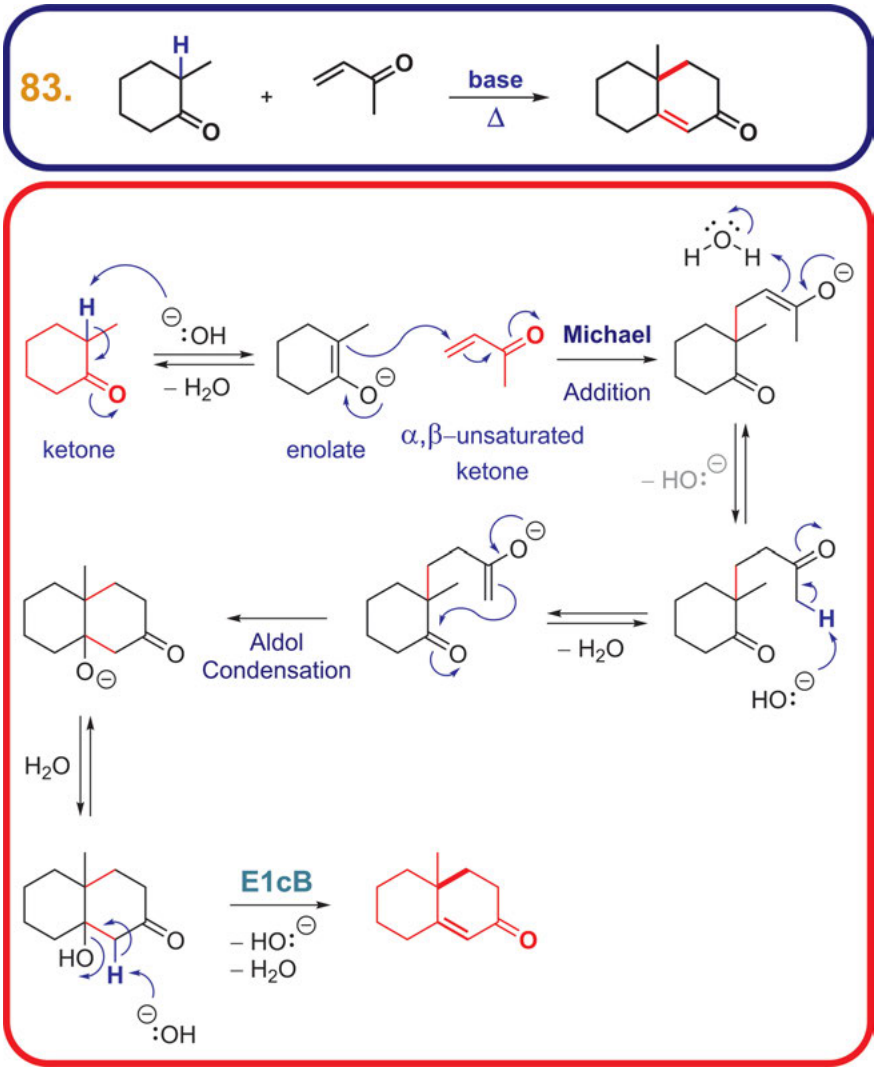


Fig. 83.1: The ***Robinson*** *annulation* mechanism.[265]

265 The ***Robinson*** *annulation* mechanism is a cascade of the ***Michael*** *conjugate addition* (see Chapter 59), followed by the *aldol condensation*, and finally **E1cB** *elimination* (see Chapter 6).

https://doi.org/10.1515/9783110608373-083

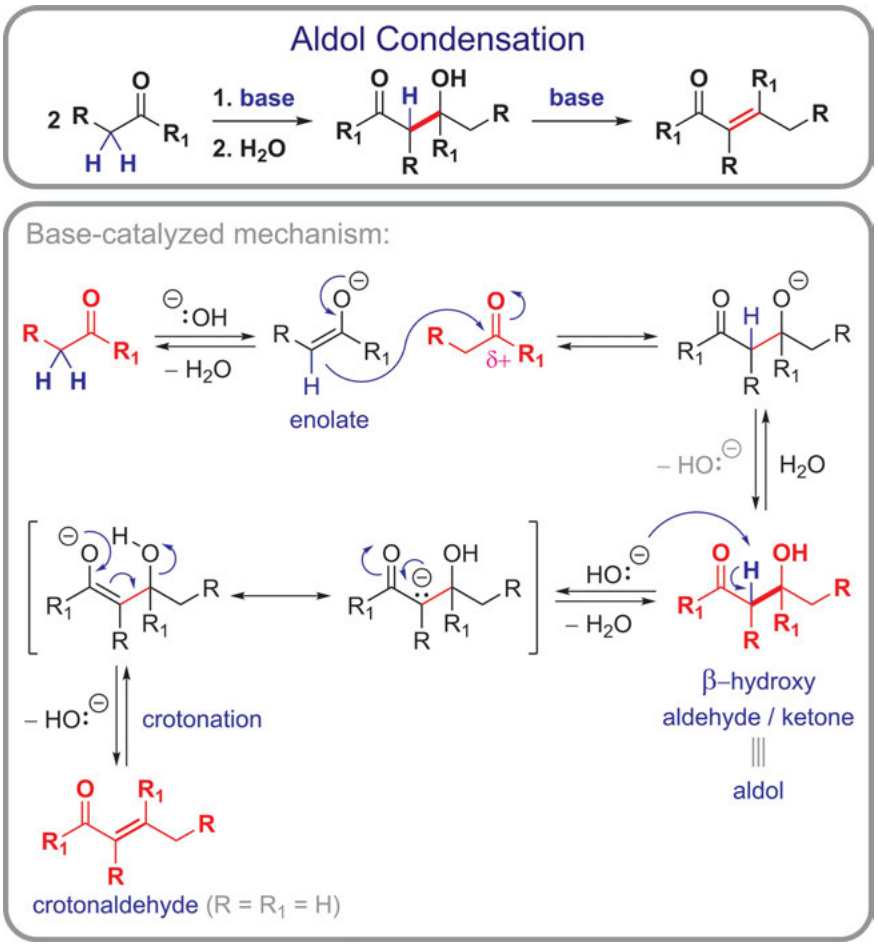


Fig. 83.2: The *aldol condensation* mechanism.[266]

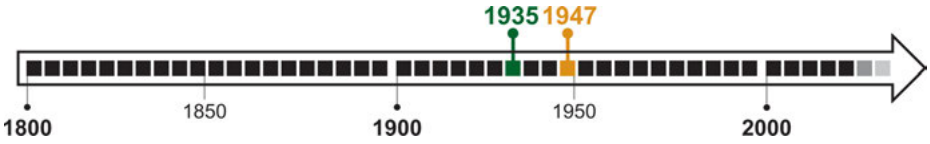


Fig. 83.3: The discovery of the ***Robinson*** *annulation*.[267]

266 The *base-catalyzed aldol condensation* can yield *β–hydroxy aldehydes* (***aldols***) or ketones. The formed *aldols* can undergo an elimination and yield *crotonaldehydes* (the *croton condensation* = *crotonation)* [1].

267 The reaction was likely first described around 1935 [83a]. In **1947**, Sir Robert Robinson received the Nobel Prize in Chemistry for his work related to alkaloids [83b].

84 Shapiro Reaction

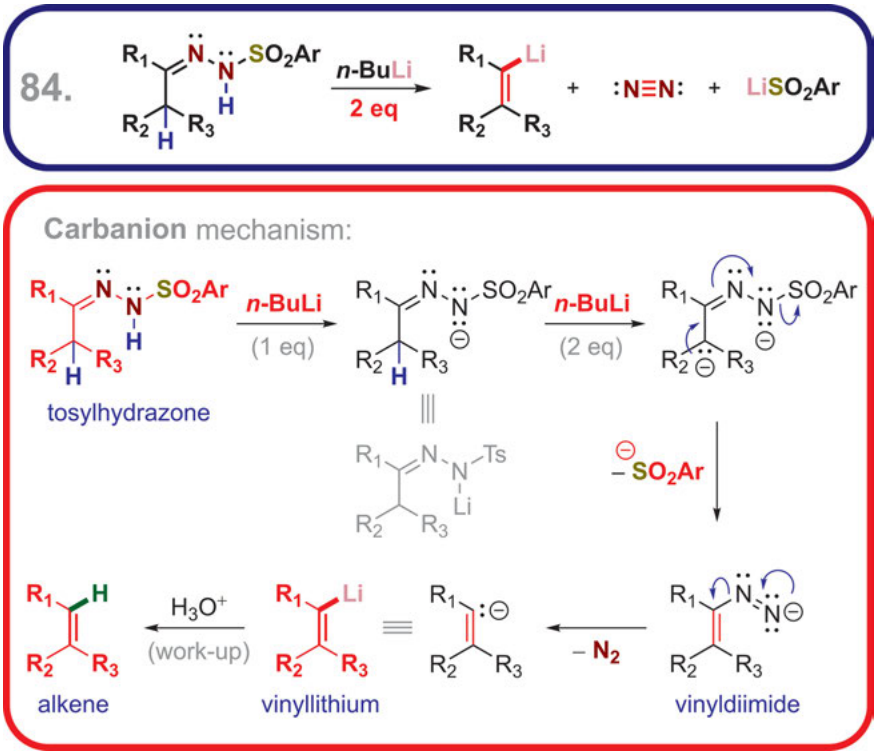


Fig. 84.1: The ***Shapiro*** *reaction* mechanism.[268]

268 The ***Shapiro*** *reaction* is a type of **elimination** reaction that undergoes the *carbanion* mechanism.

https://doi.org/10.1515/9783110608373-084

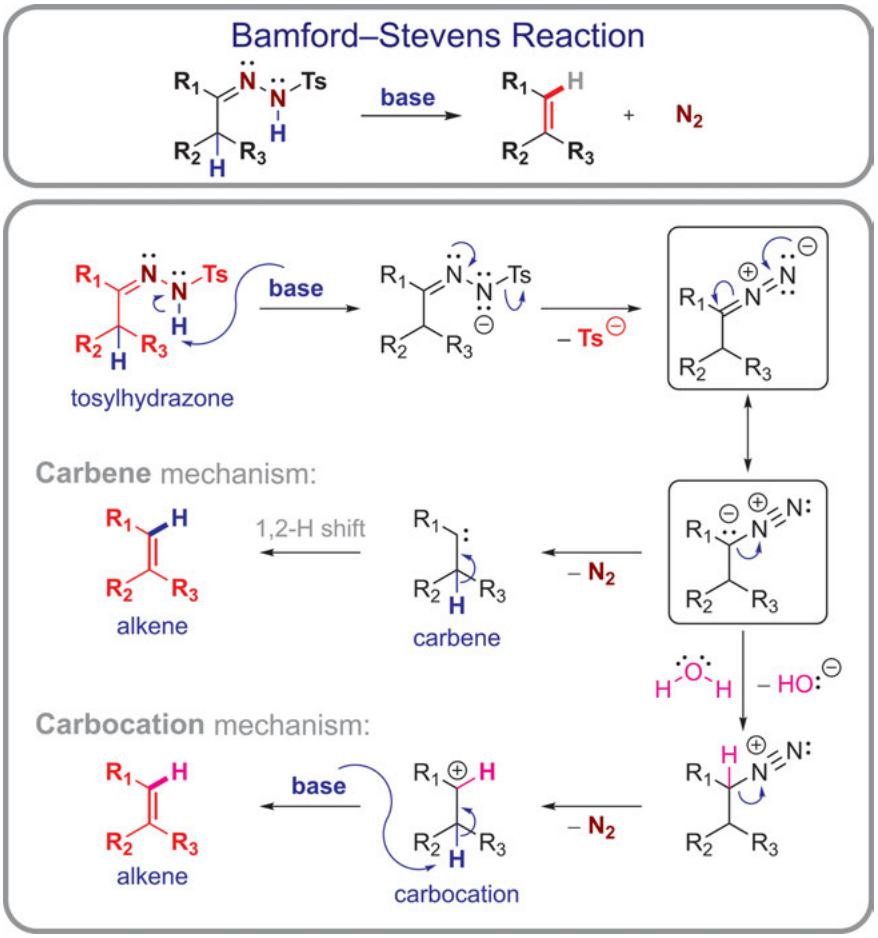


Fig. 84.2: The ***Bamford–Stevens*** *reaction* mechanism.[269]

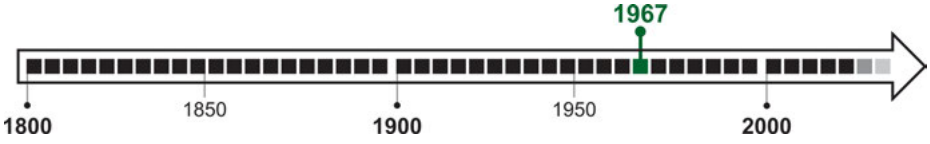


Fig. 84.3: The discovery of the ***Shapiro*** *reaction*.[270]

269 The ***Bamford–Stevens*** *reaction* is a more general variation of the ***Shapiro*** *reaction*. Two mechanisms are possible: the *carbene* mechanism and the *carbocation* mechanism (the *carbenium ion* mechanism) [84a].

270 The reaction was likely first described around 1967 [84b], see also [84c, 84d].

85 Sonogashira Cross Coupling

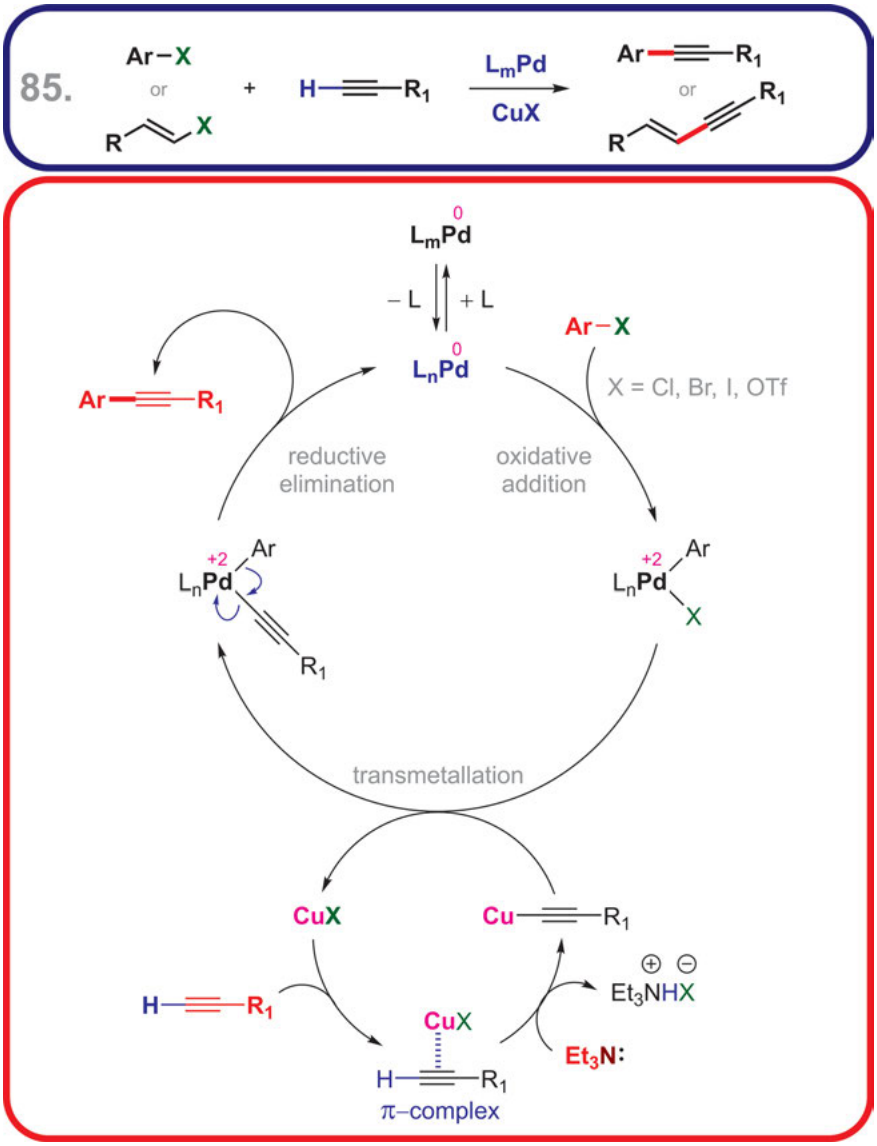


Fig. 85.1: The ***Sonogashira*** *cross coupling* mechanism.[271]

271 The ***Sonogashira*** *cross coupling* is a type of mixed ***Pd****-catalyzed* and ***Cu****-co-catalyzed cross coupling* reaction (C–C bond formation using *aryl halides* and *terminal alkynes*). For teaching purposes, a simplified and general mechanism (with two catalytic cycles using **Pd** and **Cu**) is shown.

https://doi.org/10.1515/9783110608373-085

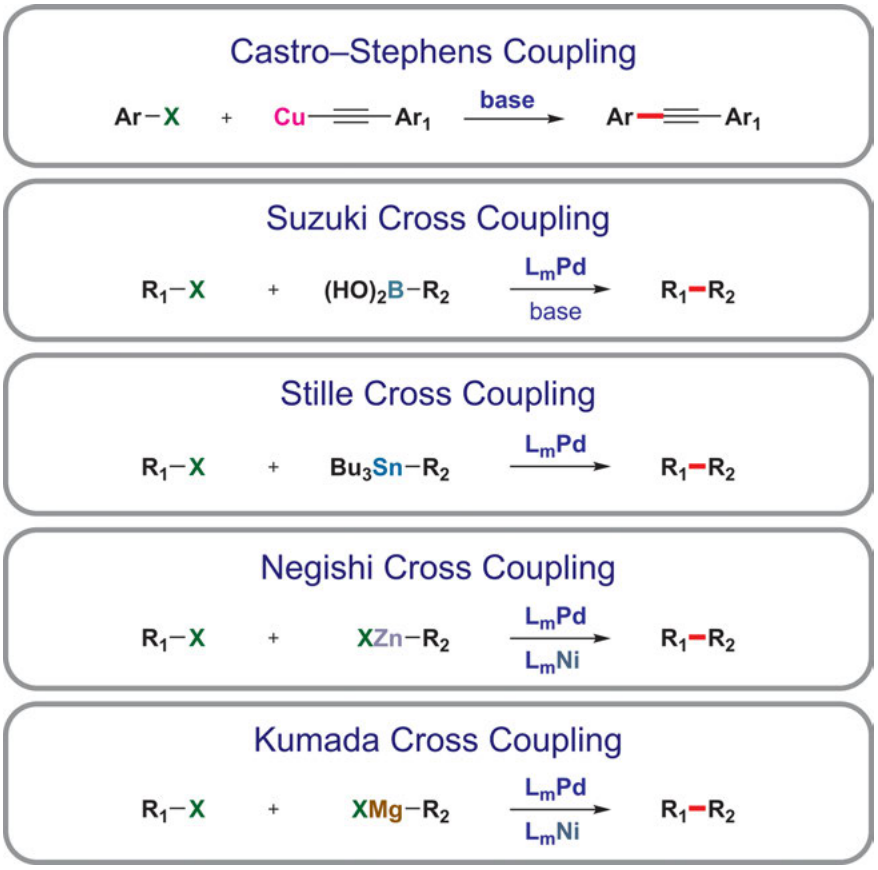


Fig. 85.2: Reactions related to the ***Sonogashira*** *cross coupling*.[272]

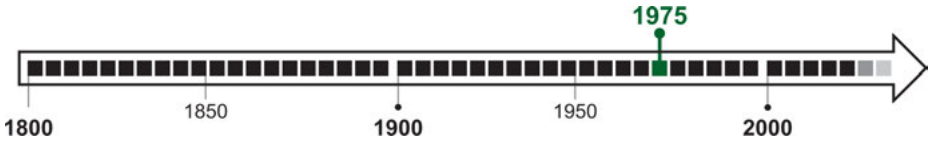


Fig. 85.3: The discovery of the ***Sonogashira*** *cross coupling*.[273]

272 The ***Castro–Stephens*** *cross coupling* is ***Cu****-catalyzed* and closely related (C–C bond formation using *aryl halides* and pre-formed or *in situ* generated *copper(I) acetylides*) [85a]. Other cross coupling reactions are also related to the ***Sonogashira*** *cross coupling:* the ***Suzuki*** (Chapter 89), the ***Stille*** (Chapter 88), the ***Negishi*** (Chapter 66), and the ***Kumada*** *cross coupling* (Chapter 53).

273 The reaction was likely first described around 1975 [85b].

86 Staudinger Reaction

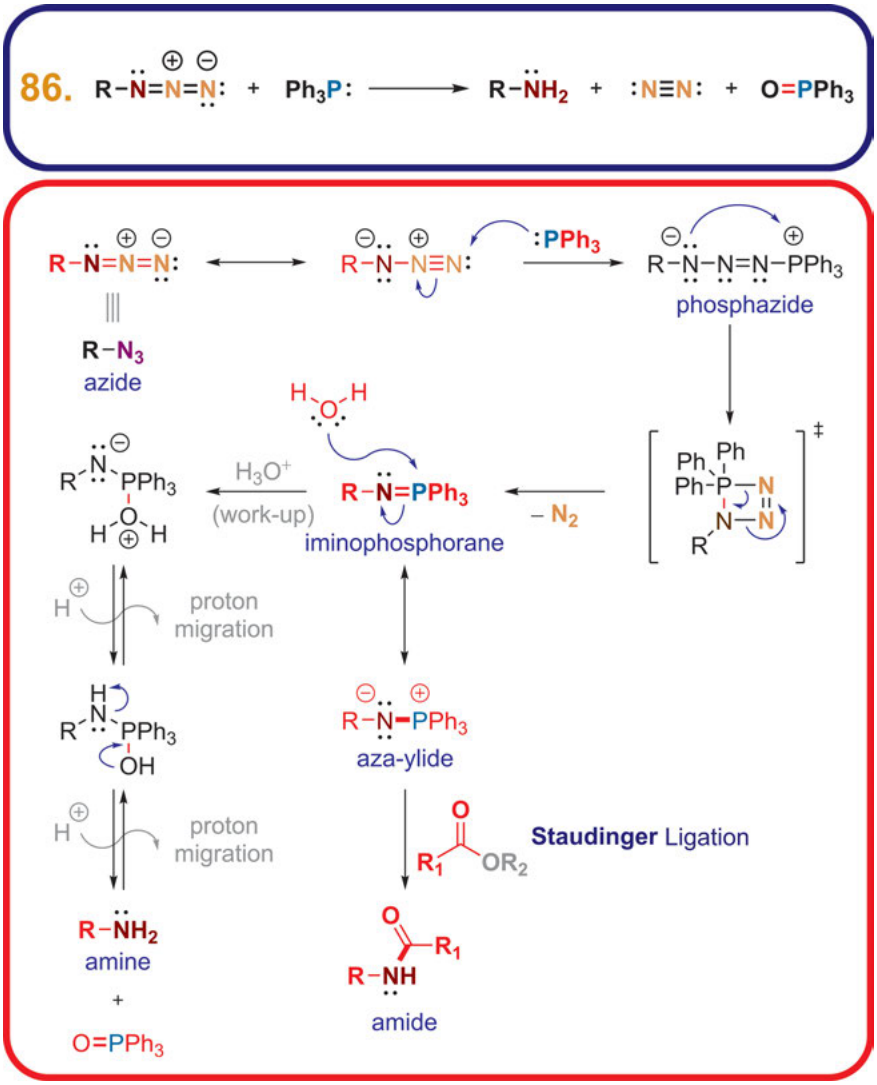


Fig. 86.1: The ***Staudinger*** *reaction* mechanism.[274]

274 The ***Staudinger*** *reaction (reduction)* is a reduction of *azides* to primary amines using *triphenylphosphine*. It should not be confused with the ***Staudinger*** *synthesis or* the ***Staudinger*** *ketene cycloaddition reaction* (for example, formation of *β–lactams*) [86a, 86b].

https://doi.org/10.1515/9783110608373-086

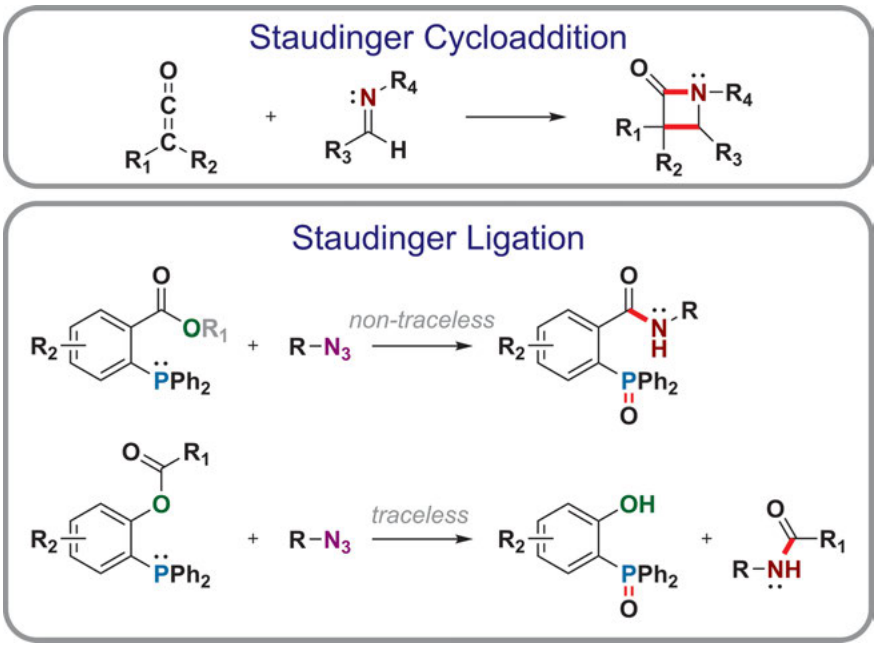


Fig. 86.2: The ***Staudinger*** *cycloaddition* and *ligation*.[275]

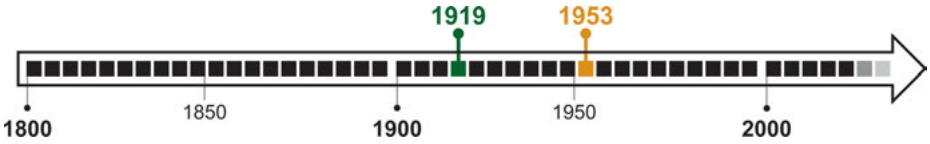


Fig. 86.3: The discovery of the ***Staudinger*** *reaction*.[276]

275 The ***Staudinger*** *ligation* [86c, 86d] is a modification of the ***Staudinger*** *reaction*: in this case, the generated *aza-ylide* is trapped with an *ester* to form an *amide* bond. There are two general types: *non-traceless* and *traceless* ***Staudinger*** *ligation* [86e].

276 The reaction was likely first described around 1919 [86f]. In **1953**, Hermann Staudinger received the Nobel Prize in Chemistry for his work in macromolecular chemistry [86g].

87 Steglich Esterification

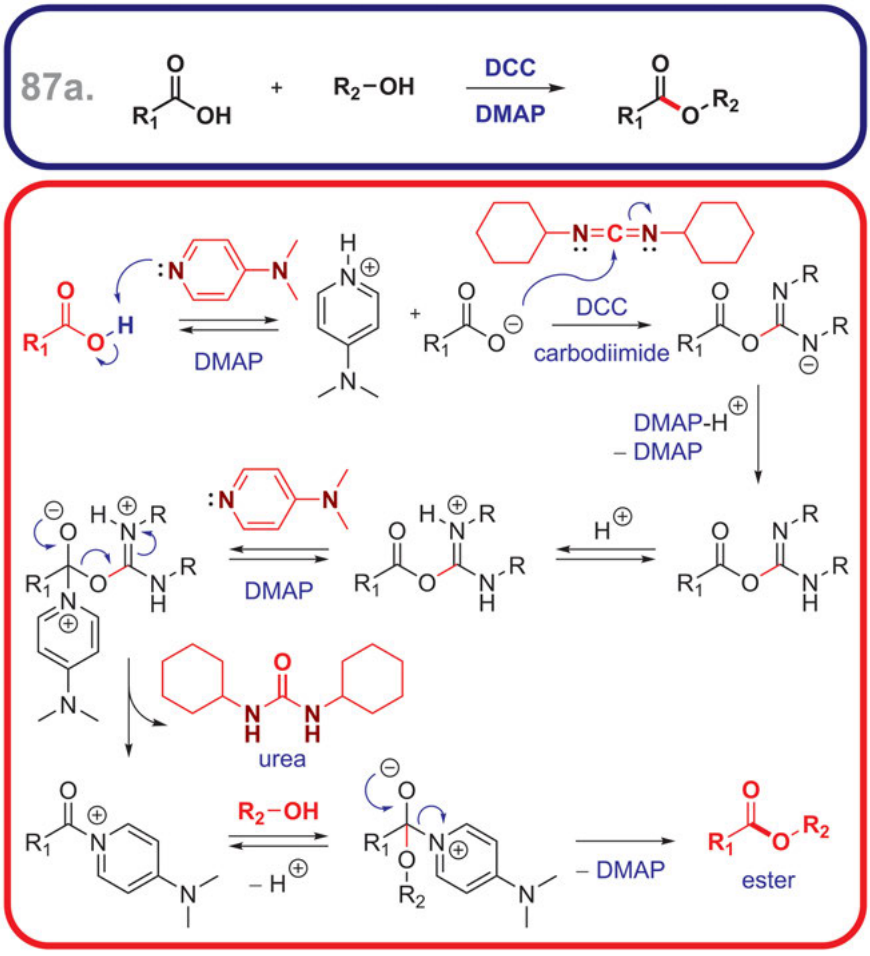


Fig. 87.1: The ***Steglich*** *esterification* mechanism (DCC + DMAP).[277]

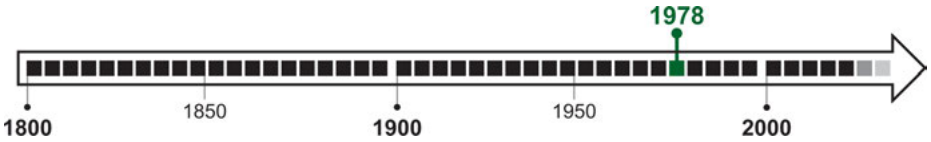


Fig. 87.2: The discovery of the ***Steglich*** *esterification*.[278]

277 The ***Steglich*** *esterification* is an *ester coupling reaction* (compare to the *peptide (amide) coupling* mechanism in Chapter 74 or the ***Fischer*** *esterification* – not covered here). The mechanism involves

https://doi.org/10.1515/9783110608373-087

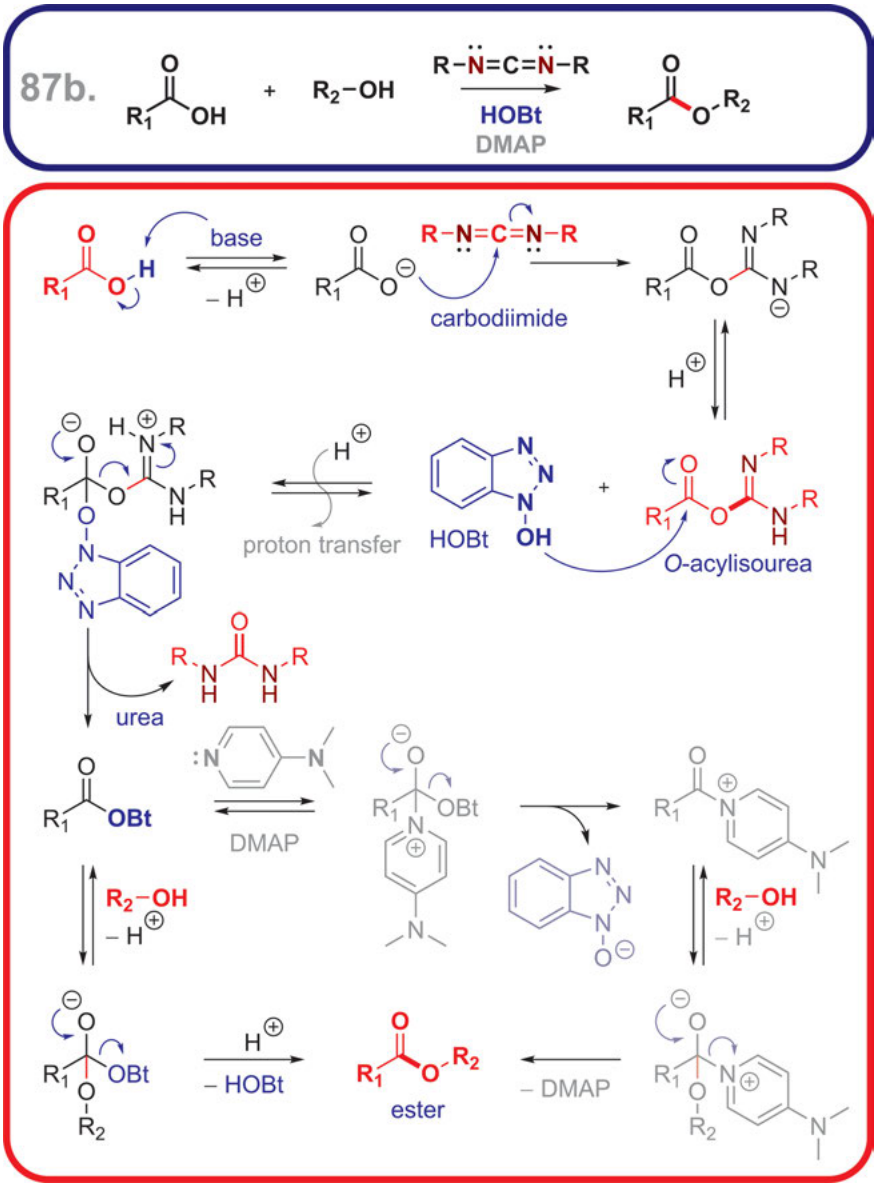


Fig. 87.3: The ***Steglich*** *esterification* mechanism (DCC + HOBt + DMAP).[279]

the use of *carbodiimide* coupling reagents (DCC) and DMAP catalyst [87a].

278 The reaction was likely first described around 1978 [87b].

279 The ***Steglich*** *esterification* can be carried out with DCC in the presence of other *peptide (amide) coupling additives* (for example, HOBt) with or without DMAP catalyst.

88 Stille Cross Coupling

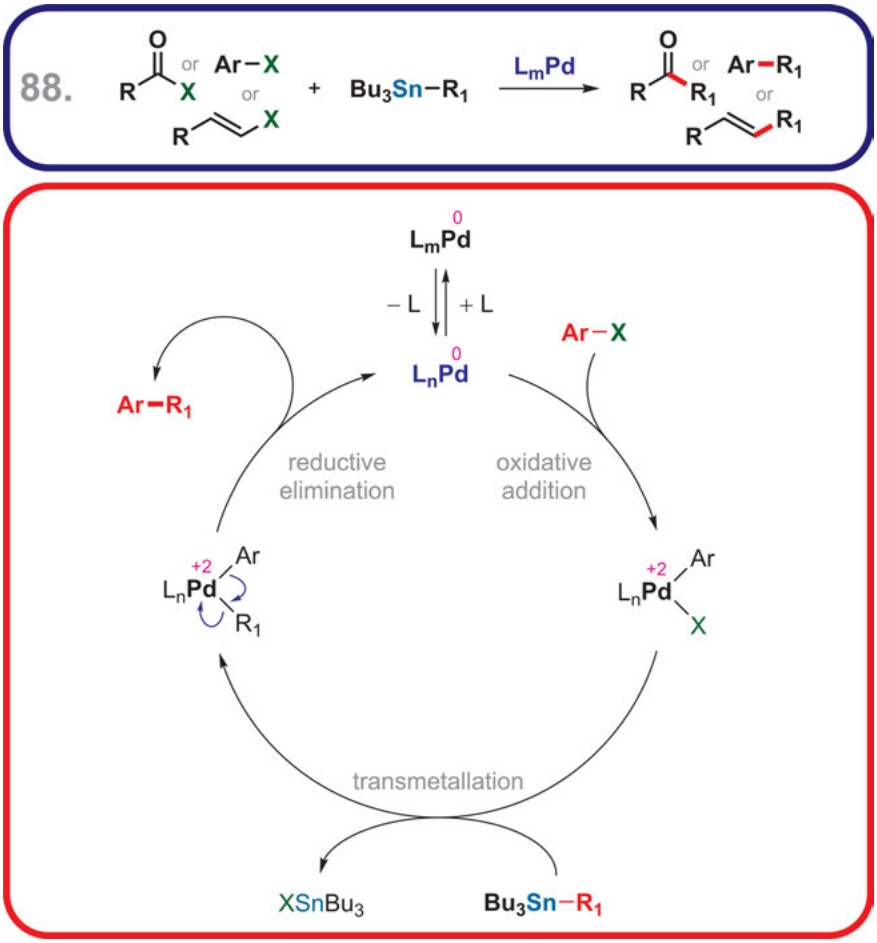


Fig. 88.1: The ***Stille*** *cross coupling* mechanism.[280]

280 The ***Stille*** *cross coupling* or the ***Migita–Kosugi–Stille*** *cross coupling* is a versatile type of ***Pd***-*catalyzed cross coupling* reaction (C–C bond formation using *aryl halides* or other *electrophiles* and *organotin compounds* = *organostannanes*). For teaching purposes, a simplified and general mechanism is shown.

https://doi.org/10.1515/9783110608373-088

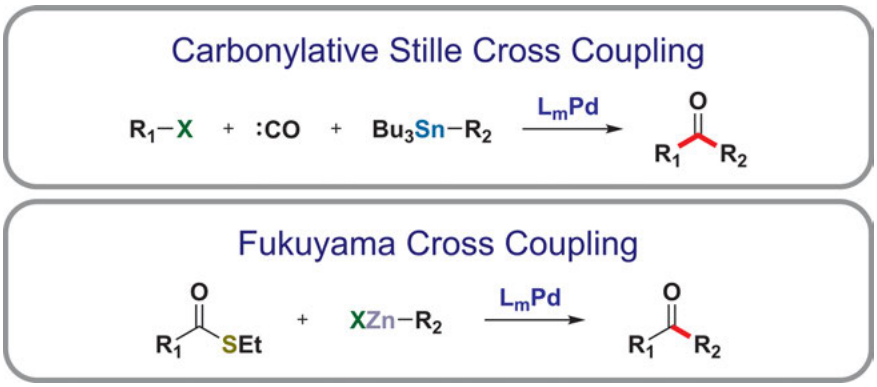


Fig. 88.2: Reactions related to the ***Stille*** *cross coupling*.[281]

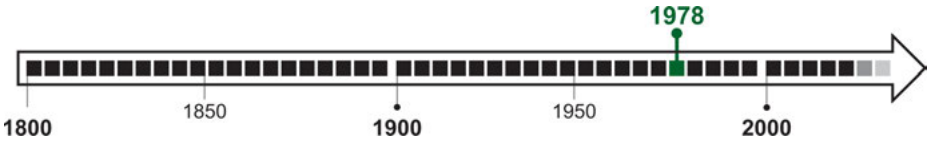


Fig. 88.3: The discovery of the ***Stille*** *cross coupling*.[282]

281 The *carbonylative* ***Stille*** *cross coupling* is related to the ***Stille*** *cross coupling*. It is a method to form *ketones* (two C–C bond formations using *aryl halides* or other *electrophiles*, *organostannanes*, and *carbon monoxide*) [88a]. Ketones can also be formed via the ***Fukuyama*** *cross coupling* (C–C bond formation using *thioesters* and *organozinc compounds*) [88b] or the ***Liebeskind–Srogl*** *cross coupling* covered in Chapter 55 (C–C bond formation using *thioesters* and *boronic acids*).

282 The reaction was likely first described around 1978 [88c, 88d].

89 Suzuki Cross Coupling

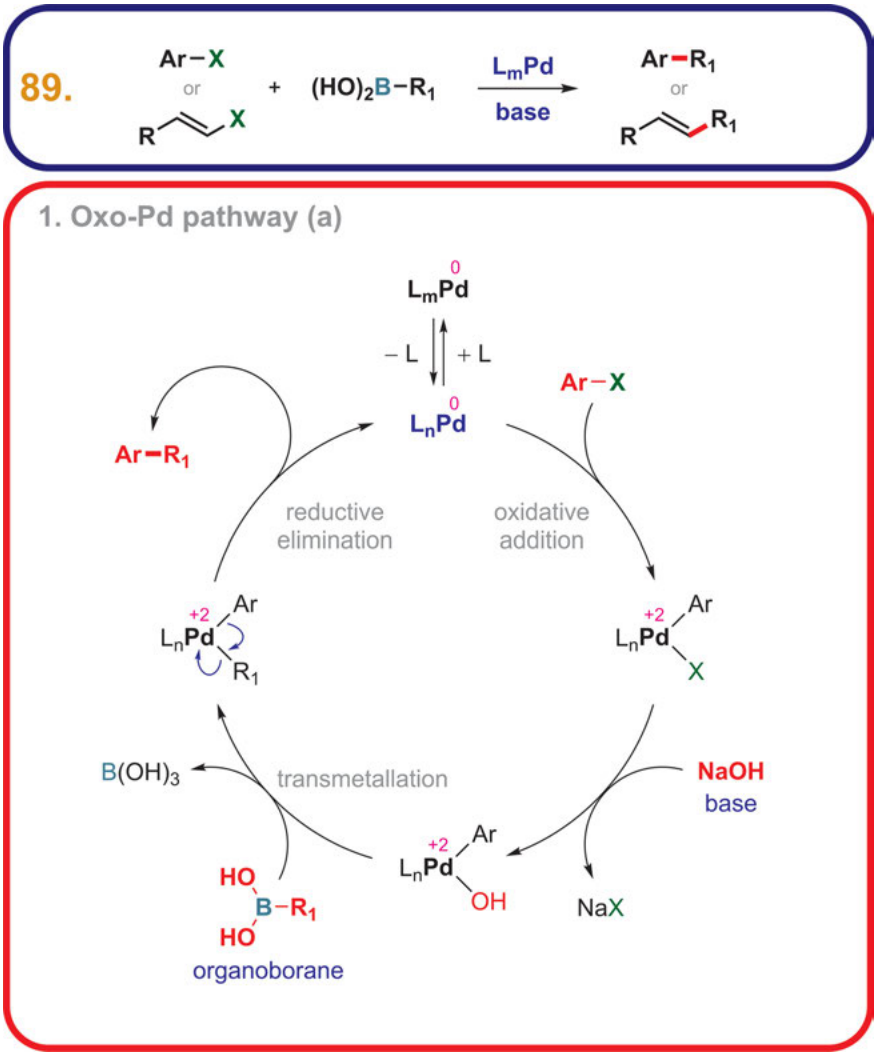


Fig. 89.1: The ***Suzuki*** *cross coupling* mechanism (oxo-**Pd** pathway (**a**)).[283]

283 The ***Suzuki*** *cross coupling* or the ***Suzuki–Miyaura*** *cross coupling* is a type of ***Pd****-catalyzed cross coupling* reaction (C–C bond formation using *aryl halides* and *organoboronic acids*). It is one of the most important reactions in synthetic organic and medicinal chemistry. The *oxo-**Pd** pathway* (**a**) is the preferred mechanism [89a].

https://doi.org/10.1515/9783110608373-089

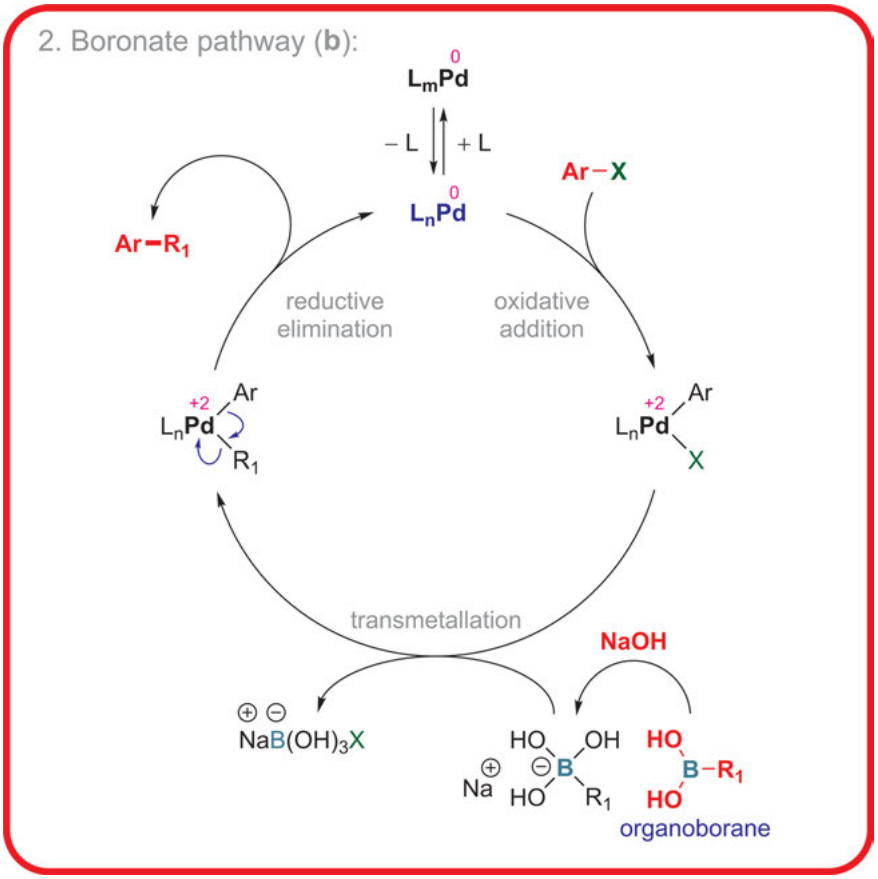


Fig. 89.2: The ***Suzuki*** *cross coupling* mechanism (boronate pathway (**b**)).[284]

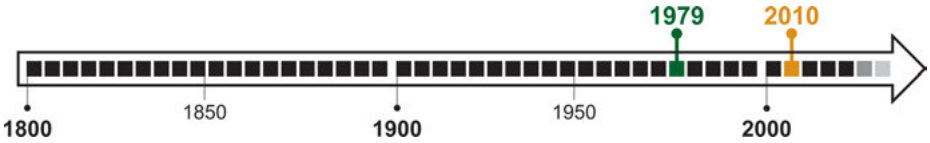


Fig. 89.3: The discovery of the ***Suzuki*** *cross coupling*.[285]

284 The reaction mechanism can also be explained by the *boronate pathway* (**b**). For teaching purposes, a simplified and general mechanism is shown [89b].

285 The reaction was likely first described around 1979 [89c, 89d]. In **2010**, Akira Suzuki (jointly with Richard F. Heck and Ei-ichi Negishi) received the Nobel Prize in Chemistry for the development of **Pd**-catalyzed cross coupling reactions [46c].

90 Swern Oxidation

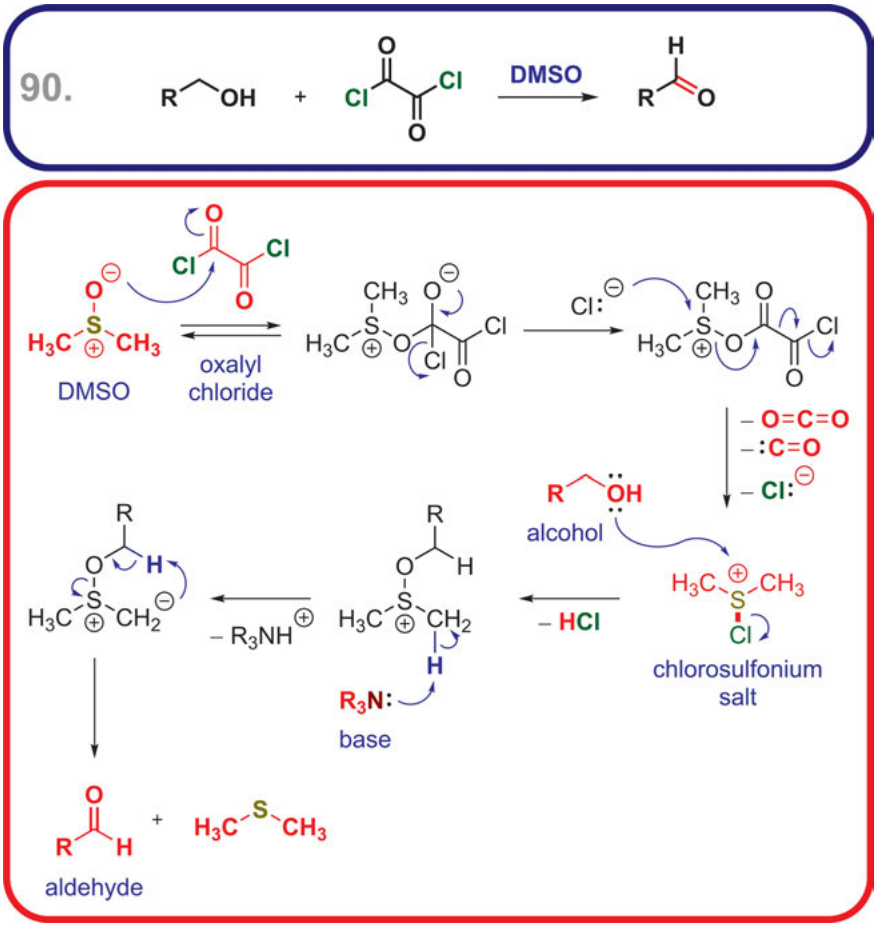


Fig. 90.1: The ***Swern*** *oxidation* mechanism.[286]

286 The ***Swern*** *oxidation* is one of the most important reactions in synthetic organic and medicinal chemistry.

https://doi.org/10.1515/9783110608373-090

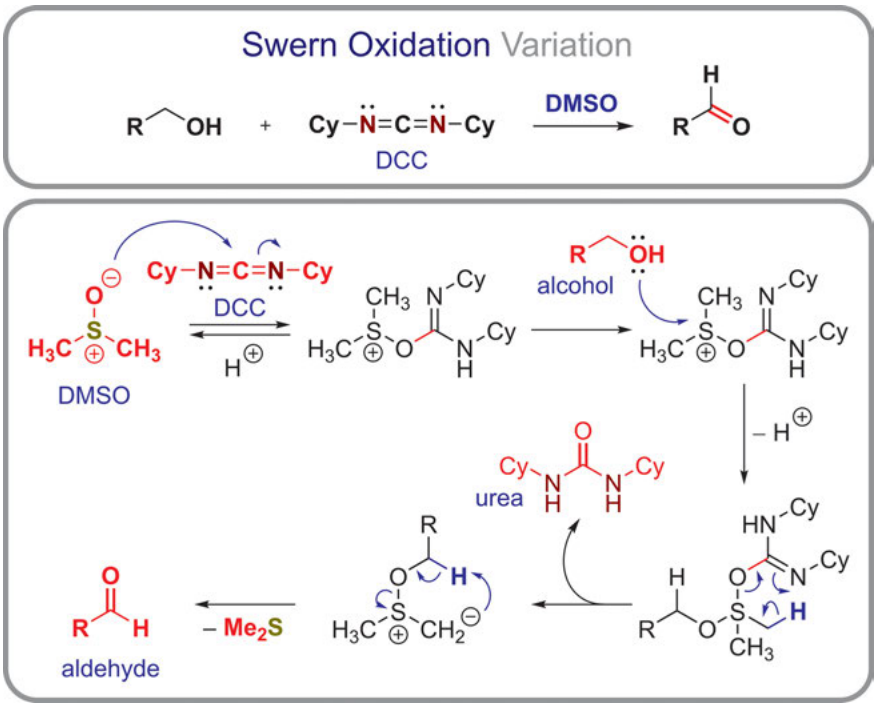


Fig. 90.2: The ***Swern*** *oxidation* variation mechanism (DCC + DMSO).[287]

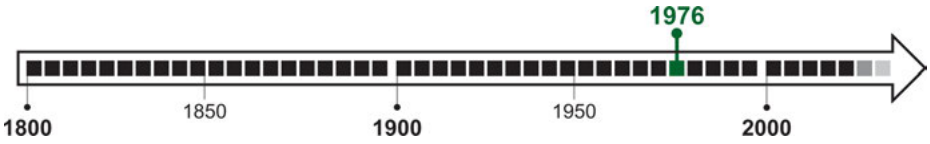


Fig. 90.3: The discovery of the ***Swern*** *oxidation*.[288]

287 There are numerous variations of the ***Swern*** *oxidation*: the ***Swern*** *variation* using TFAA and DMSO [90a] or *carbodiimide reagent* (DCC) and DMSO [90b]. Several important named oxidation reactions yield *ketones* from *alcohols*: the ***Dess–Martin*** *oxidation* (Chapter 33), the ***Jones*** *oxidation* (Chapter 51).

288 The reaction was likely first described around 1976 [90a], see also [90c, 90d].

91 Ugi Reaction

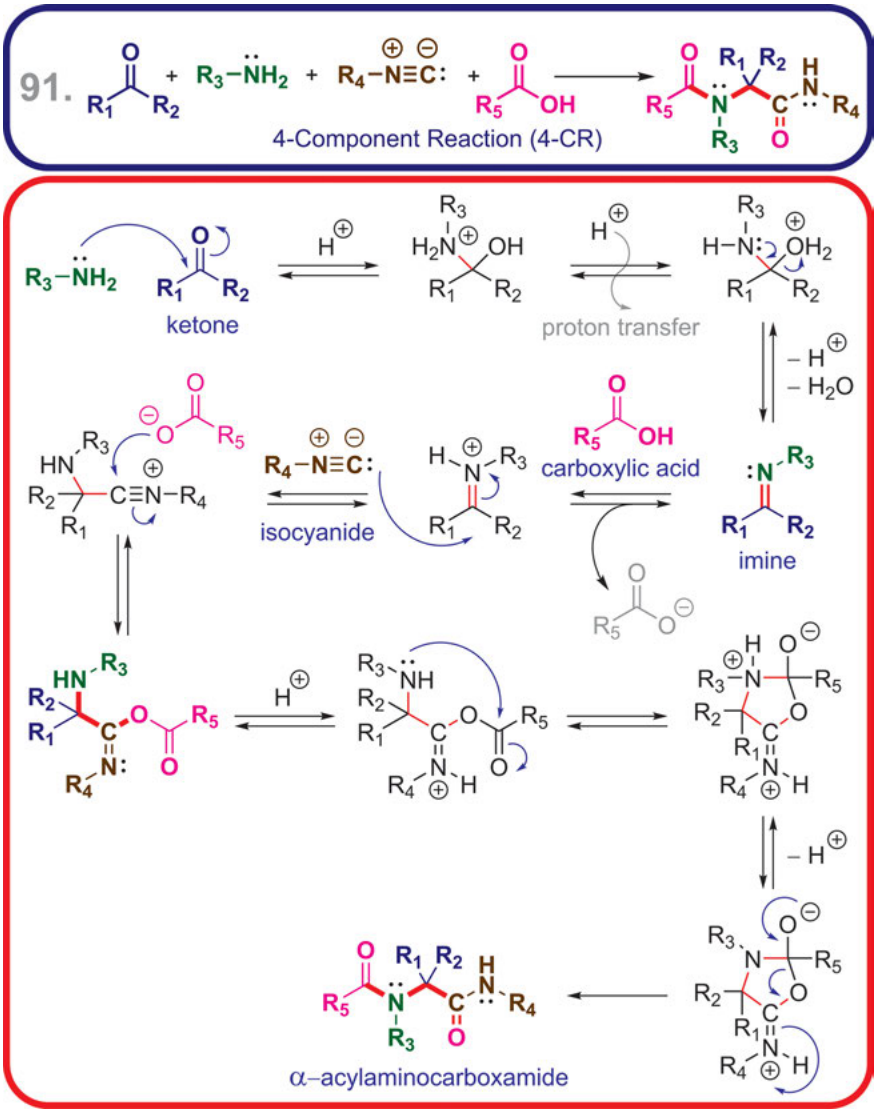


Fig. 91.1: The ***Ugi*** *reaction* mechanism.[289]

289 The ***Ugi*** *reaction* or the ***Ugi*** *condensation* is a type of multi-component reaction (MCR): a four-component reaction (4-CR).

https://doi.org/10.1515/9783110608373-091

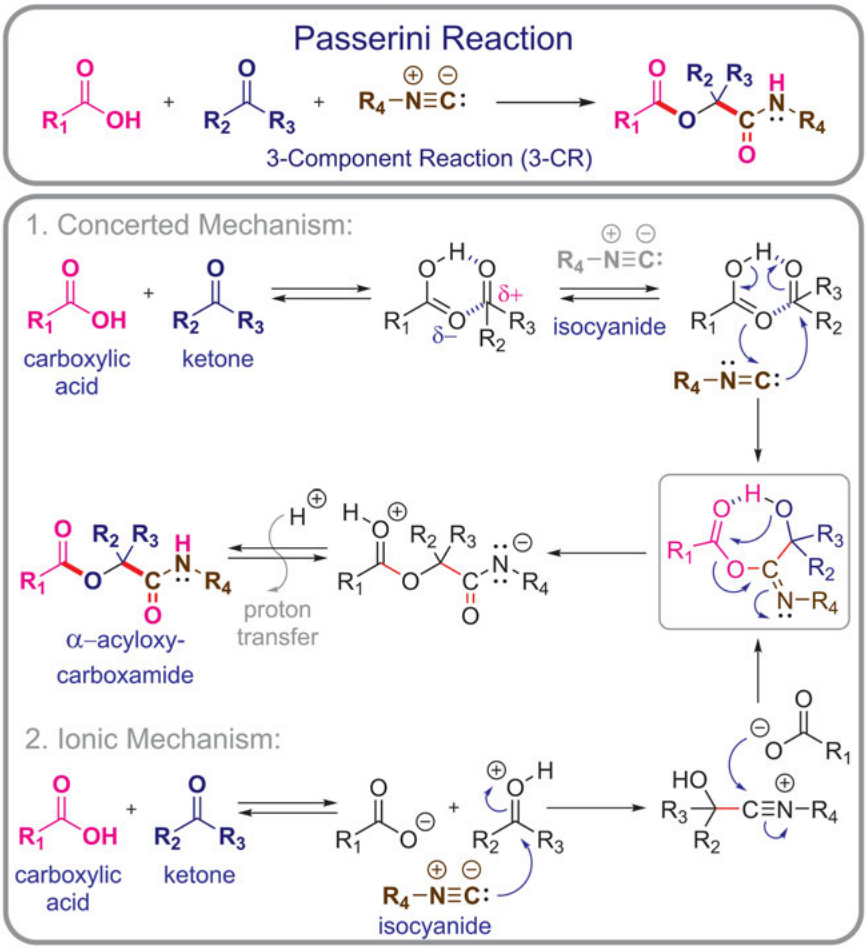


Fig. 91.2: The ***Passerini*** *reaction* mechanism.[290]

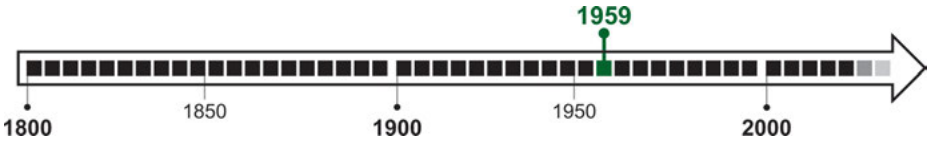


Fig. 91.3: The discovery of the ***Ugi*** *reaction*.[291]

290 The ***Passerini*** *reaction* is mechanistically related to the ***Ugi*** *reaction* [91a, 91b]. The product formation can be rationalized either via 1. the *concerted* mechanism or 2. the *ionic* mechanism. Other 3-CR's were also mentioned in this book: the ***Gewald*** *reaction* (Chapter 41), the ***Mannich*** *reaction* (Chapter 56), the ***Petasis*** *reaction* (Chapter 62), the ***Pauson–Khand*** *reaction* (Chapter 73).

291 The reaction was likely first described around 1959 [91c].

92 Ullmann Aryl–Aryl Coupling

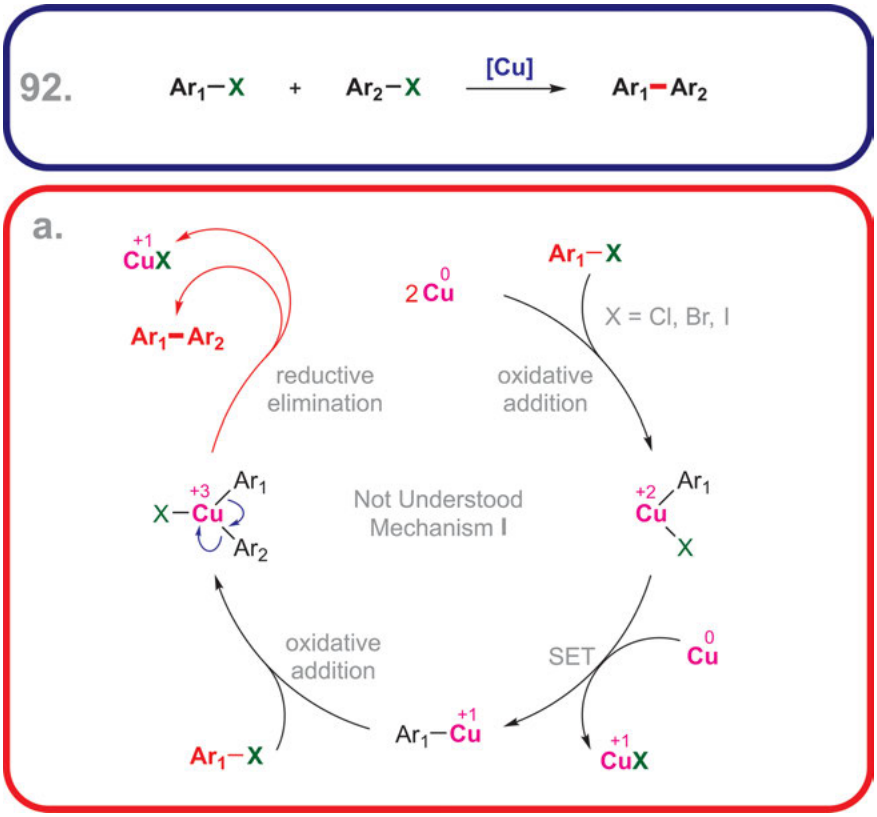


Fig. 92.1: The ***Ullmann*** *aryl–aryl coupling* mechanism I.[292]

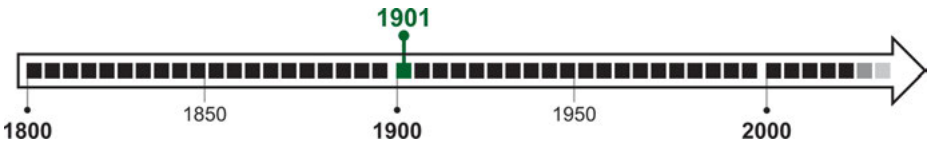


Fig. 92.2: The discovery of the ***Ullmann*** *aryl–aryl coupling*.[293]

292 The ***Ullmann*** *aryl–aryl coupling* or the ***Ullmann*** *reaction* is a ***Cu****-mediated coupling* (C–C bond formation using *aryl halides*). The mechanism is not fully understood. A possible formation of *organo-copper* intermediates (Cu(I) or Cu(II)) is postulated: mechanism I (**a**).
293 The reaction was likely first described around 1901 [92a, 92b].

https://doi.org/10.1515/9783110608373-092

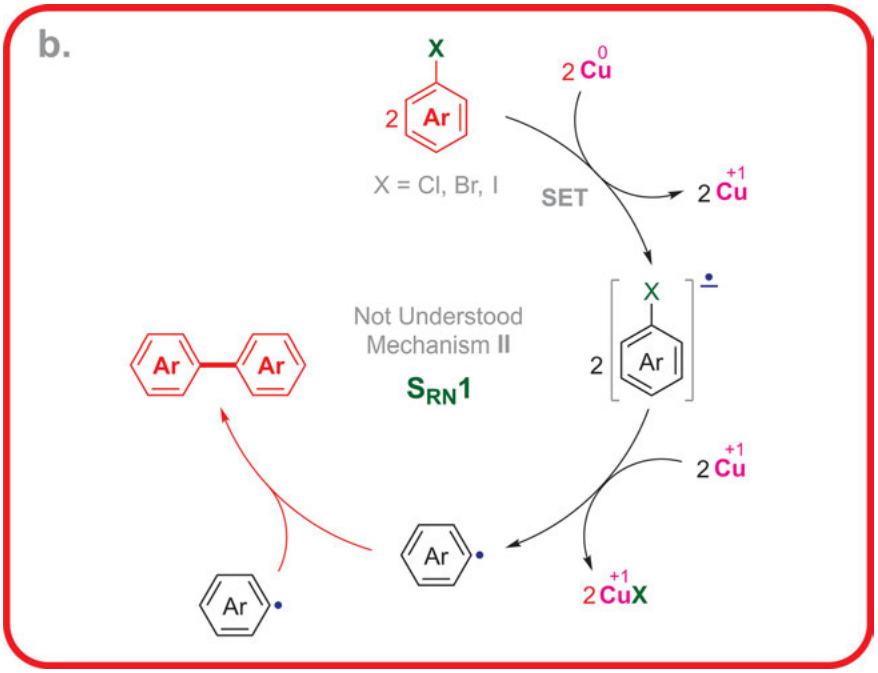


Fig. 92.3: The ***Ullmann*** *aryl–aryl coupling* mechanism II.[294]

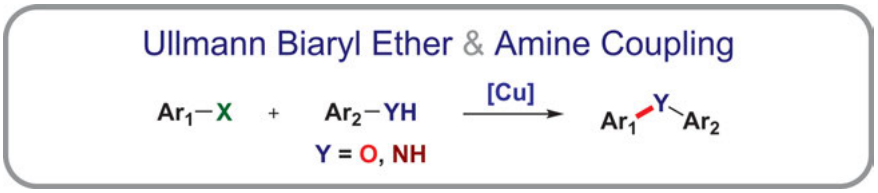


Fig. 92.4: The ***Ullmann*** *biaryl ether & amine coupling*.[295]

294 The **aromatic radical nucleophilic substitution** ($S_{RN}1$) mechanism (Chapter 5) is another explanation for the formation of the *symmetrical* or *asymmetrical biaryl* products: mechanism II (**b**).

295 The ***Ullmann*** *biaryl ether* and *biaryl amine coupling* reaction is more synthetically useful [92c, 92d]. It is also a ***Cu****-mediated coupling* (C–O and C–N bond formation using *aryl halides* with *phenols* or *anilines*) [92e]. An alternative way to synthesize *aryl ethers* and *amines* is via the ***Chan–Evans–Lam*** *cross coupling* (Chapter 23).

93 Upjohn Dihydroxylation

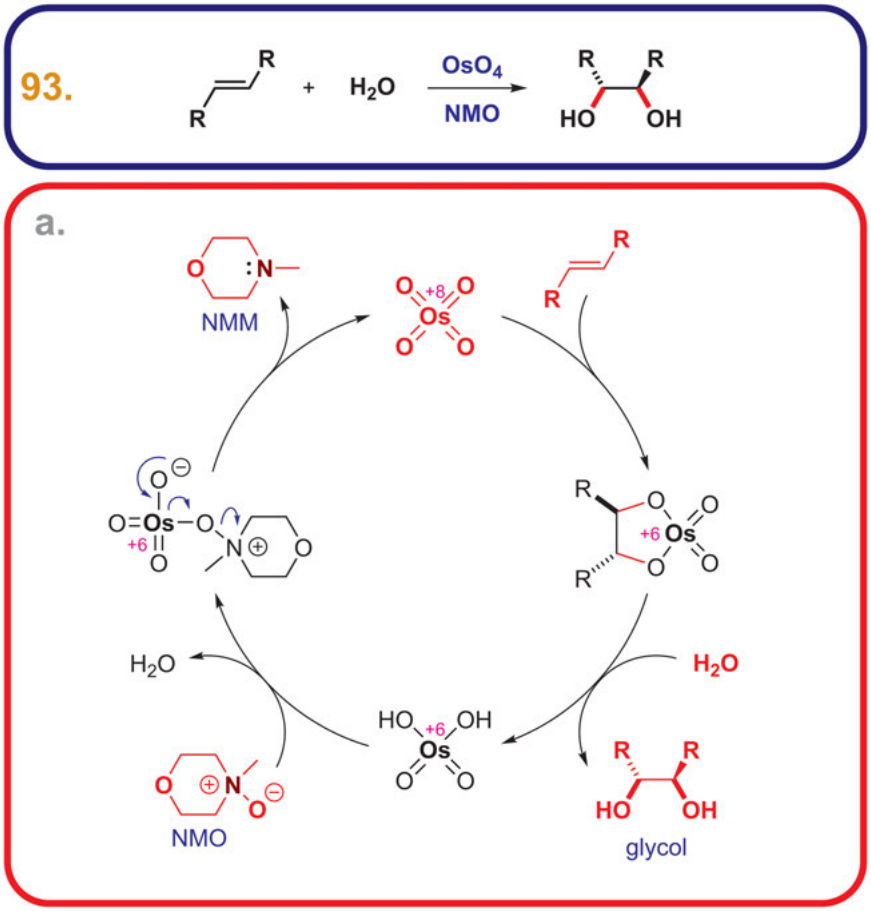


Fig. 93.1: The ***Upjohn*** *dihydroxylation* mechanism (a).[296]

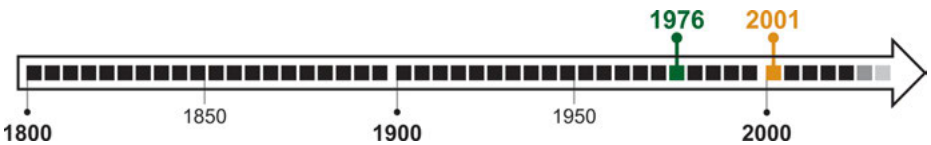


Fig. 93.2: The discovery of the ***Upjohn*** *dihydroxylation*.[297]

296 The ***Upjohn*** *dihydroxylation* (**a**) yields racemic products (*cis-1,2-glycols* = *cis*-1,2-diols) [93a].
297 The reaction was likely first described around 1976 [93f]. In **2001**, K. Barry Sharpless (together with William S. Knowles and Ryoji Noyori) received the Nobel Prize in Chemistry for the development

https://doi.org/10.1515/9783110608373-093

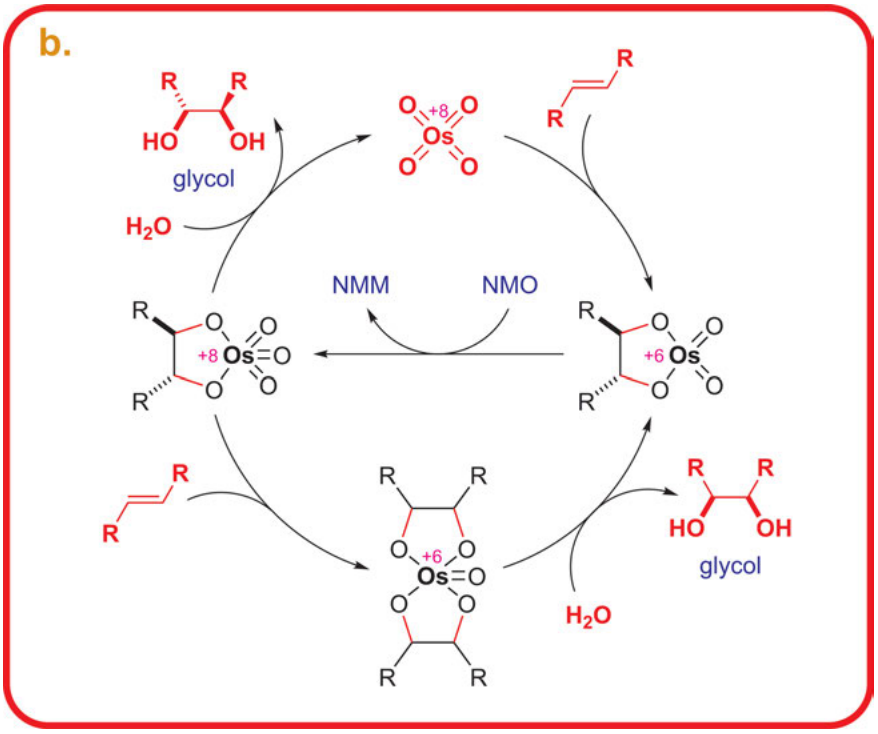


Fig. 93.3: The ***Upjohn*** *dihydroxylation* mechanism (b).[298]

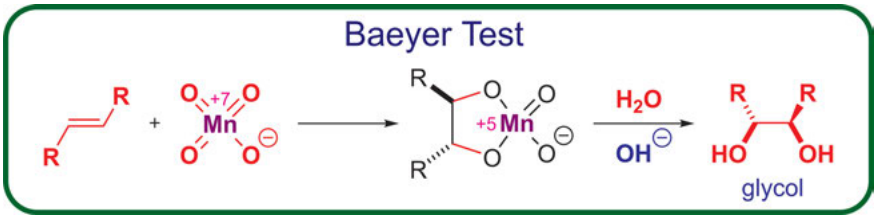


Fig. 93.4: The ***Baeyer*** *test*.[299]

of chirally catalyzed oxidation and hydrogenation reactions [93g].

298 The ***Sharpless*** *asymmetric dihydroxylation* is exemplified in a simplified mechanism (**b**). It is an asymmetric variation of the ***Upjohn*** *dihydroxylation* and it yields enantiomerically pure products [93b, 93c, 93d].

299 The ***Baeyer*** *test (**Baeyer's** test)* (potassium permanganate-based TLC stain) is a reaction related to the ***Upjohn*** *dihydroxylation*. It is used to detect the presence of *double bonds (unsaturation)* [93e].

94 Vilsmeier–Haack Reaction

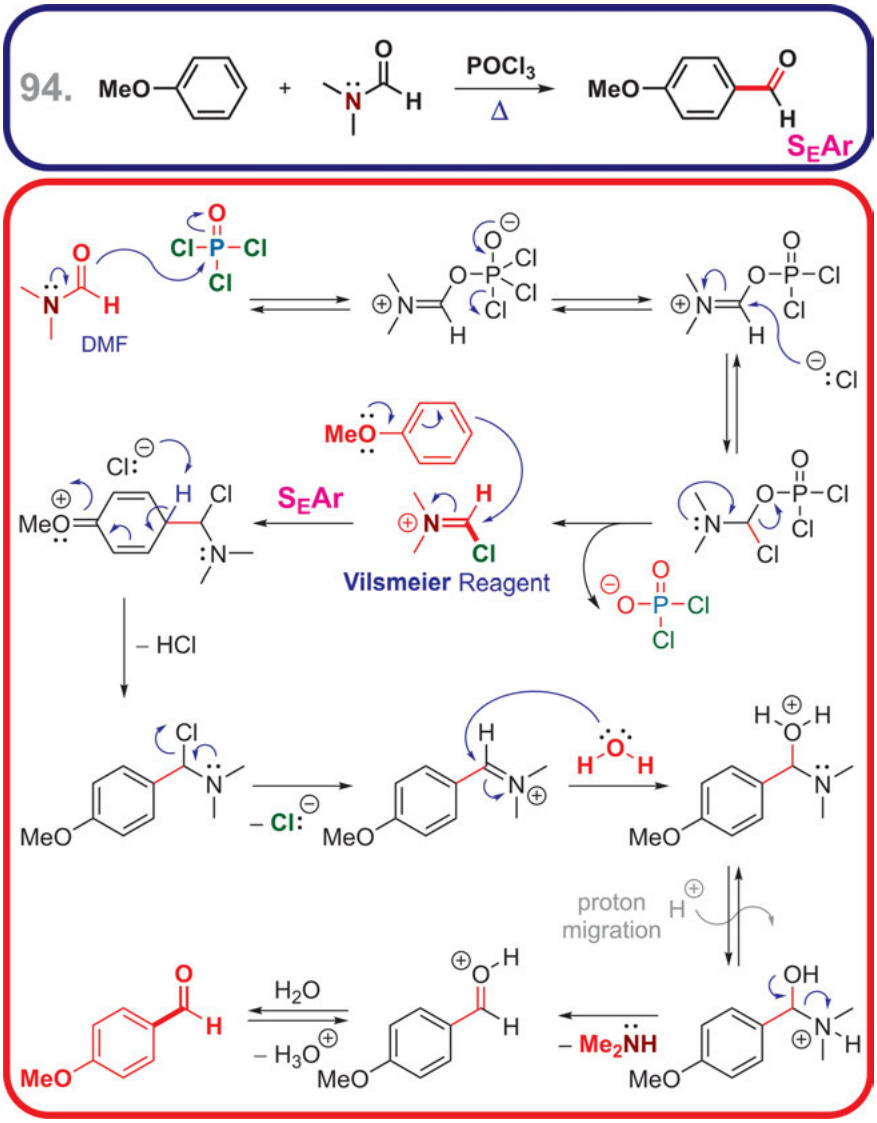


Fig. 94.1: The ***Vilsmeier–Haack*** *reaction* mechanism.[300]

300 The ***Vilsmeier–Haack*** *reaction* or the ***Vilsmeier–Haack*** *formylation* is a classic example of **aromatic electrophilic substitution** (the ***arenium ion*** mechanism = **S_EAr**, covered in Chapter 3).

https://doi.org/10.1515/9783110608373-094

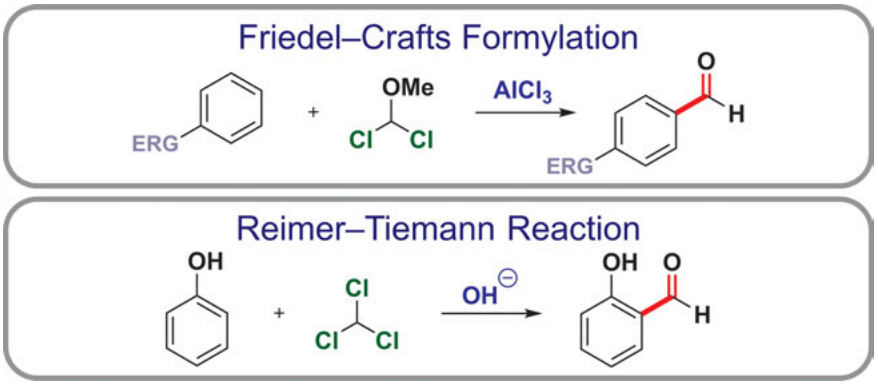


Fig. 94.2: Reactions related to the ***Vilsmeier–Haack*** *reaction*.[301]

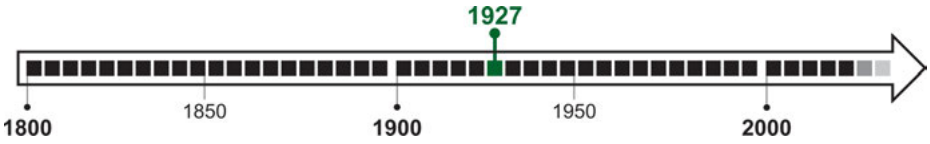


Fig. 94.3: The discovery of the ***Vilsmeier–Haack*** *reaction*.[302]

301 A few named reactions are related to the ***Vilsmeier–Haack*** *reaction*: the ***Friedel–Crafts*** *formylation* using *dichloro(methoxy)methane* (the ***Friedel–Crafts*** reaction is covered in Chapter 39), the ***Reimer–Tiemann*** *reaction* using *chloroform* (limited to the *ortho*-formylation of *phenols*) [94a], and others (not shown here) [1].

302 The reaction was likely first described around 1927 [94b].

95 Wacker Oxidation

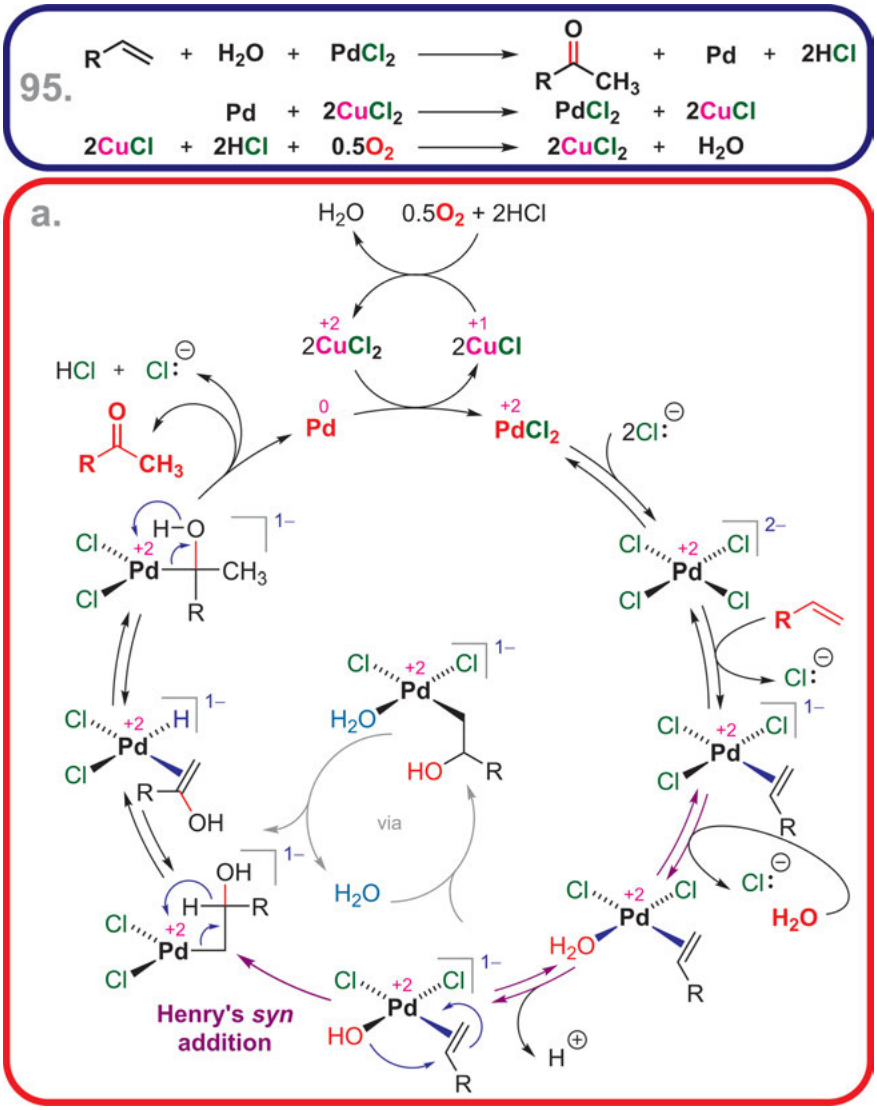


Fig. 95.1: The ***Wacker*** *oxidation* mechanism (a).[303]

303 The ***Wacker*** *oxidation* or the ***Wacker*** *process* is a ***Pd****-catalyzed* and ***Cu****-co-catalyzed* alkene (olefin) oxidation. The mechanism can vary: mechanism (**a**) is proposed by Henry: ***Henry's*** *syn addition* (inner-sphere) [95a, 95b].

https://doi.org/10.1515/9783110608373-095

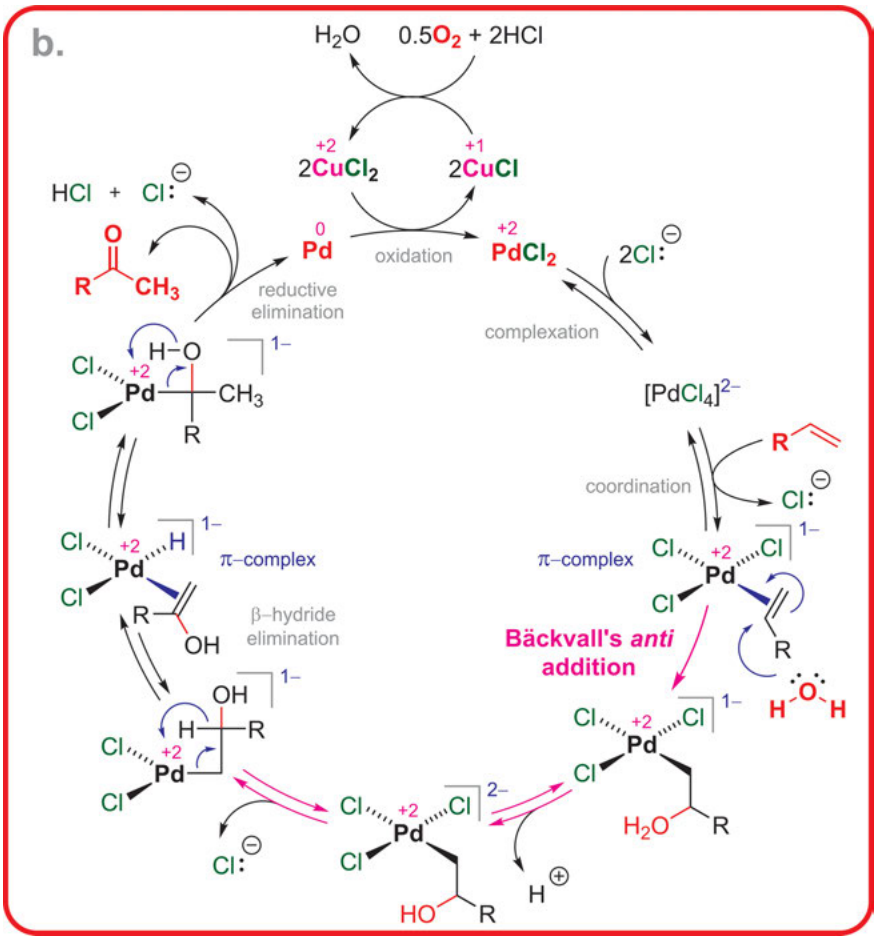


Fig. 95.2: The ***Wacker*** *oxidation* mechanism (b).[304]

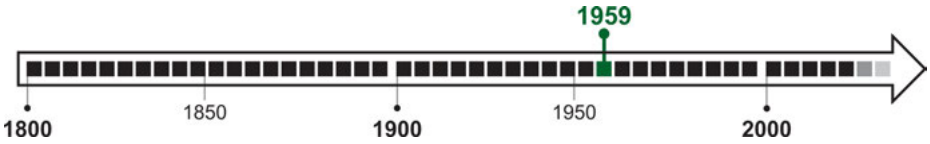


Fig. 95.3: The discovery of the ***Wacker*** *oxidation*.[305]

304 Mechanism (**b**) is proposed by Bäckvall: ***Bäckvall's*** *anti addition* (outer-sphere) [95a, 95b].
305 The reaction was likely first described around 1959 [95c].

96 Wagner–Meerwein Rearrangement

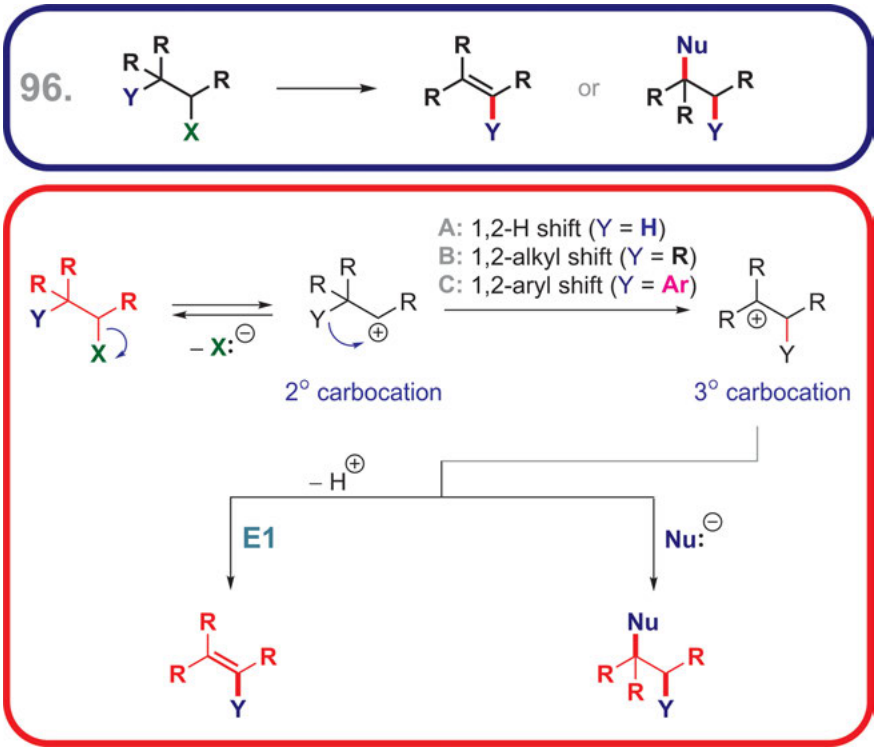


Fig. 96.1: The *general* ***Wagner–Meerwein*** *rearrangement* mechanism.[306]

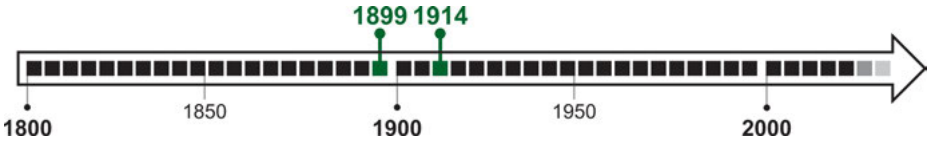


Fig. 96.2: The discovery of the ***Wagner–Meerwein*** *rearrangement*.[307]

306 The ***Wagner–Meerwein*** *rearrangement* is a rearrangement of new formed *carbocations* into more stable carbocations (1° → 2° → 3°). This reaction is related to the *pinacol-pinacolone rearrangement* and the ***Tiffeneau–Demjanov*** *rearrangement* (Chapter 76).

307 The reaction was likely first described around 1899 by Wagner [96a, 96b] and 1914 by Meerwein [96c].

https://doi.org/10.1515/9783110608373-096

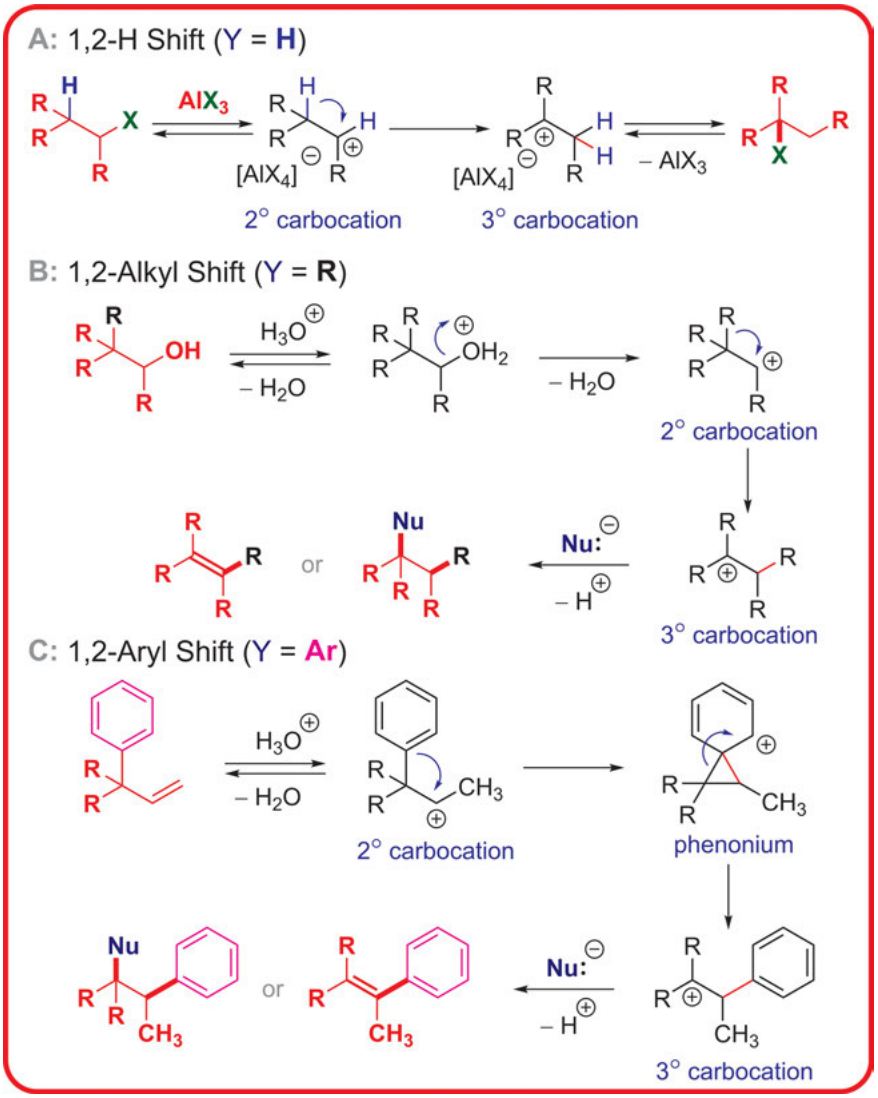


Fig. 96.3: The ***Wagner–Meerwein*** *rearrangement* mechanism (A, B, and C).[308]

308 The generated *carbocations* rearrange into more stable species via either (a) 1,2-H shift (Y = H); (b) 1,2-alkyl shift (Y = R); or (c) 1,2-aryl shift (Y = Ar). **β–Elimination** reactions (**E1**) often accompany the ***Wagner–Meerwein*** *rearrangement* [1].

97 Weinreb Ketone Synthesis

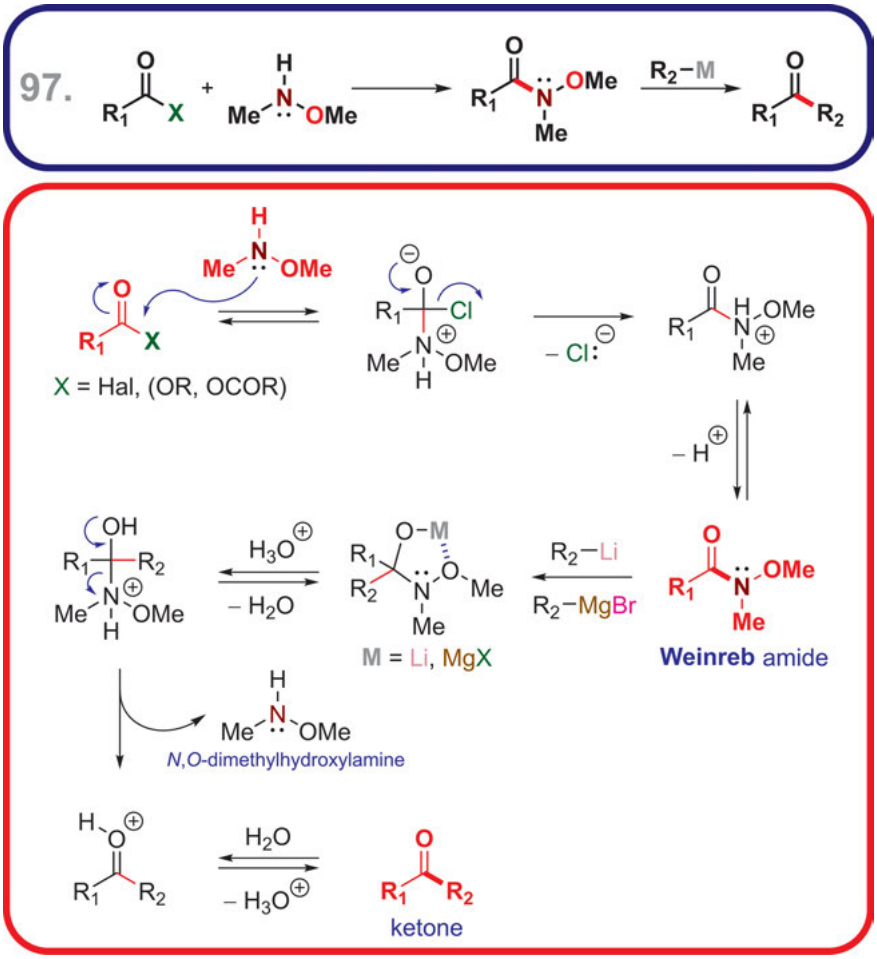


Fig. 97.1: The ***Weinreb*** *ketone synthesis* mechanism.[309]

309 The ***Weinreb*** *ketone synthesis* is a synthetic procedure (preparation of *ketones*) based on the use of a named reagent: the ***Weinreb*** *amide (**Weinreb–Nahm** amide)* [97a].

https://doi.org/10.1515/9783110608373-097

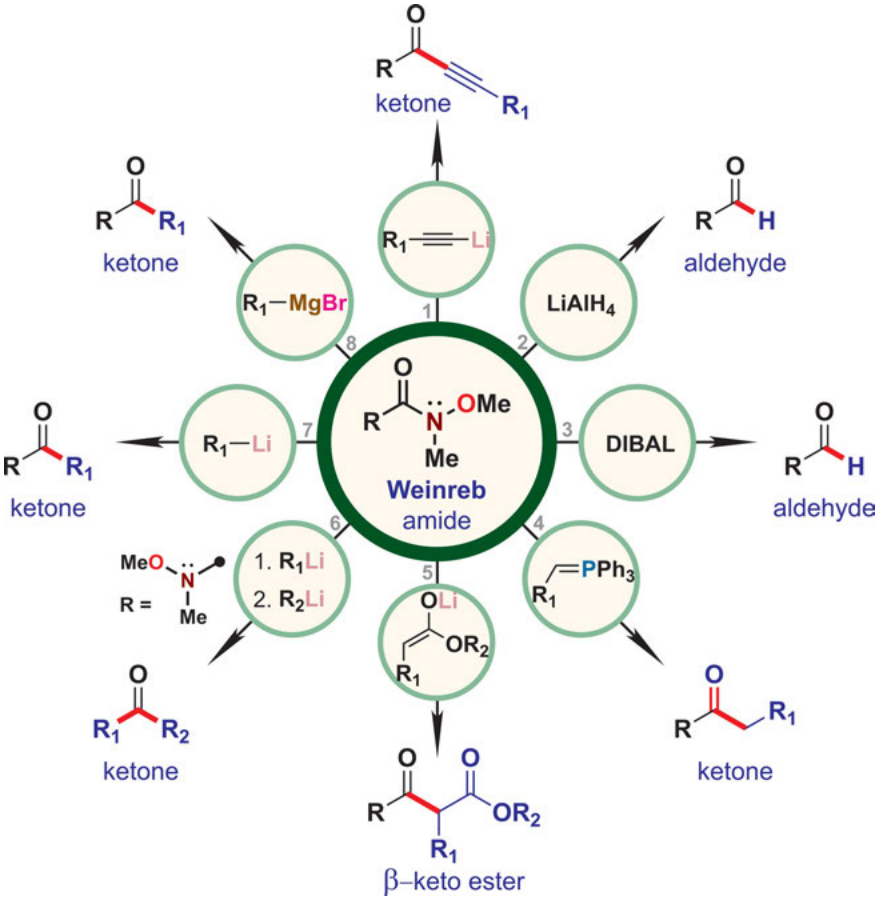


Fig. 97.2: Synthetic versatility of the ***Weinreb*** *amide*.[310]

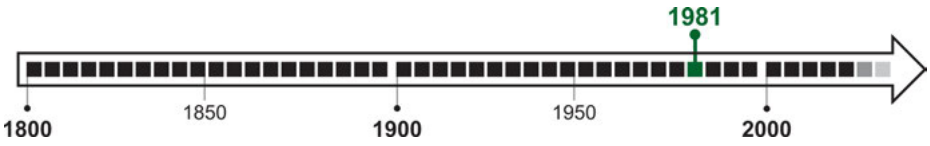


Fig. 97.3: The discovery of the ***Weinreb*** *ketone synthesis*.[311]

310 The ***Weinreb*** *amide* has wide synthetic application and it can react with a variety of nucleophilic reagents: (a) *organolithium* and *organomagnesium* = ***Grignard*** *reagents*; (b) reducing reagents like DIBAL; (c) *phosphorus ylides* or *phosphoranes* [97b]; and others [1].

311 The reaction was likely first described around 1981 [97c].

98 Wittig Reaction

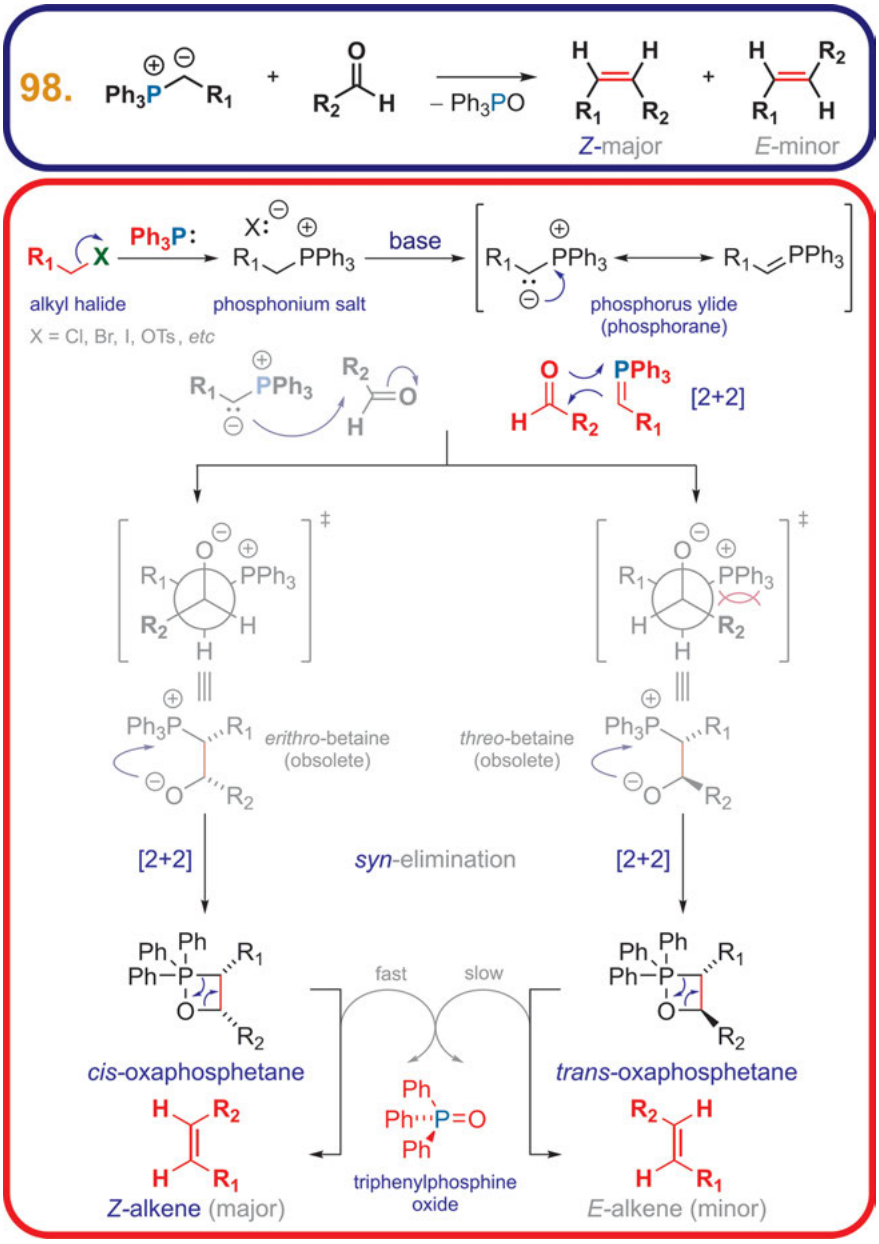


Fig. 98.1: The ***Wittig*** *reaction* mechanism.[312]

https://doi.org/10.1515/9783110608373-098

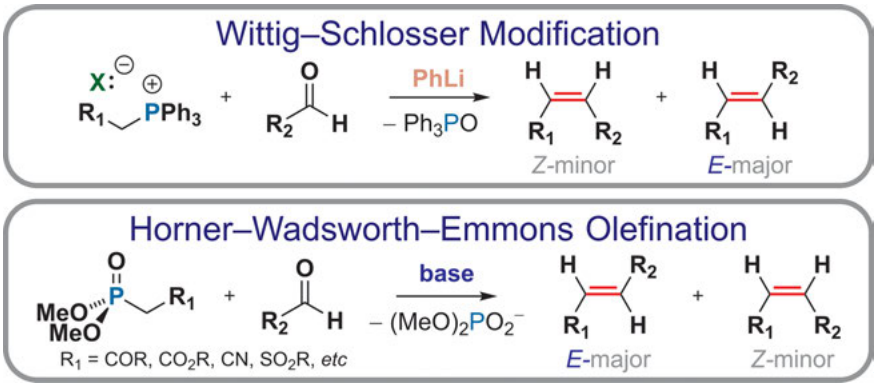


Fig. 98.2: Reactions related to the ***Wittig*** *reaction*.[313]

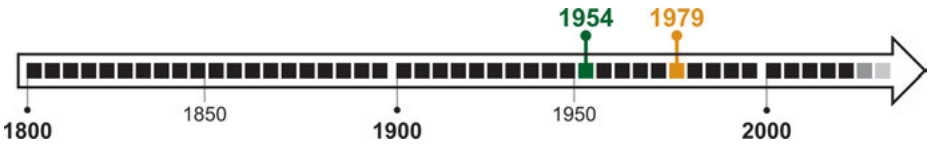


Fig. 98.3: The discovery of the ***Wittig*** *reaction*.[314]

312 The ***Wittig*** *reaction* or *the* ***Wittig*** *olefination* relies on the use of *phosphorus ylides* or *phosphoranes* formed from the *phosphonium salts* [98a].

313 Several reactions are closely related to the ***Wittig*** *reaction*: the ***Wittig–Schlosser*** *modification* (favoring *E*-alkenes with an excess of **PhLi** as a base) [98b]. The ***Horner–Wadsworth–Emmons*** *olefination* (Chapter 50) relies on the use of *phosphonates* [$PO(OR)_2R$], which can be made via the ***Arbuzov*** *reaction* (Chapter 9).

314 The reaction was likely first described around 1954 [98c, 98d]. In **1979**, Georg Wittig (jointly with Herbert C. Brown) received the Nobel Prize in Chemistry for the development of phosphorus (and boron) chemistry [20c].

99 Wohl–Ziegler Reaction

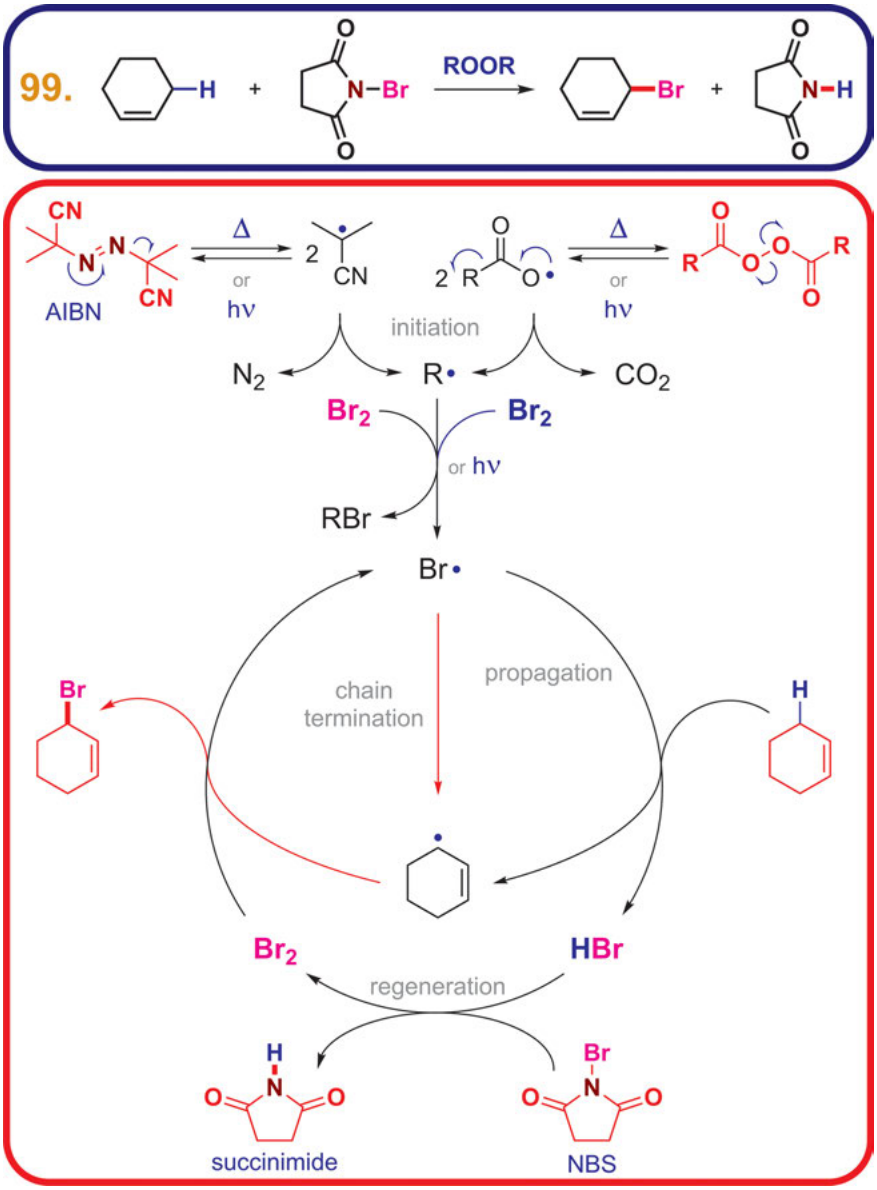


Fig. 99.1: The ***Wohl–Ziegler*** *reaction* mechanism.[315]

315 The ***Wohl–Ziegler*** *reaction*, or the ***Wohl–Ziegler*** *bromination*, is a type of the **free radical substitution** (see the ***Minisci*** *reaction* in Chapter 60).

https://doi.org/10.1515/9783110608373-099

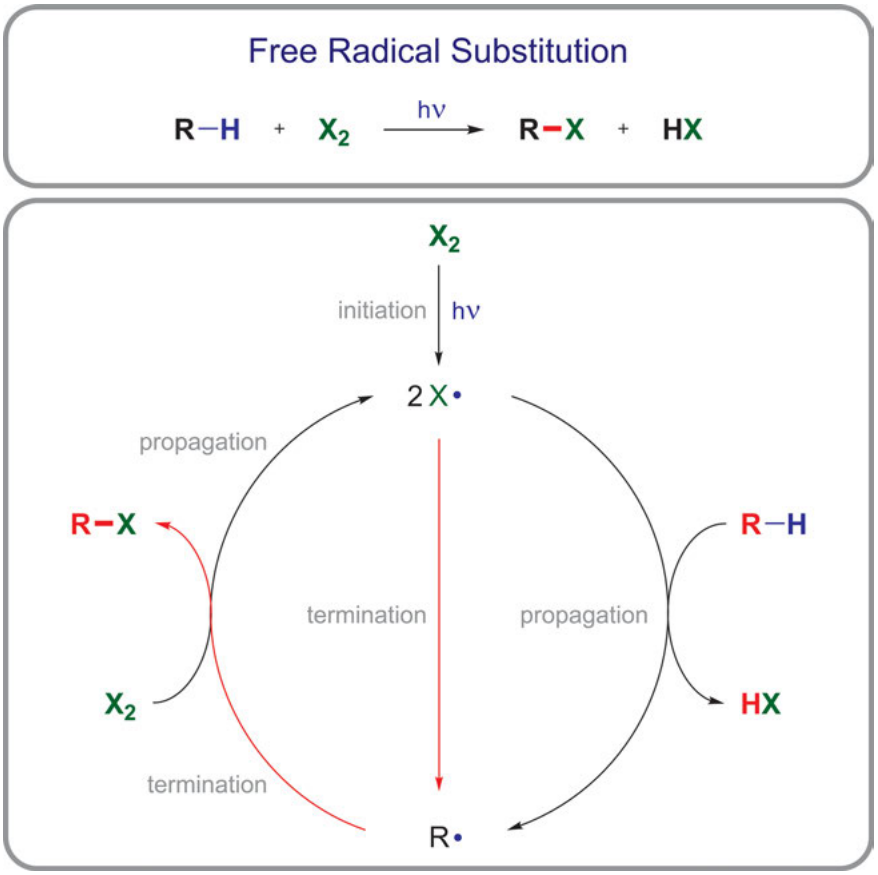


Fig. 99.2: The *free radical substitution* mechanism.[316]

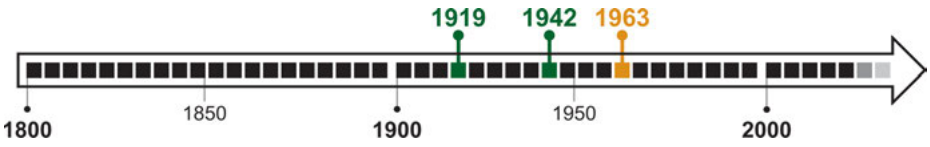


Fig. 99.3: The discovery of the ***Wohl–Ziegler*** *reaction*.[317]

316 The *free radical substitution* mechanisms usually feature three major steps: (**a**) *initiation*; (**b**) chain *propagation*; and (**c**) chain *termination*. A *free radical chlorination* of *alkanes* is a typical example [1].
317 The reaction was likely first described around 1919 by Wohl [99a] and around 1942 by Ziegler [99b]. In **1963**, Karl Ziegler (jointly with Giulio Natta) received the Nobel Prize in Chemistry [99c].

100 Wolff–Kishner Reduction

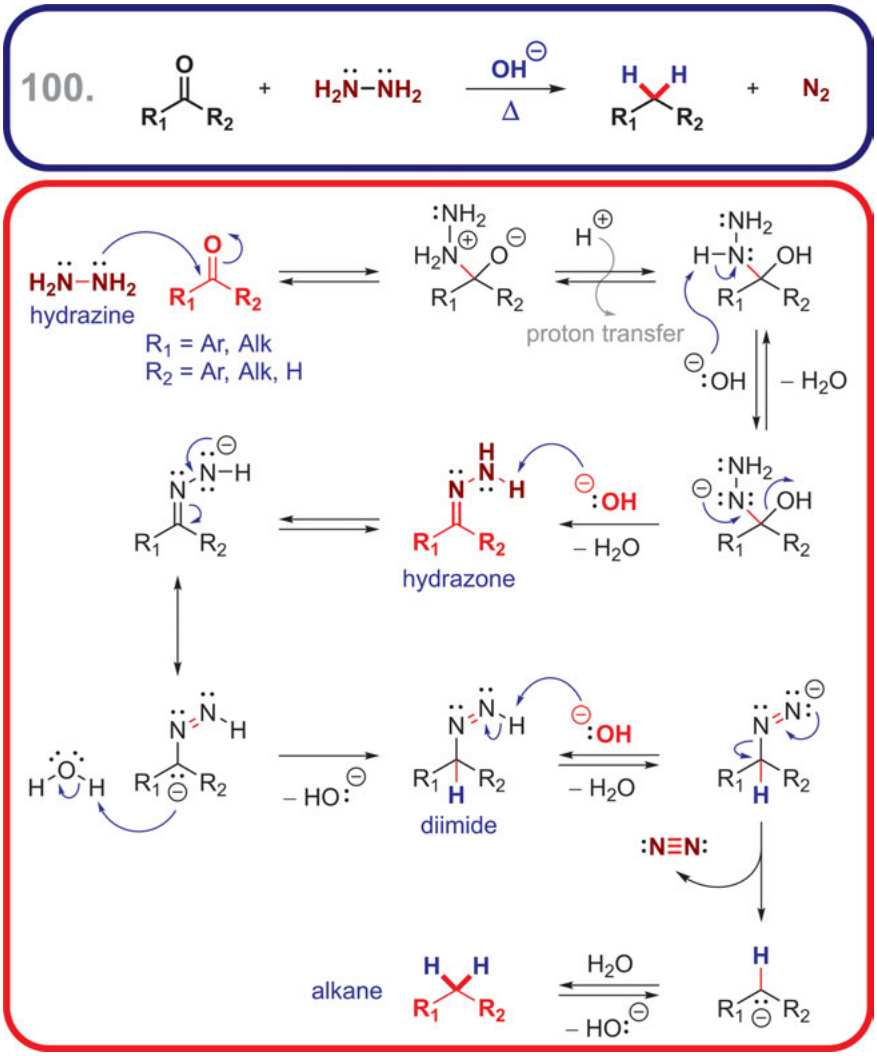


Fig. 100.1: The ***Wolff–Kishner*** *reduction* mechanism.[318]

318 There are many modifications of the ***Wolff–Kishner*** *reduction*: for example, the ***Huang–Minlon*** *modification*, and many others (not shown) [100a].

https://doi.org/10.1515/9783110608373-100

Fig. 100.2: Reactions related to the ***Wolff–Kishner*** *reduction*.[319]

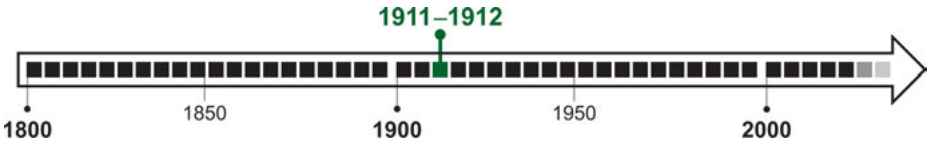


Fig. 100.3: The discovery of the ***Wolff–Kishner*** *reduction*.[320]

319 The ***Clemmensen*** *reduction* is closely related to the ***Wolff–Kishner*** *reduction* in terms of the product type formation but not the mechanism [100b].

320 The reaction was likely first described around 1911 by Kishner [100c] and around 1912 by Wolff [100d].

Acknowledgments

I envision this reference book to be one part of the intellectual and physical library that the developing chemist builds as they gain experience and expertise. This immersion, in conjunction with further learning, can provide an invaluable scientific intuition. Mechanisms have become an integral part of my continued study, research, and learning in organic chemistry and I hope this book imparts some of that to the field.

The images and infographic summaries ("*MechanoGraphics*") in this book were prepared by the author. Any reference to trademarks or service marks is based on common usage or reference in the discipline or practice, each such mark is the property of its respective owner and use here does not mean and is not intended to suggest an endorsement. All the "*MechanoGraphic*" schemes are based on common knowledge in the discipline and are supported either by original references where they were first mentioned, or other articles and reviews in the literature (where necessary). The reader should be sure to conduct primary research and utilize their own professional judgment, including consultation with peers and more experienced scientists, before planning any studies or research as the illustrations alone are not sufficient as a sole reference.

Special thanks are owned to my family, friends, and peers in the scientific community, and my students. The confluence of an idea and diligence makes possible great progress. But this combination must also be fueled by the compassion, support, and patience of those around us. I am very grateful that this constellation aligned for me and made possible the environment in which I could prepare this book. Moreover, as always, I am most grateful to my students and followers on social media. As I share and teach, I also continue to learn about the discipline as well as myself, always striving to understand, grow, and get closer to truth.

https://doi.org/10.1515/9783110608373-101

Bibliography and References

[1] (a) March J. Advanced Organic Chemistry: Reactions, Mechanisms, and Structure (Fourth Edition). New York, NY, USA, J. Wiley & Sons, 1992. (b) Carey FA, and Sundberg RJ. Advanced Organic Chemistry: Part A: Structure and Mechanisms (Third Edition). New York, NY, USA, Plenum Press, 1990. (c) Carey FA, and Sundberg RJ. Advanced Organic Chemistry: Part B: Reactions and Synthesis (Third Edition). New York, NY, USA, Plenum Press, 1990.

[2] (a) Hartwig JF. Organotransition Metal Chemistry: From Bonding to Catalysis. Mill Valley, CA, USA, University Science Books, 2010. (b) Turro NJ, Ramamurthy V, and Scaiano JC. Modern Molecular Photochemistry of Organic Molecules. Sausalito, CA, USA, University Science Books, 2010.

[3] (a) Fleming I. Molecular Orbitals and Organic Chemical Reactions (Reference Edition). Chichester, West Sussex, UK, J. Wiley & Sons, 2010. (b) Fleming I. Molecular Orbitals and Organic Chemical Reactions (Student Edition). Chichester, West Sussex, UK, J. Wiley & Sons, 2009.

[4] (a) Kürti L, and Czakó B. Strategic Applications of Named Reactions in Organic Synthesis: Background and Detailed Mechanisms. Burlington, MA, USA, Elsevier Academic Press, 2005. (b) Li JJ. Name Reactions: A Collection of Detailed Mechanisms and Synthetic Applications (Fifth Edition). Heidelberg, Germany, Springer, 2014.

[5] (a) https://www.organic-chemistry.org/ (accessed December 5, 2019). (b) http://www.name-reaction.com/ (accessedDecember 5, 2019). (c) https://www.synarchive.com/ (accessed December 5, 2019). (d) https://en.wikipedia.org/wiki/Main_Page (accessed December 5, 2019).

[6] e-EROS Encyclopedia of Reagents for Organic Synthesis. Chichester, NY, USA John Wiley & Sons, 2001. The on-line e-EROS database of reagents for organic synthesis can be found at https://onlinelibrary.wiley.com/doi/book/10.1002/047084289X (accessed December 5, 2019).

[7] (a) Bouveault L, and Blanc G. Préparation des alcools primaires au moyen des acides correspondants. *Compt. Rend*. **1903**, 136, 1676–1678. The reference is in French and can be found at https://gallica.bnf.fr/ark:/12148/bpt6k3091c/f1676.image.langFR (accessed December 5, 2019). (b) Bouveault L, and Locquin R. Action du sodium sur les éthers des acides monobasiques à fonction simple de la série grasse. *Compt. Rend*. **1905**, 140, 1593–1595. The reference is in French and can be found at https://gallica.bnf.fr/ark:/12148/bpt6k30949/f1689.image (accessed December 5, 2019).

[8] (a) Faworsky A. Isomerisationserscheinungen der Kohlen-wasserstoffe C_nH_{2n-2}. Erste Abhandlung. *J. Prakt. Chem*. **1888**, 37 (1), 382–395. (b) Faworsky A. Isomerisationserscheinungen der Kohlen-wasserstoffe C_nH_{2n-2}. Zweite Abhandlung. *J. Prakt. Chem*. **1888**, 37 (1), 417–431. (c) Faworsky A. Isomerisationserscheinungen der Kohlen-wasserstoffe C_nH_{2n-2}. Dritte Abhandlung. *J. Prakt. Chem*. **1888**, 37 (1), 531–536. Please note, these references were originally published in Russian and they are difficult to locate. They can be found in German at https://doi.org/10.1002/prac.18880370133; https://doi.org/10.1002/prac.18880370138; and https://doi.org/10.1002/prac.18880370147, respectively (all accessed December 5, 2019). (d) Brown CA, and Yamashita A. Saline hydrides and superbases in organic reactions. IX. Acetylene zipper. Exceptionally facile contrathermodynamic multipositional isomeriazation of alkynes with potassium 3-aminopropylamide. *J. Am. Chem. Soc*. **1975**, 97 (4), 891–892.

[9] (a) See more at https://en.wikipedia.org/wiki/Organophosphorus_compound (accessed December 5, 2019). (b) Michaelis A, and Kaehne R. Ueber das Verhalten der Jodalkyle gegen die sogen. Phosphorigsäureester oder *O*-Phosphine. *Ber. Dtsch. Chem. Ges*. **1898**, 31 (1), 1048–1055. (c) Arbuzov AE. On the structure of phosphonic acid and its derivates: Isometization and transition of bonds from trivalent to pentavalent phosphorus. *J. Russ. Phys. Chem*. Soc. **1906**, 38, 687. Note, the original reference is in Russian and it is difficult to locate. Additional references can be found in [1a].

https://doi.org/10.1515/9783110608373-102

[10] (a) Wolff L. Ueber Diazoanhydride. *Justus Liebigs Ann. Chem*. **1902**, 325 (2), 129–195. (b) Wolff L, and Krüche R. Über Diazoanhydride (1,2,3-Oxydiazole oder Diazoxyde) und Diazoketone. *Justus Liebigs Ann. Chem*. **1912**, 394 (1), 23–59. (c) Arndt F, and Eistert B. Ein Verfahren zur Überführung von Carbonsäuren in ihre höheren Homologen bzw. deren Derivate. *Ber. Dtsch. Chem. Ges*. A/B **1935**, 68 (1), 200–208.

[11] (a) Dakin HD. The oxidation of hydroxy derivatives of benzaldehyde, acetophenone and related substances. *Am. Chem. J*. **1909**, 42 (6), 477–498. Note, the original reference is difficult to locate. (b) Baeyer A, and Villiger V. Einwirkung des Caro'schen Reagens auf Ketone. *Ber. Dtsch. Chem. Ges*. **1899**, 32 (3), 3625–3633. (c) The Nobel Prize in Chemistry 1905. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1905/summary/).

[12] (a) Barton DHR, Dowlatshahi HA, Motherwell WB, and Villemin D. A new radical decarboxylation reaction for the conversion of carboxylic acids into hydrocarbons. *J. Chem. Soc., Chem. Commun*. **1980**, (15), 732–733. (b) Barton DHR, Crich D, and Motherwell WB. New and improved methods for the radical decarboxylation of acids. *J. Chem. Soc., Chem. Commun*. **1983**, (17), 939–941. (c) Barton DHR, and McCombie SW. A new method for the deoxygenation of secondary alcohols. *J. Chem. Soc., Perkin Trans. 1* **1975**, (16), 1574–1585. (d) Barrett AGM, Prokopiou PA, and Barton DHR. Novel method for the deoxygenation of alcohols. *J. Chem. Soc., Chem. Commun*. **1979**, (24), 1175. (e) The Nobel Prize in Chemistry 1969. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1969/summary/).

[13] (a) Baylis AB, and Hillman MED. German Patent 2155113, **1972**. (b) Morita K, Suzuki Z, and Hirose H. *Bull. Chem. Soc. Jpn*. **1968**, 41 (11), 2815. Note, the original reference can be found at https://www.journal.csj.jp/doi/abs/10.1246/bcsj.41.2815 (accessed December 5, 2019).

[14] Beckmann E. Zur Kenntniss der Isonitrosoverbindungen. *Ber. Dtsch. Chem. Ges*. **1886**, 19 (1), 988–993.

[15] (a) Matsumoto T, Ohishi M, and Inoue S. Selective cross-acyloin condensation catalyzed by thiazolium salt. Formation of 1-hydroxy 2-one from formaldehyde and other aldehydes. *J. Org. Chem*. **1985**, 50 (5), 603–606. (b) Breslow R, and Kool E. A γ-cyclodextrin thiazolium salt holoenzyme mimic for the benzoin condensation. *Tetrahedron Lett*. **1988**, 29 (14), 1635–1638. For the original discovery and additional references please see [1a]. (c) Wöhler, and Liebig. Untersuchungen über das Radikal der Benzoesäure. *Ann. Pharm*. **1832**, 3 (3), 249–282. (d) Lapworth A. XCVI. – Reactions involving the addition of hydrogen cyanide to carbon compounds. *J. Chem. Soc., Trans*. **1903**, 83, 995–1005.

[16] (a) Tadross PM, and Stoltz BM. A Comprehensive History of Arynes in Natural Product Total Synthesis. *Chem. Rev*. **2012**, 112 (6), 3550–3577. (b) Additional references can be found at https://en.wikipedia.org/wiki/Aryne (accessed December 5, 2019) and in [1, 2b]. (c) Roberts JD, Simmons HE, Carlsmith LA, and Vaughan CW. Rearrangement in the reaction of chlorobenzene-1-C^{14} with potassium amid. *J. Am. Chem. Soc*. **1953**, 75 (13), 3290–3291. Note, the reaction itself was known for a very long time. It is difficult to locate the original references.

[17] (a) Jones RR, and Bergman RG. *p*-Benzyne. Generation as an intermediate in a thermal isomerization reaction and trapping evidence for the 1,4-benzenediyl structure. *J. Am. Chem. Soc*. **1972**, 94 (2), 660–661. (b) Bergman RG. Reactive 1,4-dehydroaromatics. *Acc. Chem. Res*. **1973**, 6 (1), 25–31.

[18] (a) Kraus CA. Solutions of Metals in Non-Metallic Solvents; I. General Properties of Solutions of Metals in Liquid Ammonia. *J. Am. Chem. Soc*. **1907**, 29 (11), 1557–1571. (b) Additional references can be found at https://en.wikipedia.org/wiki/Solvated_electron (accessed December 5, 2019). (c) Birch AJ. 117. Reduction by dissolving metals. Part I. *J. Chem. Soc*. **1944**, (0), 430–436.

[19] (a) Pomeranz C. Über eine neue Isochinolinsynthese. *Monatshefte für Chemie* **1893**, 14 (1), 116–119. https://doi.org/10.1007/BF01517862 (accessed December 5, 2019). (b) Fritsch P. Synthesen in der Isocumarin- und Isochinolinreihe. *Ber. Dtsch. Chem. Ges*. **1893**, 26 (1), 419–422. (c) Bischler A, and Napieralski B. Zur Kenntniss einer neuen Isochinolinsynthese. *Ber. Dtsch. Chem. Ges*. **1893**, 26 (2), 1903–1908.

[20] (a) Soderquist JA, Roush WR, and Heo J. (2004). 9-Borabicyclo[3.3.1]nonane Dimer. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rb235.pub2. (b) Brown HC, and Rao BCS. A new technique for the conversion of olefins into organoboranes and related alcohols. *J. Am. Chem. Soc*. **1956**, 78 (21), 5694–5695. (c) The Nobel Prize in Chemistry 1979. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1979/summary/).

[21] (a) Guram AS, and Buchwald SL. Palladium-Catalyzed Aromatic Aminations with in situ Generated Aminostannanes. *J. Am. Chem. Soc*. **1994**, 116 (17), 7901–7902. (b) Paul F, Patt J, and Hartwig JF. Palladium-catalyzed formation of carbon-nitrogen bonds. Reaction intermediates and catalyst improvements in the hetero cross-coupling of aryl halides and tin amides. *J. Am. Chem. Soc*. **1994**, 116 (13), 5969–5970.

[22] (a) Cannizzaro S. Ueber den der Benzoësäure entsprechenden Alkohol. *Justus Liebigs Ann. Chem*. **1853**, 88 (1), 129–130. (b) For additional references please see: Geissman TA. (2011). The Cannizzaro Reaction. In Organic Reactions, (Ed.). doi:10.1002/0471264180.or002.03.

[23] (a) King AE, Brunold TC, and Stahl SS. Mechanistic Study of Copper-Catalyzed Aerobic Oxidative Coupling of Arylboronic Esters and Methanol: Insights into an Organometallic Oxidase Reaction. *J. Am. Chem. Soc*. **2009**, 131 (14), 5044–5045. (b) King AE, Ryland BL, Brunold TC, and Stahl SS. Kinetic and Spectroscopic Studies of Aerobic Copper(II)-Catalyzed Methoxylation of Arylboronic Esters and Insights into Aryl Transmetalation to Copper(II). *Organometallics* **2012**, 31 (22), 7948–7957. (c) Vantourout JC, Miras HN, Isidro-Llobet A, Sproules S, and Watson AJB. Spectroscopic Studies of the Chan–Lam Amination: A Mechanism-Inspired Solution to Boronic Ester Reactivity. *J. Am. Chem. Soc*. **2017**, 139 (13), 4769–4779. (d) Chan DMT, Monaco KL, Wang RP, and Winter MP. New N- and O-arylations with phenylboronic acids and cupric acetate. *Tetrahedron Lett*. **1998**, 39 (19), 2933–2936. (e) Evans DA, Katz JL, and West TR. Synthesis of diaryl ethers through the copper-promoted arylation of phenols with arylboronic acids. An expedient synthesis of thyroxine. *Tetrahedron Lett*. **1998**, 39 (19), 2937–2942. (f) Lam PYS, Clark CG, Saubern S, Adams J, Winters MP, Chan DMT, and Combs A. New aryl/heteroaryl C-N bond cross-coupling reactions via arylboronic acid/cupric acetate arylation. *Tetrahedron Lett*. **1998**, 39 (19), 2941–2944.

[24] (a) Chichibabin AE, and Zeide OA. New reaction for compounds containing the pyridine nucleus. *J. Russ. Phys. Chem. Soc*. **1914**, 46, 1216–1236. Note, the original reference is published in Russian and it is difficult to locate: Чичибабин А. Е., Зейде О. А. ЖРФХО, 46, 1216 (1914). This reference can be found at https://ru.wikipedia.org/wiki/Реакция_Чичибабина (accessed December 5, 2019). (b) Tschitschibabin AE. Eine neue Darstellungsmethode von Oxyderivaten des Pyridins, Chinolins und ihrer Homologen. *Ber. Dtsch. Chem. Ges*. A/B **1923**, 56 (8), 1879–1885.

[25] (a) Dieckmann W. Ueber ein ringförmiges Analogon des Ketipinsäureesters. *Ber. Dtsch. Chem. Ges*. **1894**, 27 (1), 965–966. (b) Claisen L, and Lowman O. Ueber eine neue Bildungsweise des Benzoylessigäthers. *Ber. Dtsch. Chem. Ges*. **1887**, 20 (1), 651–654.

[26] (a) Additional references and good summary can be found at https://en.wikipedia.org/wiki/Claisen_rearrangement (accessed December 5, 2019). (b) Claisen L. Über Umlagerung von Phenol-allyläthern in *C*-Allyl-phenole. *Ber. Dtsch. Chem. Ges*. **1912**, 45 (3), 3157–3166.

[27] (a) Sharpless KB, Lauer RF, and Teranishi AY. Electrophilic and nucleophilic organoselenium reagents. New routes to α,β-unsaturated carbonyl compounds. *J. Am. Chem. Soc*. **1973**,

95 (18), 6137–6139. (b) Sharpless KB, Young MW, and Lauer RF. Reactions of selenoxides: Thermal *syn*-elimination and $H_2{}^{18}O$ exchange. *Tetrahedron Lett*. **1973**, 14 (22), 1979–1982. (c) Cope AC, Foster TT, and Towle PH. Thermal Decomposition of Amine Oxides to Olefins and Dialkylhydroxylamines. *J. Am. Chem. Soc*. **1949**, 71 (12), 3929–3934.

[28] (a) Additional references can be found at https://en.wikipedia.org/wiki/Cope_rearrangement (accessed December 5, 2019). (b) Cope AC, and Hardy EM. The Introduction of Substituted Vinyl Groups. V. A Rearrangement Involving the Migration of an Allyl Group in a Three-Carbon System. *J. Am. Chem. Soc*. **1940**, 62 (2), 441–444.

[29] (a) Criegee R. Eine oxydative Spaltung von Glykolen (II. Mitteil. über Oxydationen mit Blei(IV)-salzen). *Ber. Dtsch. Chem. Ges*. A/B **1931**, 64 (2), 260–266. (b) Malaprade L. Action of polyalcohols on periodic acid. Analytical application. *Bull. Soc. Chim. Fr*. **1928**, 43, 683–696. (c) Malaprade L. A study of the action of polyalcohols on periodic acid and alkaline periodates. *Bull. Soc. Chim. Fr*. **1934**, 5, 833–852. Note, the original references are published in French and they are difficult to locate.

[30] (a) IUPAC. Compendium of Chemical Terminology, 2nd ed. (the "Gold Book"). Compiled by A. D. McNaught and A. Wilkinson. Blackwell Scientific Publications, Oxford (1997). Online version (2019) created by S. J. Chalk. ISBN 0-9678550-9-8. https://doi.org/10.1351/goldbook. The link to the page can be found at https://goldbook.iupac.org/terms/view/C01496 (accessed December 5, 2019). (b) Huisgen R, and Eckell A. 1.3-Dipolare additionen der azomethin-imine. *Tetrahedron Lett*. **1960**, 1 (33), 5–8. (c) Grashey R, Huisgen R, and Leitermann H. 1.3-Dipolare additionen der nitrone. *Tetrahedron Lett*. **1960**, 1 (33), 9–13. (d) Tornøe CW, Christensen C, and Meldal M. Peptidotriazoles on Solid Phase: [1,2,3]-Triazoles by Regiospecific Copper(I)-Catalyzed 1,3-Dipolar Cycloadditions of Terminal Alkynes to Azides. *J. Org. Chem*. **2002**, 67 (9), 3057–3064. (e) Rostovtsev VV, Green LG, Fokin VV, and Sharpless KB. A Stepwise Huisgen Cycloaddition Process: Copper(I)-Catalyzed Regioselective "Ligation" of Azides and Terminal Alkynes. *Angew. Chem. Int. Ed*. **2002**, 41 (14), 2596–2599. (f) Worrell BT, Malik JA, and Fokin VV. Direct Evidence of a Dinuclear Copper Intermediate in Cu(I)-Catalyzed Azide-Alkyne Cycloadditions. *Science* **2013**, 340 (6131), 457–460.

[31] (a) Curtius T. Ueber Stickstoffwasserstoffsäure (Azoimid) N_3H. *Ber. Dtsch. Chem. Ges*. **1890**, 23 (2), 3023–3033. (b) Curtius T. 20. Hydrazide und Azide organischer Säuren I. Abhandlung. *J. Prakt. Chem*. **1894**, 50 (1), 275–294. (c) Schmidt KF. Aus den Sitzungen der Abteilungen. *Angew. Chem*. **1923**, 36 (57), 506–523. The reference can be found at https://doi.org/10.1002/ange.19230366703 (accessed December 5, 2019). (d) Schmidt KF. Über den Imin-Rest. *Ber. Dtsch. Chem. Ges*. A/B **1924**, 57, 704–706. (e) Hofmann AW. Ueber die Einwirkung des Broms in alkalischer Lösung auf Amide. *Ber. Dtsch. Chem. Ges*. **1881**, 14 (2), 2725–2736. (f) Lossen W. Ueber Benzoylderivate des Hydroxylamins. *Justus Liebigs Ann. Chem*. **1872**, 161 (2–3), 347–362.

[32] (a) In 1990 Elias James Corey received the Nobel Prize in Chemistry: The Nobel Prize in Chemistry 1990. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1990/summary/). (b) Corey EJ, and Chaykovsky M. Dimethyloxosulfonium Methylide ($(CH_3)_2SOCH_2$) and Dimethylsulfonium Methylide ($(CH_3)_2SCH_2$). Formation and Application to Organic Synthesis. *J. Am. Chem. Soc*. **1965**, 87 (6), 1353–1364. (c) Darzens G. Method generale de synthese des aldehyde a l'aide des acides glycidique substitues. *Compt. Rend*. **1904**, 139, 1214–1217. The reference is in French and can be accessed at https://gallica.bnf.fr/ark:/12148/bpt6k30930/f1214.image.langFR (accessed December 5, 2019).

[33] (a) Boeckman RJ, and George KM. (2009). 1,1,1-Triacetoxy-1,1-dihydro-1,2-benziodoxol-3(1*H*)-one.In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rt157m.pub2. (b) Zhdankin VV. Organoiodine(V) Reagents in Organic

Synthesis. *J. Org. Chem*. **2011**, 76 (5), 1185–1197. (c) Dess DB, and Martin JC. Readily accessible 12-I-5 oxidant for the conversion of primary and secondary alcohols to aldehydes and ketones. *J. Org. Chem*. **1983**, 48 (22), 4155–4156.

[34] (a) This term appears in some publications and can be found at https://en.wikipedia.org/wiki/Diazonium_compound (accessed December 5, 2019). (b) Griess P. Vorläufige Notiz über die Einwirkung von salpetriger Säure auf Amidinitro- und Aminitrophenylsäure. *Annalen der Chemie und Pharmacie* **1858**, 106 (1), 123–125. The original reference is in German and can be found at https://babel.hathitrust.org/cgi/pt?id=njp.32101044011037&view=1up&seq=541 (accessed December 5, 2019).

[35] (a) Diels O, and Alder K. Synthesen in der hydroaromatischen Reihe. *Justus Liebigs Ann. Chem*. **1928**, 460 (1), 98–122. (b) Additional summary of 27 references can be found at https://en.wikipedia.org/wiki/Diels%E2%80%93Alder_reaction (accessed December 5, 2019). (c) The Nobel Prize in Chemistry 1950. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1950/summary/).

[36] (a) Zimmerman HE, and Grunewald GL. The Chemistry of Barrelene. III. A Unique Photoisomerization to Semibullvalene. *J. Am. Chem. Soc*. **1966**, 88 (1), 183–184. (b) Zimmerman HE, Binkley RW, Givens RS, and Sherwin MA. Mechanistic organic photochemistry. XXIV. The mechanism of the conversion of barrelene to semibullvalene. A general photochemical process. *J. Am. Chem. Soc*. **1967**, 89 (15), 3932–3933.

[37] (a) Smissman EE, and Hite G. The Quasi-Favorskii Rearrangement. I. The Preparation of Demerol and β-Pethidine. *J. Am. Chem. Soc*. **1959**, 81 (5), 1201–1203. (b) Smissman EE, and Hite G. The Quasi-Favorskii Rearrangement. II. Stereochemistry and Mechanism. *J. Am. Chem. Soc*. **1960**, 82 (13), 3375–3381. (c) Favorskii AE. *J. Russ. Phys. Chem. Soc*. **1894**, 26, 590. Note, the original reference is published in Russian and it is difficult to locate: Favorskii AE. *Zh. Russ. Khim. Obshch*. **1894**, 26, 590. (d) Faworsky A. Über die Einwirkung von Phosphorhalogenverbindungen auf Ketone, Bromketone und Ketonalkohole. *J. Prakt. Chem*. **1913**, 88 (1), 641–698.

[38] (a) Shine HJ, Zmuda H, Park KH, Kwart H, Horgan AG, Collins C, and Maxwell BE. Mechanism of the benzidine rearrangement. Kinetic isotope effects and transition states. Evidence for concerted rearrangement. *J. Am. Chem. Soc*. **1981**, 103 (4), 955–956. (b) Fischer E, and Jourdan F. Ueber die Hydrazine der Brenztraubensäure. *Ber. Dtsch. Chem. Ges*. **1883**, 16 (2), 2241–2245. (c) Fischer E, and Hess O. Synthese von Indolderivaten. *Ber. Dtsch. Chem. Ges*. **1884**, 17 (1), 559–568. (d) The Nobel Prize in Chemistry 1902. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1902/summary/).

[39] (a) Ador E, and Crafts J. Ueber die Einwirkung des Chlorkohlenoxyds auf Toluol in Gegenwart von Chloraluminium. *Ber. Dtsch. Chem. Ges*. **1877**, 10 (2), 2173–2176. (b) Friedel C, and Crafts JM. A New General Synthetical Method of Producing Hydrocarbons. *J. Chem. Soc*. **1877**, 32 (0), 725–791. The reference can be found at DOI: 10.1039/JS8773200725 (accessed December 5, 2019).

[40] (a) Ing HR, and Manske RHF. CCCXII. – A modification of the Gabriel synthesis of amines. *J. Chem. Soc*. **1926**, 129 (0), 2348–2351. (b) Delépine M. Sur l'hexamethylene-amine (suite). Solubilities, hydrate, bromure, sulfate, phosphate. *Bull. Soc. Chim. Fr*. **1895**, 13 (3), 352–361. Note, the original reference is published in French and it is difficult to locate. (c) Gabriel S. Ueber eine Darstellungsweise primärer Amine aus den entsprechenden Halogenverbindungen. *Ber. Dtsch. Chem. Ges*. **1887**, 20 (2), 2224–2236.

[41] (a) Knoevenagel E. Condensation von Malonsäure mit aromatischen Aldehyden durch Ammoniak und Amine. *Ber. Dtsch. Chem. Ges*. **1898**, 31 (3), 2596–2619. (b) Gewald K, Schinke E, and Böttcher H. Heterocyclen aus CH-aciden Nitrilen, VIII. 2-Amino-thiophene aus methylenaktiven Nitrilen, Carbonylverbindungen und Schwefel. *Chem. Ber*. **1966**, 99 (1), 94–100.

[42] (a) Eglinton G, and Galbraith AR. 182. Macrocyclic acetylenic compounds. Part I. *Cyclo*tetradeca-1:3-diyne and related compounds. *J. Chem. Soc*. **1959**, (0), 889–896. (b) Behr OM, Eglinton G, Galbraith AR, and Raphael RA. 722. Macrocyclic acetylenic compounds. Part II. 1,2:7,8-Dibenzocyclododeca-1,7-diene-3,5,9,11-tetrayne. *J. Chem. Soc*. **1960**, (0), 3614–3625. (c) Glaser C. Beiträge zur Kenntniss des Acetenylbenzols. *Ber. Dtsch. Chem. Ges*. **1869**, 2 (1), 422–424. (d) Hay A. Communications- Oxidative Coupling of Acetylenes. *J. Org. Chem*. **1960**, 25 (7), 1275–1276. (e) Hay AS. Oxidative Coupling of Acetylenes. II *J. Org. Chem*. **1962**, 27 (9), 3320–3321. (f) Shi W, and Lei A. 1,3-Diyne chemistry: synthesis and derivations. *Tetrahedron Lett*. **2014**, 55 (17), 2763–2772. See also references therein.

[43] (a) Grignard V. Sur quelques nouvelles combinaisons organométaliques du magnésium et leur application à des synthèses d'alcools et d'hydrocabures. *Compt. Rend*. **1900**, 130, 1322–1324. The original reference is in French and can be accessed at https://gallica.bnf.fr/ark:/12148/bpt6k3086n/f1322.table (accessed December 5, 2019). (b) The Nobel Prize in Chemistry 1912. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1912/summary/).

[44] (a) Prantz K, and Mulzer J. Synthetic Applications of the Carbonyl Generating Grob Fragmentation. *Chem. Rev*. **2010**, 110 (6), 3741–3766. (b) Grob CA, and Baumann W. Die 1,4-Eliminierung unter Fragmentierung. *Helv. Chim. Acta* **1955**, 38 (3), 594–610. (c) Grob CA, and Schiess PW. Heterolytic Fragmentation. A Class of Organic Reactions. *Angew. Chem. Int. Ed. Engl*. **1967**, 6 (1), 1–15.

[45] (a) Surellas GS. Notes sur l'Hydriodate de potasse et l'Acide hydriodique. – Hydriodure de carbone; moyen d'obtenir, à l'instant, ce composé triple. **1822**. The original reference is in French and can be accessed at https://gallica.bnf.fr/ark:/12148/bpt6k6137757n/f2.image (accessed December 5, 2019). (b) Liebig J. Ueber die Verbindungen, welche durch die Einwirkung des Chlors auf Alkohol, Aether, ölbildendes Gas und Essiggeist entstehen. *Ann. Phys*. **1832**, 100 (2), 243–295. (c) Lieben A. Ueber Entstehung von Jodoform und Anwendung dieser Reaction in der chemischen Analyse. *Annalen der Chemie. Supplementband*. **1870**, 7, 218–236. The original reference is in German and can be accessed at https://babel.hathitrust.org/cgi/pt?id=uiug.30112018225695&view=1up&seq=230 (accessed December 5, 2019). Note, additional references can be found at https://en.wikipedia.org/wiki/Haloform_reaction (accessed December 5, 2019).

[46] (a) Heck RF. Acylation, methylation, and carboxyalkylation of olefins by Group VIII metal derivatives. *J. Am. Chem. Soc*. **1968**, 90 (20), 5518–5526. (b) Mizoroki T, Mori K, and Ozaki A. Arylation of Olefin with Aryl Iodide Catalyzed by Palladium. *Bull. Chem. Soc. Jpn*. **1971**, 44 (2), 581. (c) The Nobel Prize in Chemistry 2010. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/2010/summary/).

[47] (a) Hell C. Ueber eine neue Bromirungsmethode organischer Säuren. *Ber. Dtsch. Chem. Ges*. **1881**, 14 (1), 891–893. (b) Volhard J. 4) Ueber Darstellung α-bromirter Säuren. *Justus Liebigs Ann. Chem*. **1887**, 242 (1–2), 141–163. (c) Zelinsky N. Ueber eine bequeme Darstellungsweise von α-Brompropionsäureester. *Ber. Dtsch. Chem. Ges*. **1887**, 20 (1), 2026.

[48] (a) Denmark SE, and Regens CS. Palladium-Catalyzed Cross-Coupling Reactions of Organosilanols and Their Salts: Practical Alternatives to Boron- and Tin-Based Methods. *Acc. Chem. Res*. **2008**, 41 (11), 1486–1499. (b) Hatanaka Y, and Hiyama T. Cross-coupling of organosilanes with organic halides mediated by a palladium catalyst and tris(diethylamino) sulfonium difluorotrimethylsilicate. *J. Org. Chem*. **1988**, 53 (4), 918–920.

[49] (a) Saytzeff A. Zur Kenntniss der Reihenfolge der Analgerung und Ausscheidung der Jodwasserstoffelemente in organischen Verbindungen. *Justus Liebigs Ann. Chem*. **1875**, 179 (3), 296–301. (b) Cope AC, and Trumbull ER. (2011). Olefins from Amines: The Hofmann Elimination Reaction and Amine Oxide Pyrolysis. In Organic Reactions, (Ed.).

doi:10.1002/0471264180.or011.05. (c) Hofmann AW. Beiträge zur Kenntniss der flüchtigen organischen Basen. *Justus Liebigs Ann. Chem*. **1851**, 78 (3), 253–286. (d) Hofmann AW. Beiträge zur Kenntniss der flüchtigen organischen Basen. *Justus Liebigs Ann. Chem*. **1851**, 79 (1), 11–39.

[50] (a) Maryanoff BE, and Reitz AB. The Wittig olefination reaction and modifications involving phosphoryl-stabilized carbanions. Stereochemistry, mechanism, and selected synthetic aspects. *Chem. Rev*. **1989**, 89 (4), 863–927. (b) Peterson DJ. Carbonyl olefination reaction using silyl-substituted organometallic compounds. *J. Org. Chem*. **1968**, 33 (2), 780–784. (c) Horner L, Hoffmann H, and Wippel HG. Phosphororganische Verbindungen, XII. Phosphinoxyde als Olefinierungsreagenzien. *Chem. Ber*. **1958**, 91 (1), 61–63. (d) Horner L, Hoffmann H, Wippel HG, and Klahre G. Phosphororganische Verbindungen, XX. Phosphinoxyde als Olefinierungsreagenzien. *Chem. Ber*. **1959**, 92 (10), 2499–2505. (e) Wadsworth WS, and Emmons WD. The Utility of Phosphonate Carbanions in Olefin Synthesis. *J. Am. Chem. Soc*. **1961**, 83 (7), 1733–1738.

[51] (a) Freeman F. (2001). Chromic Acid. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rc164. (b) Piancatelli G, and Luzzio FA. (2007). Pyridinium Chlorochromate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/9780470842898.rp288.pub2. (c) Piancatelli G. (2001). Pyridinium Dichromate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rp290. (d) Bowden K, Heilbron IM, Jones ERH, and Weedon BCL. 13. Researches on acetylenic compounds. Part I. The preparation of acetylenic ketones by oxidation of acetylenic carbinols and glycols. *J. Chem. Soc*. **1946**, (0), 39–45.

[52] (a) Markownikoff W. I. Ueber die Abhängigkeit der verschiedenen Vertretbarkeit des Radicalwasserstoffs in den isomeren Buttersäuren. *Justus Liebigs Ann. Chem*. **1870**, 153 (2), 228–259. (b) Kutscheroff M. Ueber eine neue Methode direkter Addition von Wasser (Hydratation) an die Kohlenwasserstoffe der Acetylenreihe. *Ber. Dtsch. Chem. Ges*. **1881**, 14 (1), 1540–1542.

[53] (a) Corriu RJP, and Masse JP. Activation of Grignard reagents by transition-metal complexes. A new and simple synthesis of *trans*-stilbenes and polyphenyls. *J. Chem. Soc., Chem. Commun*. **1972**, (3), 144a. (b) Tamao K, Sumitani K, and Kumada M. Selective carbon-carbon bond formation by cross-coupling of Grignard reagents with organic halides. Catalysis by nickel-phosphine complexes. *J. Am. Chem. Soc*. **1972**, 94 (12), 4374–4376. (c) Tamao K, Kiso Y, Sumitani K, and Kumada M. Alkyl group isomerization in the cross-coupling reaction of secondary alkyl Grignard reagents with organic halides in the presence of nickel-phosphine complexes as catalysts. *J. Am. Chem. Soc*. **1972**, 94 (26), 9268–9269.

[54] (a) Ley SV, Norman J, and Wilson AJ. (2011). Tetra-*n*-propylammonium Perruthenate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rt074.pub2. (b) Griffith WP, Ley SV, Whitcombe GP, and White AD. Preparation and use of tetra-n-butylammonium per-ruthenate (TBAP reagent) and tetra-n-propylammonium per-ruthenate (TPAP reagent) as new catalytic oxidants for alcohols. *J. Chem. Soc., Chem. Commun*. **1987**, (21), 1625–1627.

[55] (a) Liebeskind LS, and Srogl J. Thiol Ester–Boronic Acid Coupling. A Mechanistically Unprecedented and General Ketone Synthesis. *J. Am. Chem. Soc*. **2000**, 122 (45), 11260–11261. (b) Cheng HG, Chen H, Liu Y, and Zhou Q. The Liebeskind–Srogl Cross-Coupling Reaction and its Synthetic Applications. *Asian J. Org. Chem*. **2018**, 7 (3), 490–508. The open access paper can be found at https://onlinelibrary.wiley.com/doi/epdf/10.1002/ajoc.201700651 (accessed December 5, 2019).

[56] (a) Kleinman EF. (2001). Dimethyl(methylene)ammonium Iodide. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rd346. (b) Mannich C, and Krösche W. Ueber ein Kondensationsprodukt aus Formaldehyd, Ammoniak und Antipyrin. *Arch. Pharm. Pharm. Med. Chem*. **1912**, 250 (1), 647–667.

[57] (a) Fittig R. Ueber einige Producte der trockenen Destillation essigsaurer Salze. *Justus Liebigs Ann. Chem*. **1859**, 110 (1), 17–23. (b) Demselben. Ueber einige Metamorphosen des Acetons der Essigsäure. *Justus Liebigs Ann. Chem*. **1859**, 110 (1), 23–45. (c) McMurry JE, and Fleming MP. New method for the reductive coupling of carbonyls to olefins. Synthesis of β–carotene. *J. Am. Chem. Soc*. **1974**, 96 (14), 4708–4709.

[58] (a) Meerwein H, and Schmidt R. Ein neues Verfahren zur Reduktion von Aldehyden und Ketonen. *Justus Liebigs Ann. Chem*. **1925**, 444 (1), 221–238. (b) Verley A. Sur l'échange de groupements fonctionnels entre deux molécules. Passage de la fonction alcool à la fonction aldéhyde et inversement. *Bull. Soc. Chim. Fr*. **1925**, 37, 537–542. Note, the original reference is published in French and it is difficult to locate. (c) Ponndorf W. Der reversible Austausch der Oxydationsstufen zwischen Aldehyden oder Ketonen einerseits und primären oder sekundären Alkoholen anderseits. *Angew. Chem*. **1926**, 39 (5), 138–143.

[59] (a) Stetter H, and Schreckenberg M. A New Method for Addition of Aldehydes to Activated Double Bonds. *Angew. Chem. Int. Ed. Engl*. **1973**, 12 (1), 81. (b) Michael A. Ueber die Addition von Natriumacetessig- und Natriummalonsäureäthern zu den Aethern ungesättigter Säuren. *J. Prakt. Chem*. **1887**, 35 (1), 349–356.

[60] (a) Hong Y. (2001). Hydrogen Peroxide–Iron(II) Sulfate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rh043. (b) Mihailović ML, Čeković Ž, and Mathes BM. (2005). Lead(IV) Acetate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rl006.pub2. (c) Kolbe H. Untersuchungen über die Elektrolyse organischer Verbindungen. *Justus Liebigs Ann. Chem*. **1849**, 69 (3), 257–294. (d) Minisci F, Galli R, Cecere M, Malatesta V, and Caronna T. Nucleophilic character of alkyl radicals: new syntheses by alkyl radicals generated in redox processes. *Tetrahedron Lett*. **1968**, 9 (54), 5609–5612. (e) Minisci F, Bernardi R, Bertini F, Galli R, and Perchinummo M. Nucleophilic character of alkyl radicals – VI: A new convenient selective alkylation of heteroaromatic bases. *Tetrahedron* **1971**, 27 (15), 3575–3579.

[61] (a) Jenkins ID, and Mitsunobu O. (2001). Triphenylphosphine–Diethyl Azodicarboxylate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rt372. (b) Hughes DL. (2004). The Mitsunobu Reaction. In Organic Reactions, (Ed.). doi:10.1002/0471264180.or042.02. (c) Swamy KCK, Kumar NNB, Balaraman E, and Kumar KVPP. Mitsunobu and Related Reactions: Advances and Applications. *Chem. Rev*. **2009**, 109 (6), 2551–2651. (d) Mitsunobu O, Yamada M, and Mukaiyama T. Preparation of Esters of Phosphoric Acid by the Reaction of Trivalent Phosphorus Compounds with Diethyl Azodicarboxylate in the Presence of Alcohols. *Bull. Chem. Soc. Jpn*. **1967**, 40 (4), 935–939. The open access paper can be found at https://doi.org/10.1246/bcsj.40.935 (accessed December 5, 2019). (e) Mitsunobu O, and Yamada M. Preparation of Esters of Carboxylic and Phosphoric Acid via Quaternary Phosphonium Salts. *Bull. Chem. Soc. Jpn*. **1967**, 40 (10), 2380–2382. The open access paper can be found at https://doi.org/10.1246/bcsj.40.2380 (accessed December 5, 2019).

[62] (a) Ishiyama T, Chen H, Morken JP, Mlynarski SN, Ferris GE, Xu S, and Wang J. (2018). 4,4,4′,4′,5,5,5′,5′-Octamethyl-2,2′-bi-1,3,2-dioxaborolane. In e-EROS Encyclopedia of Reagents for Organic Synthesis. doi:10.1002/047084289X.rn00188.pub4. (b) Petasis NA, and Akritopoulou I. The boronic acid mannich reaction: A new method for the synthesis of geometrically pure allylamines. *Tetrahedron Lett*. **1993**, 34 (4), 583–586. (c) Ishiyama T, Murata M, and Miyaura N. Palladium(0)-Catalyzed Cross-Coupling Reaction of Alkoxydiboron with Haloarenes: A Direct Procedure for Arylboronic Esters. *J. Org. Chem*. **1995**, 60 (23), 7508–7510.

[63] (a) Tokuyasu T, Kunikawa S, Masuyama A, and Nojima M. Co(III)–Alkyl Complex- and Co(III)–Alkylperoxo Complex-Catalyzed Triethylsilylperoxidation of Alkenes with Molecular Oxygen and Triethylsilane. *Org. Lett*. **2002**, 4 (21), 3595–3598. (b) Mukaiyama T, Isayama S, Inoki S, Kato K, Yamada T, and Takai T. Oxidation-Reduction Hydration of Olefins with Molecular Oxygen

and 2-Propanol Catalyzed by Bis(acetylacetonato)cobalt(II). *Chem. Lett*. **1989**, 18 (3), 449–452. (c) Inoki S, Kato K, Takai T, Isayama S, Yamada T, and Mukaiyama T. Bis(trifluoroacetylacetonato) cobalt(II) Catalyzed Oxidation-Reduction Hydration of Olefins Selective Formation of Alcohols from Olefins. *Chem. Lett*. **1989**, 18 (3), 515–518. (d) Isayama S, and Mukaiyama T. A New Method for Preparation of Alcohols from Olefins with Molecular Oxygen and Phenylsilane by the Use of Bis(acetylacetonato)cobalt(II). *Chem. Lett*. **1989**, 18 (6), 1071–1074.

[64] (a) Woodward RB, and Hoffmann R. Stereochemistry of Electrocyclic Reactions. *J. Am. Chem. Soc*. **1965**, 87 (2), 395–397. (b) Woodward RB, and Hoffmann R. The Conservation of Orbital Symmetry. *Angew. Chem. Int. Ed. Engl*. **1969**, 8 (11), 781–853. (c) In 1965 Robert Burns Woodward received the Nobel Prize in Chemistry (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1965/summary/). In 1981 Roald Hoffmann (jointly with Kenichi Fukui) received the Nobel Prize in Chemistry (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1981/summary/). (d) Nazarov IN, and Zaretskaya II. Acetylene derivatives. XVII. Hydration of Hydrocarbons of the Divinylacetylene Series. *Izv. Akad. Nauk. SSSR, Ser. Khim*. **1941**, 211–224. (e) Nazarov IN, and Zaretskaya II. Derivatives of acetylene. XXVII. Hydration of divinylacetylene. *Bull. acad. sci. U.R.S.S*., *Classe sci. chim*. **1942**, 200–209. Note, the original references are published in Russian and they are difficult to locate. See also (f) Santelli-Rouvier C, and Santelli M. The Nazarov Cyclisation. *Synthesis* **1983** (6), 429–442. (g) Frontier AJ, and Collison C. The Nazarov cyclization in organic synthesis. Recent advances. *Tetrahedron* **2005**, 61 (32), 7577–7606. Other review references can be found in [5c].

[65] (a) Kornblum N, and Brown RA. The Action of Acids on Nitronic Esters and Nitroparaffin Salts. Concerning the Mechanisms of the Nef and the Hydroxamic Acid Forming Reactions of Nitroparaffins. *J. Am. Chem. Soc*. **1965**, 87 (8), 1742–1747. (b) Konovalov MI. *J. Russ. Phys. Chem. Soc*. **1893**, 25, 509. Note, the original reference is published in Russian and it is difficult to locate: Konovalov MI. *Zhur. Russ. Khim. Obshch*. **1893**, 25, 389, 472, 509. (c) Nef JU. Ueber die Constitution der Salze der Nitroparaffine. *Justus Liebigs Ann. Chem*. **1894**, 280 (2–3), 263–291. (d) Nef JU. Ueber das zweiwerthige Kohlenstoffatom. *Justus Liebigs Ann. Chem*. **1894**, 280 (2–3), 291–342.

[66] (a) King AO, Okukado N, and Negishi E. Highly general stereo-, regio-, and chemo-selective synthesis of terminal and internal conjugated enynes by the Pd-catalysed reaction of alkynylzinc reagents with alkenyl halides. *J. Chem. Soc., Chem. Commun*. **1977**, (19), 683–684. (b) Negishi E, King AO, and Okukado N. Selective carbon-carbon bond formation via transition metal catalysis. 3. A highly selective synthesis of unsymmetrical biaryls and diarylmethanes by the nickel- or palladium-catalyzed reaction of aryl- and benzylzinc derivatives with aryl halides. *J. Org. Chem*. **1977**, 42 (10), 1821–1823.

[67] (a) Norrish RGW, and Kirkbride FW. 204. Primary photochemical processes. Part I. The decomposition of formaldehyde. *J. Chem. Soc*. **1932**, (0), 1518–1530. (b) Norrish RGW, and Appleyard MES. 191. Primary photochemical reactions. Part IV. Decomposition of methyl ethyl ketone and methyl butyl ketone. *J. Chem. Soc*. **1934**, (0), 874–880. (c) Norrish RGW, Crone HG, and Saltmarsh OD. 318. Primary photochemical reactions. Part V. The spectroscopy and photochemical decomposition of acetone. *J. Chem. Soc*. **1934**, (0), 1456–1464. (d) Bamford CH, and Norrish RGW. 359. Primary photochemical reactions. Part VII. Photochemical decomposition of *iso*valeraldehyde and di-*n*-propyl ketone. *J. Chem. Soc*. **1935**, (0), 1504–1511. (e) Norrish RGW, and Bamford CH. Photodecomposition of Aldehydes and Ketones. *Nature* **1936**, 138, 1016. (f) Norrish RGW, and Bamford CH. Photo-decomposition of Aldehydes and Ketones. *Nature* **1937**, 140, 195–196. (g) The Nobel Prize in Chemistry 1967. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1967/summary/).

[68] (a) Nelson DJ, Manzini S, Urbina-Blanco CA, and Nolan SP. Key processes in ruthenium-catalysed olefin metathesis. *Chem. Commun*. **2014**, 50 (72), 10355–10375. (b) Ziegler K, Holzkamp E, Breil H, and Martin H. Polymerisation von Äthylen und anderen Olefinen. *Angew. Chem*. **1955**, 67 (16), 426. (c) Anderson AW, and Merckling NG. Polymeric bicyclo-(2,2,1)-2-heptene. US Patent Office 2721189, **1955** (E. I. du Pont de Nemours and Company). (d) The Nobel Prize in Chemistry 2005. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/2005/summary/). (e) Takacs JM, and Atkins JM. (2002). Dichloro-bis(tricyclohexylphosphine)methyleneruthenium. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rn00110. (f) Diver ST, and Middleton MD. (2010). Ruthenium, [1,3-Bis(2,4,6-trimethylphenyl)-2-imidazolidinylidene]dichloro(phenylmethylene)(tricyclohexylphosphine) (Grubbs' Second-Generation Catalyst). In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rn01100. (g) Garber SB, Khan RKM, Mann TJ, and Hoveyda AH. (2013). Dichloro[[2-(1-methylethoxy-*O*)phenyl]-methylene] (tricyclohexylphosphine) Ruthenium. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rn00129.pub2.

[69] Oppenauer RV. Eine Methode der Dehydrierung von Sekundären Alkoholen zu Ketonen. I. Zur Herstellung von Sterinketonen und Sexualhormonen. *Recl. Trav. Chim. Pays- Bas* **1937**, 56 (2), 137–144.

[70] (a) Criegee R, and Wenner G. Die Ozonisierung des 9,10-Oktalins. *Justus Liebigs Ann. Chem*. **1949**, 564 (1), 9–15. (b) Criegee R. Mechanism of Ozonolysis. *Angew. Chem. Int. Ed. Engl*. **1975**, 14 (11), 745–752. (c) Criegee R. Mechanismus der Ozonolyse. *Angew. Chem*. **1975**, 87 (21), 765–771. (d) Wee AG, Liu B, Jin Z, and Shah AK. (2012). Sodium Periodate–Osmium Tetroxide. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). https://onlinelibrary.wiley.com/doi/abs/10.1002/047084289X.rs095m.pub2 (accessed December 5, 2019). (e) Berglund RA, and Kreilein MM. (2006). Ozone. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.ro030.pub2. (f) Wee AG, and Liu B. (2001). Sodium Periodate–Potassium Permanganate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rs096. (g) Harries C. Ueber die Einwirkung des Ozons auf organische Verbindungen. *Justus Liebigs Ann. Chem*. **1905**, 343 (2–3), 311–344. Note, the original reference is very old (1840) and it is difficult to locate. See also references in [70g].

[71] (a) Voss J. (2006). 2,4-Bis(4-methoxyphenyl)-1,3,2,4-dithiadiphosphetane 2,4-Disulfide. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rb170.pub2. (b) Paal C. Ueber die Derivate des Acetophenonacetessigesters und des Acetonylacetessigesters. *Ber. Dtsch. Chem. Ges*. **1884**, 17 (2), 2756–2767. (c) Knorr L. Synthese von Furfuranderivaten aus dem Diacetbernsteinsäureester. *Ber. Dtsch. Chem. Ges*. **1884**, 17 (2), 2863–2870.

[72] (a) Paternò E, and Chieffi G. Sintesi in chimica organica per mezzo della luce. Nota II. Composti degli idrocarburi non saturi con aldeidi e chetoni. *Gazz. Chim. Ital*. **1909**, 39, 341. Note, the original reference is published in Italian and it is difficult to locate. (b) Büchi G, Inman CG, and Lipinsky ES. Light-catalyzed Organic Reactions. I. The Reaction of Carbonyl Compounds with 2-Methyl-2-butene in the Presence of Ultraviolet Light. *J. Am. Chem. Soc*. **1954**, 76 (17), 4327–4331.

[73] (a) Brummonda KM, and Kent JL. Recent Advances in the Pauson–Khand Reaction and Related [2+2+1] Cycloadditions. *Tetrahedron* **2000**, 56 (21), 3263–3283. Please check additional review articles in [5]. (b) Khand IU, Knox GR, Pauson PL, and Watts WE. Organocobalt complexes. Part I. Arene complexes derived from dodecacarbonyltetracobalt. *J. Chem. Soc., Perkin Trans. 1* **1973**, (0), 975–977. (c) Khand IU, Knox GR, Pauson PL, Watts WE, and Foreman MI.

Organocobalt complexes. Part II. Reaction of acetylenehexacarbonyldicobalt complexes, $(R^1C_2R^2)Co_2(CO)_6$, with norbornene and its derivatives. *J. Chem. Soc., Perkin Trans. 1* **1973**, (0), 977–981. (d) Pauson PL, and Khand IU. Uses of Cobalt-Carbonyl Acetylene Complexes in Organic Synthesis. *Ann. N. Y. Acad. Sci*. **1977**, 295 (1), 2–14.

[74] (a) Valeur E, and Bradley M. Amide bond formation: beyond the myth of coupling reagents. *Chem. Soc. Rev*. **2009**, 38 (2), 606–631. (b) El-Faham A, and Albericio F. Peptide Coupling Reagents, More than a Letter Soup. *Chem. Rev*. **2011**, 111 (11), 6557–6602. (c) Carpino LA, Imazumi H, El-Faham A, Ferrer FJ, Zhang C, Lee Y, Foxman BM, Henklein P, Hanay C, Mügge C, Wenschuh H, Klose J, Beyermann M, and Bienert M. The Uronium/Guanidinium Peptide Coupling Reagents: Finally the True Uronium Salts. *Angew. Chem. Int. Ed*. **2002**, 41 (3), 441–445. (d) Albert JS, Hamilton AD, Hart AC, Feng X, Lin L, and Wang Z. (2017). 1,3-Dicyclohexylcarbodiimide. In e-EROS Encyclopedia of Reagents for Organic Synthesis. doi:10.1002/047084289X.rd146.pub3. (e) Pottorf RS, Szeto P, and Srinivasarao M. (2017). 1-Ethyl-3-(3′-dimethylaminopropyl)carbodiimide Hydrochloride. In e-EROS Encyclopedia of Reagents for Organic Synthesis. doi:10.1002/047084289X.re062.pub2. (f) Albericio F, and Kates SA. (2001). *O*-Benzotriazol-1-yl-*N*,*N*,*N*′,*N*′-tetramethyluronium Hexafluorophosphate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rb038. (g) Albericio F, Kates SA, and Carpino LA. (2001). *N*-[(Dimethylamino)-1*H*-1,2,3-triazolo[4,5-*b*]pyridin-1-ylmethylene]-*N*-methylmethanaminium Hexafluorophosphate *N*-Oxide. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). https://onlinelibrary.wiley.com/doi/10.1002/047084289X.rd312s (accessed December 5, 2019). (h) Coste J, and Jouin P. (2003). (1*H*-Benzotriazol-1-yloxy)tripyrrolidino-phosphonium Hexafluorophosphate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rn00198. (i) Lygo B, and Pelletier G. (2013). 1-Hydroxybenzotriazole. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rh052.pub2. (j) Fischer E, and Fourneau E. Ueber einige Derivate des Glykocolls. *Ber. Dtsch. Chem. Ges*. **1901**, 34 (2), 2868–2877. (k) Sheehan JC, and Hess GP. A New Method of Forming Peptide Bonds. *J. Am. Chem. Soc*. **1955**, 77 (4), 1067–1068. (l) Dourtoglou V, Ziegler JC, and Gross B. L'hexafluorophosphate de O-benzotriazolyl-N,N-tetramethyluronium: Un reactif de couplage peptidique nouveau et efficace. *Tetrahedron Lett*. **1978**, 19 (15), 1269–1272.

[75] (a) Baldwin JE. Rules for ring closure. *J. Chem. Soc., Chem. Commun*. **1976**, (18), 734–736. (b) Pictet A, and Spengler T. Über die Bildung von Isochinolin-derivaten durch Einwirkung von Methylal auf Phenyl-äthylamin, Phenyl-alanin und Tyrosin. *Ber. Dtsch. Chem. Ges*. **1911**, 44 (3), 2030–2036.

[76] (a) Demjanov NJ, and Lushnikov M. *J. Russ. Phys. Chem. Soc*. **1903**, 35, 26–42. Note, the original reference is published in Russian and it is difficult to locate: Demjanov NJ, and Lushnikov M. *Zhur. Russ. Khim. Obshch*. **1903**, 35, 26–42. (b) Tiffeneau M, Weill P, and Tchoubar B. Isomérisation de l'oxyde de méthylène cyclohexane en hexahydrobenzaldéhyde et désamination de l'aminoalcool correspondant en cycloheptanone. *Compt. Rend*. **1937**, 205, 54–56. The reference is in French and can be viewed at https://gallica.bnf.fr/ark:/12148/bpt6k3157c.image.f54 (accessed December 5, 2019). (c) Fittig R. 41. Ueber einige Derivate des Acetons. *Justus Liebigs Ann. Chem*. **1860**, 114 (1), 54–63.

[77] (a) Cave A, Kan-Fan C, Potier P, and Men JL. Modification de la reaction de polonovsky: Action de l'anhydride trifluoroacetique sur un aminoxide. *Tetrahedron* **1967**, 23 (12), 4681–4689. (b) Ahond A, Cave A, Kan-Fan C, Husson HP, Rostolan J, and Potier P. Facile N-O bond cleavages of amine oxides. *J. Am. Chem. Soc*. **1968**, 90 (20), 5622–5623. (c) Polonovski M, and Polonovski M. Sur les aminoxydes des alcaloides. III. Action des anhydrides et chlorules d'acides organiques. Preparations des bases nor. *Bull. Soc. Chim. Fr*. **1927**, 41, 1190–1208. Note, the original reference is published in French and it is difficult to locate.

[78] (a) Katsuki T, and Sharpless KB. The first practical method for asymmetric epoxidation. *J. Am. Chem. Soc*. **1980**, 102 (18), 5974–5976. (b) Tu Y, Wang ZX, and Shi Y. An Efficient Asymmetric Epoxidation Method for *trans*-Olefins Mediated by a Fructose-Derived Ketone. *J. Am. Chem. Soc*. **1996**, 118 (40), 9806–9807. (c) Prileschajew N. Oxydation ungesättigter Verbindungen mittels organischer Superoxyde. *Ber. Dtsch. Chem. Ges*. **1909**, 42 (4), 4811–4815.

[79] (a) Dobbs AP, Guesné SJJ, Parker RJ, Skidmore J, Stephensond RA, and Hursthouse MB. A detailed investigation of the aza-Prins reaction. *Org. Biomol. Chem*. **2010**, 8 (5), 1064–1080. (b) Reddy BVS, Nair PN, Antony A, Lalli C, and Grée R. The Aza-Prins Reaction in the Synthesis of Natural Products and Analogues. *Eur. J. Org. Chem*. **2017**, (14), 1805–1819. (c) Rajasekaran P, Singh GP, Hassam M, and Vankar YD. A Cascade "Prins-Pinacol-Type Rearrangement and C4-OBn Participation" on Carbohydrate Substrates: Synthesis of Bridged Tricyclic Ketals, Annulated Sugars and C2-Branched Heptoses. *Chem. Eur. J*. **2016**, 22 (51), 18383–18387. (d) Prins HJ. Over de condensatie van formaldehyd met onverzadigde verbindingen. *Chem. Weekblad* **1919**, 16, 1072–1073. (e) Prins HJ. The reciprocal condensation of unsaturated organic compounds. *Chem. Weekblad* **1919**, 16, 1510–1526. Note, the original references are difficult to locate.

[80] Pummerer R. Über Brom-Additionsprodukte von Aryl-thioglykolsäuren. *Ber. Dtsch. Chem. Ges*. **1909**, 42 (2), 2275–2282.

[81] (a) See more at https://en.wikipedia.org/wiki/Cheletropic_reaction (accessed December 5, 2019). (b) Philips JC, and Morales O. Sulphur dioxide extrusion from substituted thiiren 1,1-dioxides. *J. Chem. Soc., Chem. Commun*. **1977**, (20), 713–714. (c) Ramberg L, and Bäcklund B. *Ark. Kemi. Mineral. Geol*. **1940**, 27, Band 13A, 1–50. Note, the original reference is difficult to locate (see also *Chem. Abstr*. **1940**, 34, 4725).

[82] (a) Blaise EE. *Comp. Rend. Hebd. Seances Acad. Sci*. **1901**, 132, 478–480. Note, the original reference is difficult to locate. (b) Cason J, Rinehart KL, and Thornton SD. The Preparation of β-Keto Esters from Nitriles and α-Bromoesters. *J. Org. Chem*. **1953**, 18 (11), 1594–1600. (c) Reformatsky S. Neue Synthese zweiatomiger einbasischer Säuren aus den Ketonen. *Ber. Dtsch. Chem. Ges*. **1887**, 20 (1), 1210–1211.

[83] (a) Rapson WS, and Robinson R. 307. Experiments on the synthesis of substances related to the sterols. Part II. A new general method for the synthesis of substituted cyclohexenones. *J. Chem. Soc*. **1935**, (0), 1285–1288. (b) The Nobel Prize in Chemistry 1947. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1947/summary/).

[84] (a) Bamford WR, and Stevens TS. 924. The decomposition of toluene-*p*-sulphonylhydrazones by alkali. *J. Chem. Soc*. **1952**, (0), 4735–4740. (b) Shapiro RH, and Heath MJ. Tosylhydrazones. V. Reaction of Tosylhydrazones with Alkyllithium Reagents. A New Olefin Synthesis. *J. Am. Chem. Soc*. **1967**, 89 (22), 5734–5735. (c) Shapiro RH, Lipton MF, Kolonko KJ, Buswell RL, and Capuano LA. Tosylhydrazones and alkyllithium reagents: More on the regiospecificity of the reaction and the trapping of three intermediates. *Tetrahedron Lett*. **1975**, 16 (22–23), 1811–1814. (d) Shapiro RH. (2011). Alkenes from Tosylhydrazones. In Organic Reactions, (Ed.). doi:10.1002/0471264180.or023.03.

[85] (a) Stephens RD, and Castro CE. The Substitution of Aryl Iodides with Cuprous Acetylides. A Synthesis of Tolanes and Heterocyclics. *J. Org. Chem*. **1963**, 28 (12), 3313–3315. (b) Sonogashira K, Tohda Y, and Hagihara N. A convenient synthesis of acetylenes: catalytic substitutions of acetylenic hydrogen with bromoalkenes, iodoarenes and bromopyridines. *Tetrahedron Lett*. **1975**, 16 (50), 4467–4470.

[86] (a) Staudinger H. Zur Kenntniss der Ketene. Diphenylketen. *Justus Liebigs Ann. Chem*. **1907**, 356 (1–2), 51–123. (b) Staudinger H. Über Ketene. 4. Mitteilung: Reaktionen des Diphenylketens. *Ber. Dtsch. Chem. Ges*. **1907**, 40 (1), 1145–1148. (c) Saxon E, and Bertozzi CR. Cell Surface

Engineering by a Modified Staudinger Reaction. *Science* **2000**, 287 (5460), 2007–2010. (d) Saxon E, Armstrong JI, and Bertozzi CR. A "Traceless" Staudinger Ligation for the Chemoselective Synthesis of Amide Bonds. *Org. Lett*. **2000**, 2 (14), 2141–2143. (e) Wang ZPA, Tiana CL, and Zheng JS. The recent developments and applications of the traceless-Staudinger reaction in chemical biology study. *RSC Adv*. **2015**, 5 (130), 107192–107199. (f) Staudinger H, and Meyer J. Über neue organische Phosphorverbindungen III. Phosphinmethylenderivate und Phosphinimine. *Helv. Chim. Acta* **1919**, 2 (1), 635–646. (g) The Nobel Prize in Chemistry 1953. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1953/summary/).

[87] (a) Albert JS, and Hamilton AD. (2001). 1,3-Dicyclohexylcarbodiimide–4-Dimethylaminopyridine. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rd147. (b) Neises B, and Steglich W. Simple Method for the Esterification of Carboxylic Acids. *Angew. Chem. Int. Ed. Engl*. **1978**, 17 (7), 522–524.

[88] (a) Merrifield JH, Godschalx JP, and Stille JK. Synthesis of unsymmetrical diallyl ketones: the palladium-catalyzed coupling of allyl halides with allyltin reagents in the presence of carbon monoxide. *Organometallics* **1984**, 3 (7), 1108–1112. (b) Tokuyama H, Yokoshima S, Yamashita T, and Fukuyama T. A novel ketone synthesis by a palladium-catalyzed reaction of thiol esters and organozinc reagents. *Tetrahedron Lett*. **1998**, 39 (20), 3189–3192. (c) Milstein D, and Stille JK. A general, selective, and facile method for ketone synthesis from acid chlorides and organotin compounds catalyzed by palladium. *J. Am. Chem. Soc*. **1978**, 100 (11), 3636–3638. (d) Milstein D, and Stille JK. Palladium-catalyzed coupling of tetraorganotin compounds with aryl and benzyl halides. Synthetic utility and mechanism. *J. Am. Chem. Soc*. **1979**, 101 (17), 4992–4998.

[89] (a) Carrow BP, and Hartwig JF. Distinguishing Between Pathways for Transmetalation in Suzuki–Miyaura Reactions. *J. Am. Chem. Soc*. **2011**, 133 (7), 2116–2119. (b) Thomas AA, and Denmark SE. Pre-transmetalation intermediates in the Suzuki-Miyaura reaction revealed: The missing link. *Science* **2016**, 352 (6283), 329–332. (c) Miyaura N, Yamada K, and Suzuki A. A new stereospecific cross-coupling by the palladium-catalyzed reaction of 1-alkenylboranes with 1-alkenyl or 1-alkynyl halides. *Tetrahedron Lett*. **1979**, 20 (36), 3437–3440. (d) Miyaura N, and Suzuki A. Stereoselective synthesis of arylated (*E*)-alkenes by the reaction of alk-1-enylboranes with aryl halides in the presence of palladium catalyst. *J. Chem. Soc., Chem. Commun*. **1979**, (19), 866–867.

[90] (a) Omura K, Sharma AK, and Swern D. Dimethyl sulfoxide-trifluoroacetic anhydride. New reagent for oxidation of alcohols to carbonyls. *J. Org. Chem*. **1976**, 41 (6), 957–962. (b) Tidwell TT. (2001). Dimethyl Sulfoxide–Dicyclohexylcarbodiimide. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.rd375. Please also see (c) Omura K, and Swern D. Oxidation of alcohols by "activated" dimethyl sulfoxide. A preparative, steric and mechanistic study. *Tetrahedron* **1978**, 34 (11), 1651–1660. (d) Mancuso AJ, Brownfain DS, and Swern D. Structure of the dimethyl sulfoxide-oxalyl chloride reaction product. Oxidation of heteroaromatic and diverse alcohols to carbonyl compounds. *J. Org. Chem*. **1979**, 44 (23), 4148–4150.

[91] (a) Passerini M, and Simone L. Sopra gli isonitrili (I). Composto del *p*-isonitril-azobenzolo con acetone ed acido acetico. *Gazz. Chim. Ital*. **1921**, 51, 126–129. (b) Passerini M. Sopra gli isonitrili (II). Composti con aldeidi o con chetoni ed acidi organici monobasici. *Gazz. Chim. Ital*. **1921**, 51, 181–189. Note, the original references are published in Italian and they are difficult to locate. (c) Ugi I, Meyr R, and Fetzer U. Versammlungsberichte. *Angew. Chem*. **1959**, 71 (11), 373–388. The citation can be found at https://onlinelibrary.wiley.com/doi/abs/10.1002/ange.19590711110 (accessed December 5, 2019).

[92] (a) Ullmann F, and Bielecki J. Ueber Synthesen in der Biphenylreihe. *Ber. Dtsch. Chem. Ges*. **1901**, 34 (2), 2174–2185. (b) Ullmann F. Ueber symmetrische Biphenylderivate. *Justus*

Liebigs Ann. Chem. **1904**, 332 (1–2), 38–81. (c) Ullmann F. Ueber eine neue Bildungsweise von Diphenylaminderivaten. *Ber. Dtsch. Chem. Ges*. **1903**, 36 (2), 2382–2384. (d) Ullmann F, and Sponagel P. Ueber die Phenylirung von Phenolen. *Ber. Dtsch. Chem. Ges*. **1905**, 38 (2), 2211–2212. (e) Sambiagio C, Marsden SP, Blackera AJ, and McGowan PC. Copper catalysed Ullmann type chemistry: from mechanistic aspects to modern development. *Chem. Soc. Rev*. **2014**, 43 (10), 3525–3550.

[93] (a) Gao Y, and Cheun Y. (2013). Osmium Tetroxide–*N*-Methylmorpholine *N*-Oxide. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/047084289X.ro009.pub2. (b) Hentges SG, and Sharpless KB. Asymmetric induction in the reaction of osmium tetroxide with olefins. *J. Am. Chem. Soc*. **1980**, 102 (12), 4263–4265. (c) Wai JSM, Marko I, Svendsen JS, Finn MG, Jacobsen EN, and Sharpless KB. A mechanistic insight leads to a greatly improved osmium-catalyzed asymmetric dihydroxylation process. *J. Am. Chem. Soc*. **1989**, 111 (3), 1123–1125. (d) Ogino Y, Chen H, Kwong HL, and Sharpless KB. On the timing of hydrolysis / reoxidation in the osmium-catalyzed asymmetric dihydroxylation of olefins using potassium ferricyanide as the reoxidant. *Tetrahedron Lett*. **1991**, 32 (32), 3965–3968. (e) Lee DG, Ribagorda M, and Adrio J. (2007). Potassium Permanganate. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). doi:10.1002/9780470842898.rp244.pub2. (f) VanRheenen V, Kelly RC, and Cha DY. An improved catalytic OsO_4 oxidation of olefins to cis-1,2-glycols using tertiary amine oxides as the oxidant. *Tetrahedron Lett*. **1976**, 17 (23), 1973–1976. (g) The Nobel Prize in Chemistry 2001. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/2001/summary/).

[94] (a) Reimer K, and Tiemann F. Ueber die Einwirkung von Chloroform auf alkalische Phenolate. *Ber. Dtsch. Chem. Ges*. **1876**, 9 (1), 824–828. (b) Vilsmeier A, and Haack A. Über die Einwirkung von Halogenphosphor auf Alkyl-formanilide. Eine neue Methode zur Darstellung sekundärer und tertiärer *p*-Alkylamino-benzaldehyde. *Ber. Dtsch. Chem. Ges*. A/B **1927**, 60 (1), 119–122.

[95] (a) Keith JA, Nielsen RJ, Oxgaard J, and Goddard WA. Unraveling the Wacker Oxidation Mechanisms. *J. Am. Chem. Soc*. **2007**, 129 (41), 12342–12343. (b) Keith JA, and Henry PM. The Mechanism of the Wacker Reaction: A Tale of Two Hydroxypalladations. *Angew. Chem. Int. Ed*. **2009**, 48 (48), 9038–9049. (c) Smidt J, Hafner W, Jira R, Sedlmeier J, Sieber R, Rüttinger R, and Kojer H. Katalytische Umsetzungen von Olefinen an Platinmetall-Verbindungen Das Consortium-Verfahren zur Herstellung von Acetaldehyd. *Angew. Chem*. **1959**, 71 (5), 176–182.

[96] (a) Wagner G. *J. Russ. Phys. Chem. Soc*. **1899**, 31, 690–693. Note, the original reference is published in Russian and it is difficult to locate. (b) Wagner G, and Brickner W. Ueber die Beziehung der Pinenhaloïdhydrate zu den Haloïdanhydriden des Borneols. *Ber. Dtsch. Chem. Ges*. **1899**, 32 (2), 2302–2325. (c) Meerwein H. Über den Reaktionsmechanismus der Umwandlung von Borneol in Camphen; [Dritte Mitteilung über Pinakolinumlagerungen.]. *Justus Liebigs Ann. Chem*. **1914**, 405 (2), 129–175.

[97] (a) Weinreb SM, Folmer JJ, Ward TR, and Georg GI. (2006). *N*,*O*-Dimethylhydroxylamine. In e-EROS Encyclopedia of Reagents for Organic Synthesis, (Ed.). https://onlinelibrary.wiley.com/doi/10.1002/047084289X.rd341.pub2 (accessed December 5, 2019). (b) Hisler K, Tripoli R, and Murphy JA. Reactions of Weinreb amides: formation of aldehydes by Wittig reactions. *Tetrahedron Lett*. **2006**, 47 (35), 6293–6295. (c) Nahm S, and Weinreb SM. N-methoxy-N-methylamides as effective acylating agents. *Tetrahedron Lett*. **1981**, 22 (39), 3815–3818.

[98] (a) Byrnea PA, and Gilheany DG. The modern interpretation of the Wittig reaction mechanism. *Chem. Soc. Rev*. **2013**, 42 (16), 6670–6696. (b) Schlosser M, and Christmann KF. Trans-Selective Olefin Syntheses. *Angew. Chem. Int. Ed. Engl*. **1966**, 5 (1), 126–126. (c) Wittig G, and Schöllkopf U. Über Triphenyl-phosphin-methylene als olefinbildende Reagenzien (I. Mitteil.). *Chem. Ber*. **1954**, 87 (9), 1318–1330. (d) Wittig G, and Haag W. Über Triphenyl-phosphinmethylene als olefinbildende Reagenzien (II. Mitteil.). *Chem. Ber*. **1955**, 88 (11), 1654–1666.

[99] (a) Wohl A. Bromierung ungesättigter Verbindungen mit *N*-Brom-acetamid, ein Beitrag zur Lehre vom Verlauf chemischer Vorgänge. *Ber. Dtsch. Chem. Ges*. A/B **1919**, 52 (1), 51–63. (b) Ziegler K, Späth A, Schaaf E, Schumann W, and Winkelmann E. Die Halogenierung ungesättigter Substanzen in der Allylstellung. *Justus Liebigs Ann. Chem*. **1942**, 551 (1), 80–119. (c) The Nobel Prize in Chemistry 1963. NobelPrize.org. Nobel Media AB 2019 (accessed December 5, 2019, at https://www.nobelprize.org/prizes/chemistry/1963/summary/).

[100] (a) Huang-Minlon. A Simple Modification of the Wolff-Kishner Reduction. *J. Am. Chem. Soc*. **1946**, 68 (12), 2487–2488. (b) Clemmensen E. Reduktion von Ketonen und Aldehyden zu den entsprechenden Kohlenwasserstoffen unter Anwendung von amalgamiertem Zink und Salzsäure. *Ber. Dtsch. Chem. Ges*. **1913**, 46 (2), 1837–1843. (c) Kishner N. *J. Russ. Phys. Chem. Soc*. **1911**, 43, 582–592. Note, the original reference is published in Russian and it is difficult to locate. (d) Wolff L. Chemischen Institut der Universität Jena: Methode zum Ersatz des Sauerstoffatoms der Ketone und Aldehyde durch Wasserstoff. [Erste Abhandlung.]. *Justus Liebigs Ann. Chem*. **1912**, 394 (1), 86–108.