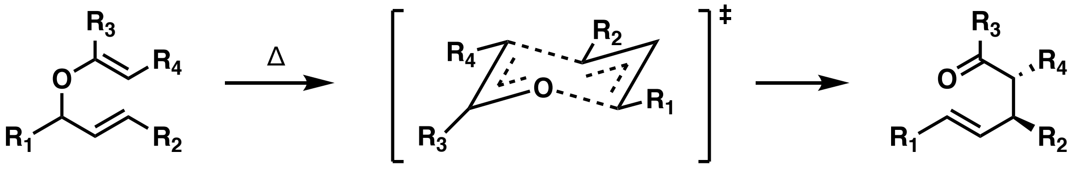
Claisen rearrangement



2021/ 11/ 13 (Sat)
Kazuki Takeda

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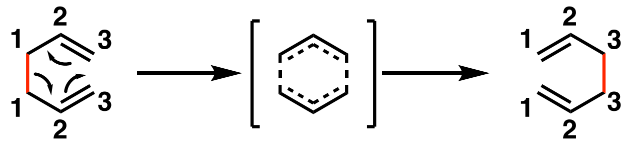
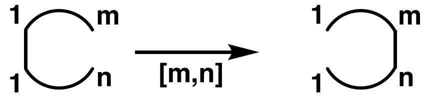
1. Introduction

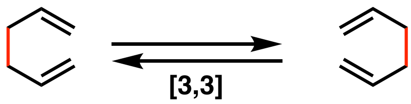
1-1. Sigmatropic rearrangement



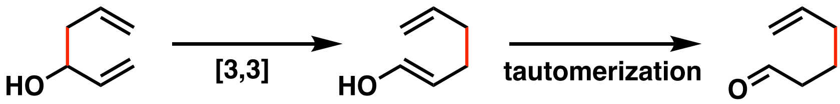


1-2. Examples of Sigmatropic rearrangement

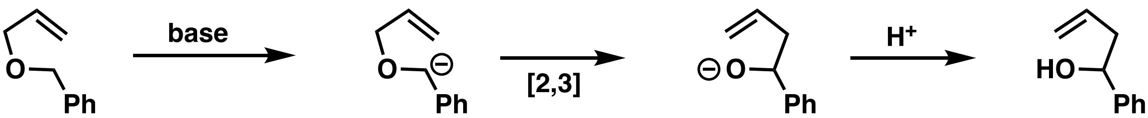
Cope rearrangement



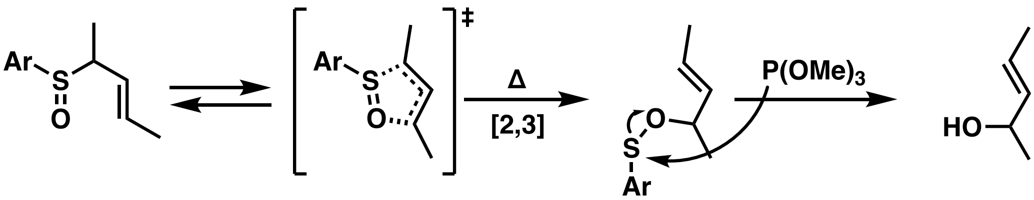
oxy-Cope rearrangement



[2,3]-Wittig rearrangement

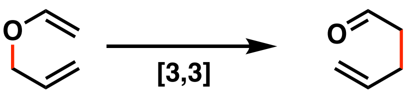


Mislow-Evans rearrangement

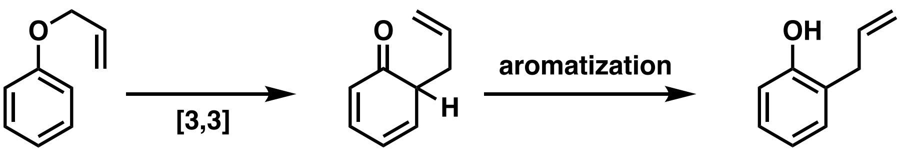


Claisen rearrangement

aliphatic Claisen rearrangement



aromatic Claisen rearrangement



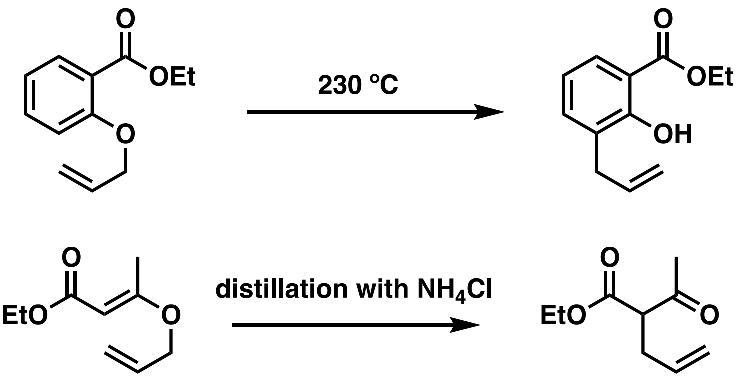
Review

a) Lutz. R. P. *Chem. Rev.* **1984**. *84*. 205. b) Castro. A. M. M. *Chem. Rev.* **2004**. *104*. 2939.
c) Manjumdar. K. C. *et. al. Tetrahedron.* **2007**. *64*. 597. d) Hiersemann. M. *et. al. Synthesis.* **2013**. *45*. 1121.
d) Comprehensive Organic Synthesis II, Volume 5. 912-977

2. Outline of Claisen rearrangement

2-1. About Claisen rearrangement

Original condition (1912, Claisen) [1]



Rainer Ludwig Claisen

"O-Allyl-acetessigester wird beim Destillieren über etwas Salmiak fast vollständig in C-Allyl-acetessigester verwandelt" [2]

Mechanistic study (1963, Bailey) [3]

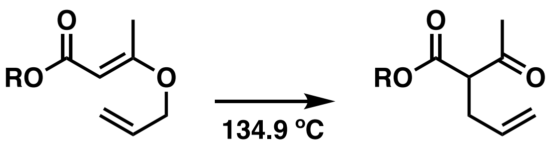


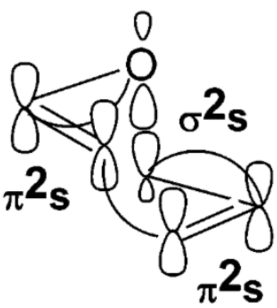
TABLE II
REARRANGEMENT OF ALLYL 3-ALLYLOXY-2-BUTENOATE CATALYZED BY AMMONIUM CHLORIDE (NO BUTYLATED HYDROXYTOLUENE) AT 134.9°

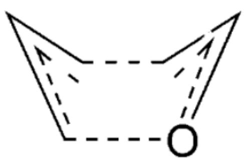
Heating time, min.	No NH_4Cl	% 1 remaining 18–35	35–60	60–80	80–100 mesh
30		41.8	41.4		38.6
45			30.1		28.9
60	38.0	33.7	33.0	33.0	30.3
90	29.3	21.6	21.5	19.7	18.8
120	18.0	12.4	12.6	11.4	11.2
150	15.6	8.2	7.3	7.2	7.5
180	14.6	7.6	7.2	6.7	6.5
210		7.6	7.7	8.0	8.1
240	12.8	6.2	6.2	6.4	6.3

⇨ **NH_4Cl act as heterogeneous Brønsted acid**

Proposed transition state [4]

17





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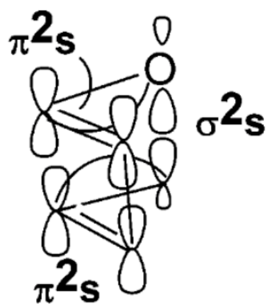


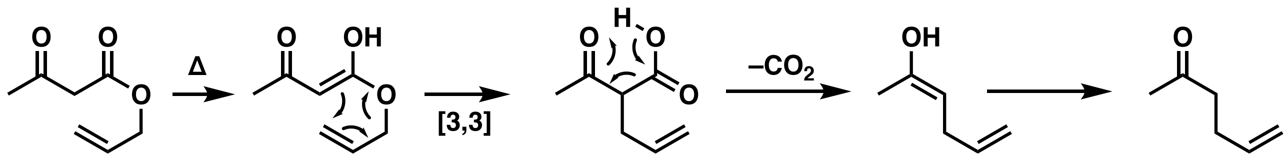
chairlike intermediates **boatlike intermediates**

1) Claisen, L. *et. al. Chem. Ber.* **1912**, *45*, 3157.
2) Lauer, W. *et. al. J. Am. Chem. Soc.* **1937**, *59*, 2586.
3) Bailey, G-F. *et. al. J. Org. Chem.* **1963,** *28,* 3521.
4) Roth, W. R. *et. al. Tetrahedron.* **1962,** *18,* 67.

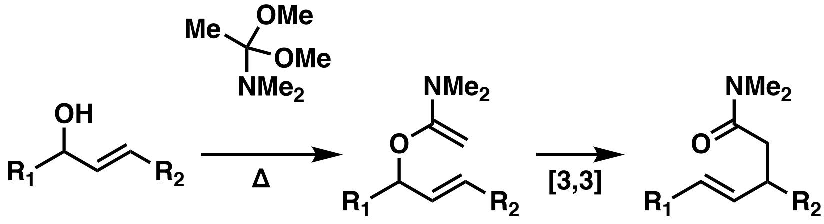
2. Outline of Claisen rearrangement

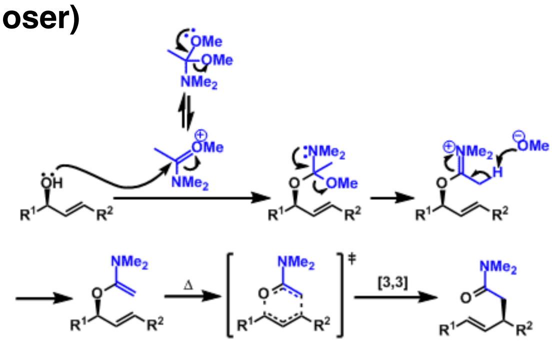
2-2. Related [3,3]-Sigmatropic rearrangement

Caroll rearrangement (1940, Caroll) [1]

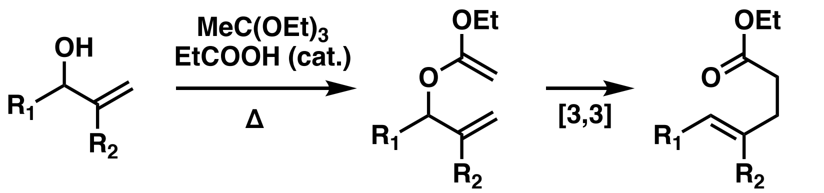


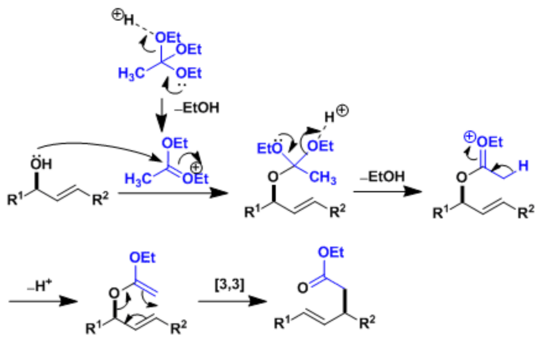
Eschenmoser Claisen rearrangement (1964, Eschenmoser)



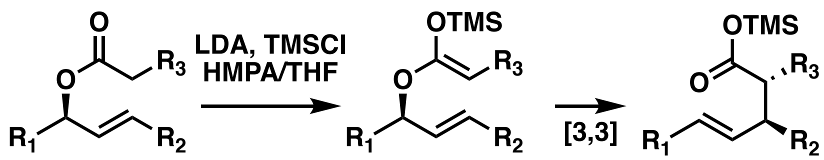


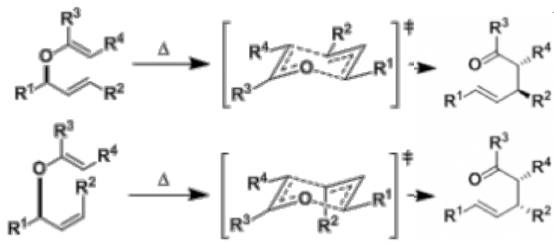
Johnson Claisen rearrangement (1970, Johnson) [2]



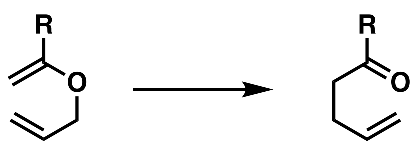


Ireland Claisen rearrangement (1972, Ireland) [3]





Other name reaction



R	variant	initial report
$C(sp^3)$	Claisen	1912
H	Hurd–Claisen	1938
OH	Carroll–Claisen	1940
OMetal	Arnold–Claisen	1949
NR_2	Meerwein–Eschenmoser–Claisen	1961
COAr	Barnes–Claisen	1963
OR	Johnson–Claisen	1970
$OSiR_3$	Ireland–Claisen	1972
CO_2R	Gosteli–Claisen	1972

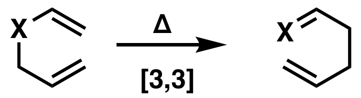
1) Carroll, M. F. *J. Chem. Soc.* **1940**, 704.
2) Johnson. W. S. *et. al.* *J. Am. Chem. Soc.* **1970**, *92*, 741.
3) Ireland. R. E. *et. al.* *J. Am. Chem. Soc.* **1972**, *94*, 5897.

2. Outline of Claisen rearrangement

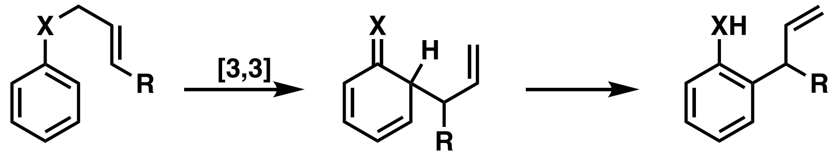
2-3. Related hetero [3,3]-Sigmatropic rearrangements

aza-Claisen rearrangement, thio-Claisen rearrangement

aliphatic

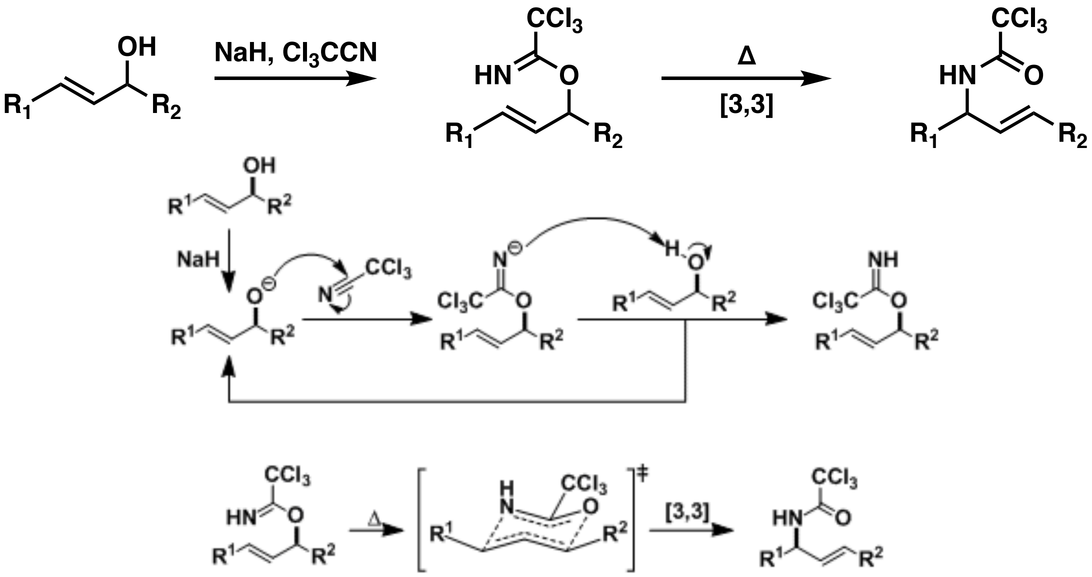


aromatic

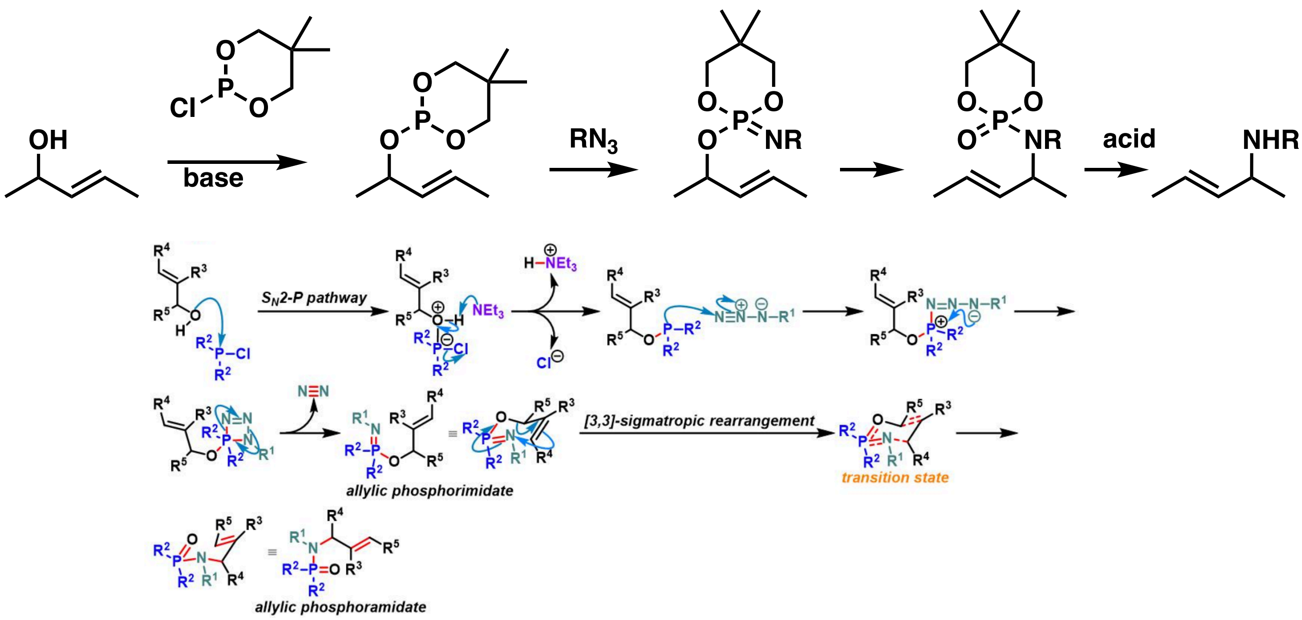


X = NH, S

Overman rearrangement (1974, Overman) [1]



Chen-Mapp rearrangement ([3,3]-Phosphorimidate Rearrangement) [2]



1) Overman. L. E. *et. al.* *J. Am. Chem. Soc.* **1974**, *96*, 597.
2) Chen, B.; Mapp, A. K. *J. Am. Chem. Soc.* **2005**, *127*, 6712.

3. Reactivity and Stereoselectivity of Claisen rearragement

3-1. Substituent effect [1]

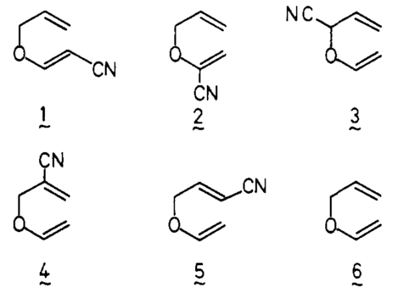
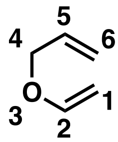


Table I. Kinetic Data for Compounds 1–6

compd	temp range, °C	ΔH‡, kcal/mol	ΔS‡, cal/(mol K)	k_{rel}, 100 °C
1	124–174	27.08 ± 0.09	−11.6 ± 0.2	0.90
2	66–115	22.84 ± 0.19	−13.4 ± 0.5	111
3	55–101	22.33 ± 0.20	−13.0 ± 0.6	270
4	90–140	22.58 ± 0.26	−18.0 ± 1.3	15.6
5	135–185	28.76 ± 0.54	−11.2 ± 1.2	0.11
6	113–173	25.40 ± 0.65	−15.9 ± 1.5	(1)



ELECTRON DONATING GROUP ACCELERATION

Position	Group
1	-O,-NH_2, -F, -CH_3
2	-$OSi(CH_3)_3$, -CH_3, -$CH^{-}SO_2Ph$, -F
4	-CH_3, -OCH_3
6	-CH_3, -OCH_3

ELECTRON DONATING GROUP DECELERATION

Position	Group
5	-CH_3, -OCH_3

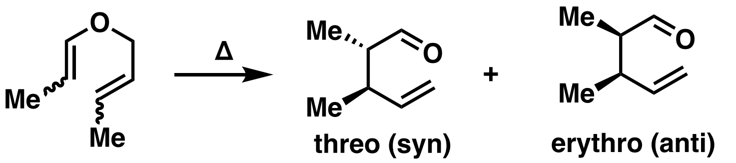
ELECTRON WITHDRAWING GROUP ACCELERATION

Position	Group
2	-CN, -CO_2^-, -CO_2CH_3, -CF_3
4	-CN, -CF_3
5	-CN

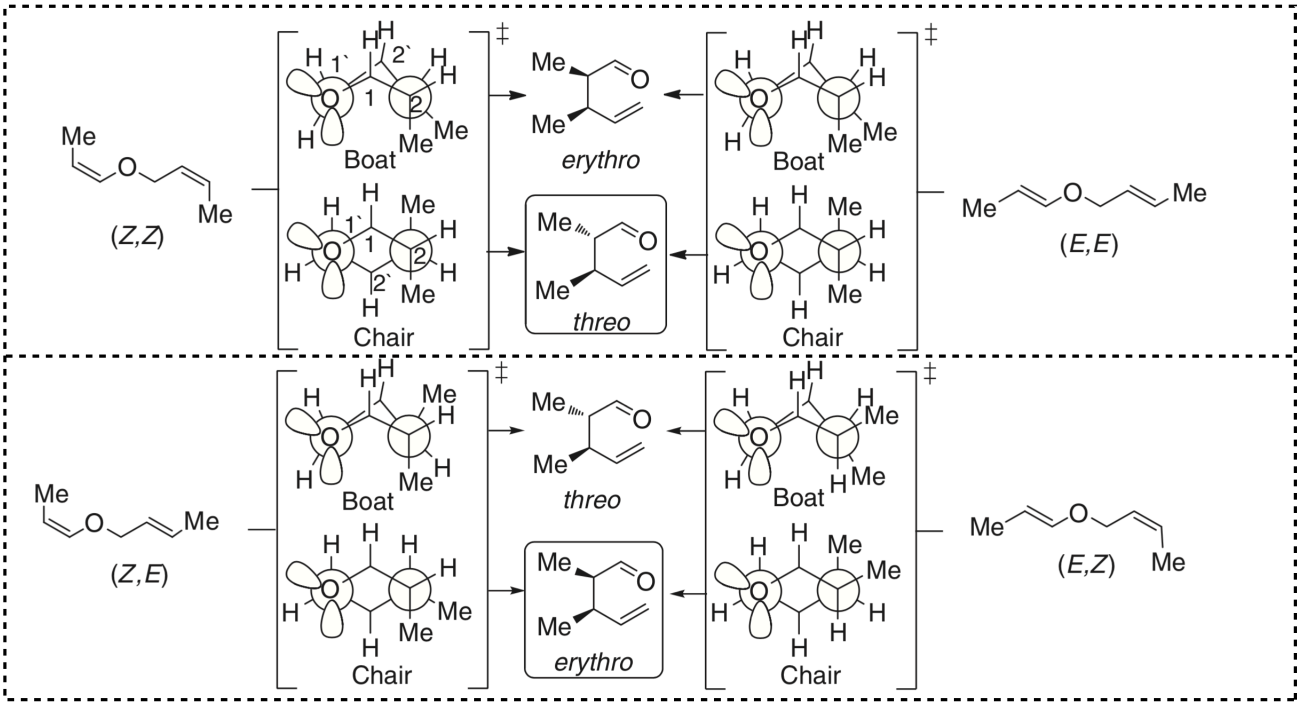
ELECTRON WITHDRAWING GROUP DECELERATION

Position	Group
1	-CN, -CO_2CF_3
6	-CN

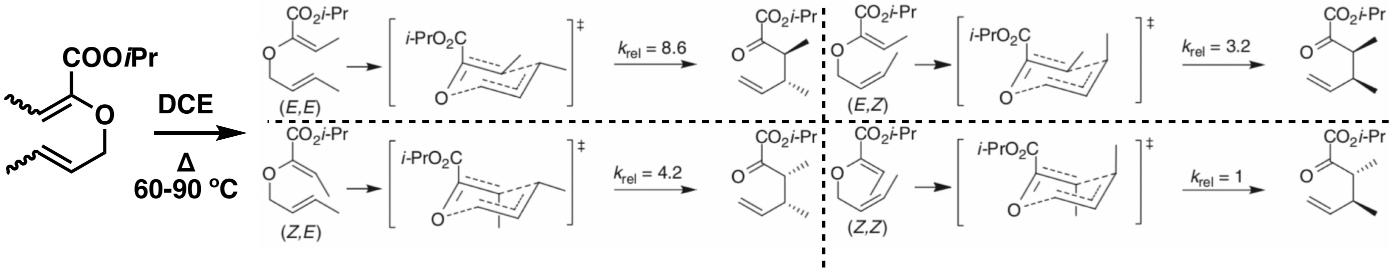
3-2. Doublebond geometry of Claisen rearrangement [2]



configuration	temp.	erythro	threo
(Z,Z)	160-190	5.3	94.7
(E,E)	142-160	4.1	95.9
(Z,E)	145-165	95.5	4.5
(E,Z)	145-170	95.4	4.6



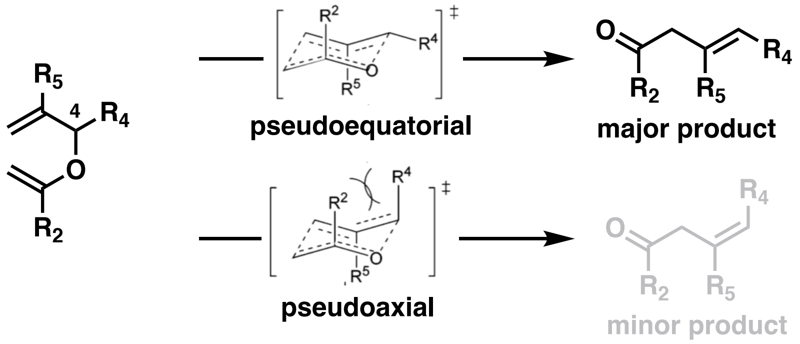
Kinetic study [3]



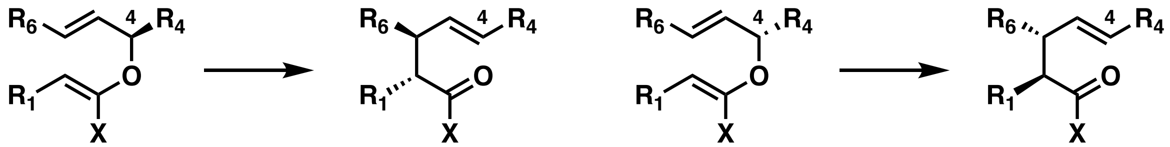
1) Carpenter. B-K. *et. al.* *J. Am. Chem. Soc.* **1981**, *103*, 6983.
2) Schmid. H-J. *et. al.* *Helv. Chim. Acta.* **1975**, *58*, 1293.
3) Hiersemann. M. *et. al.* *J. Org. Chem.* **2009**, *74*, 1531.

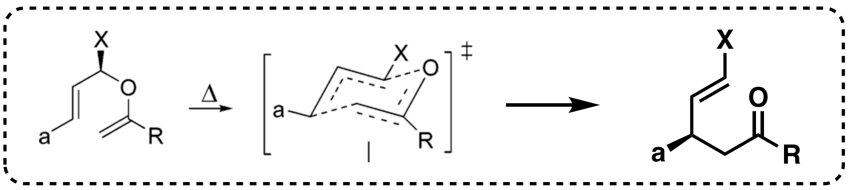
3. Stereoselectivity of Claisen rearragement

3-3. C4 substituent [1]

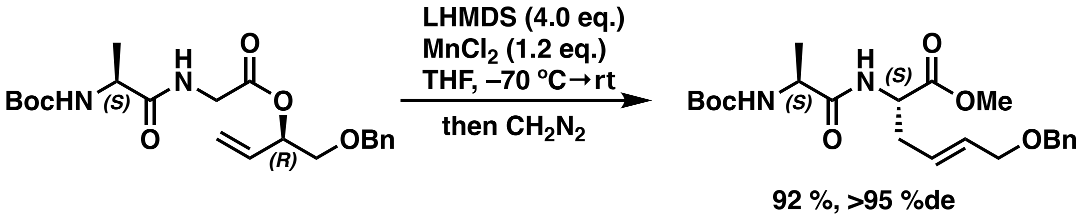


C4 Chiral substituent

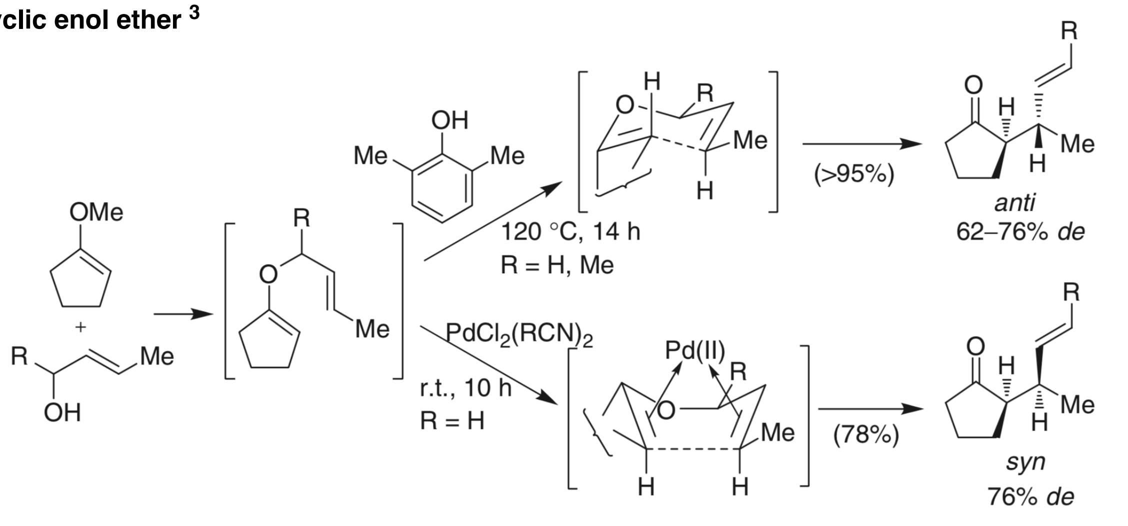




Example of chiral transfer [2]



Cyclic enol ether [3]



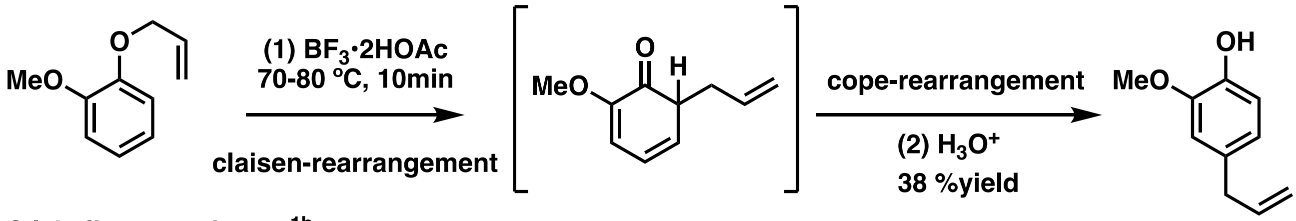
1) Taguchi. T. *et. al. Chem. Soc. Rev.* **1999**, *28*, 43.
2) Kazmaier. U. *et. al. Euro. J. Org. Chem.* **2000**, 1241.
3) Nakai. T. *et. al. Tetrahedron. Lett.* **1987**, 28, 5879.

4. Catalyst of Claisen rearrangement

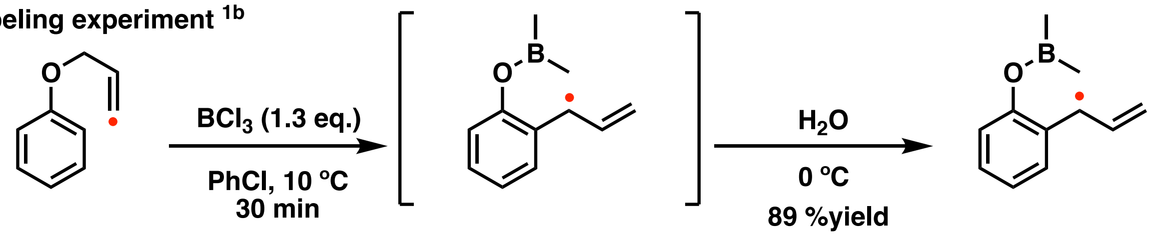
4-1 Lewis acid promoter

Boron derivative catalyst

First report of Lewis acid catalyst (1941, Bryusova) [1a]



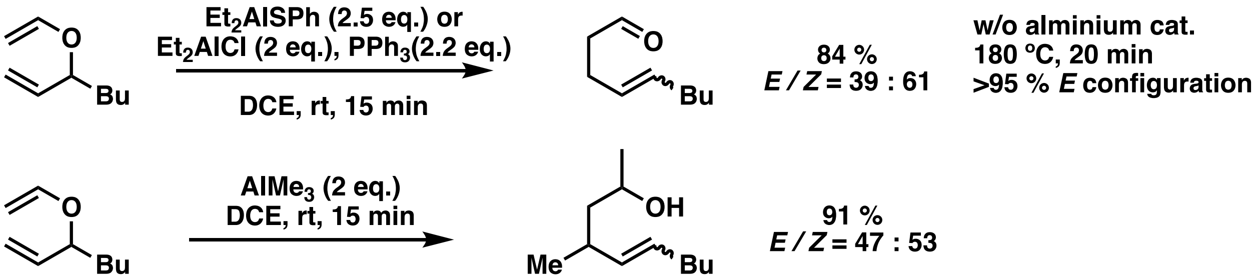
14C labeling experiment [1b]



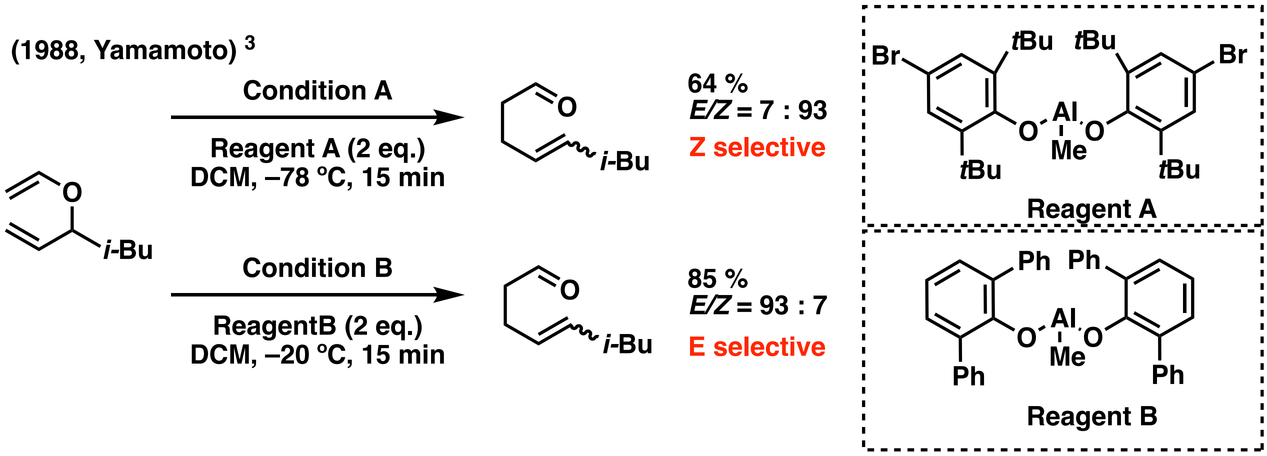
stoichiometric amounts of BCl_3 (1/3 eq.) resulted in incomplete reaction. ⇨ **intermediates of boron derivatives such as $(ArO)_2BCl$ are not effective for catalyst**

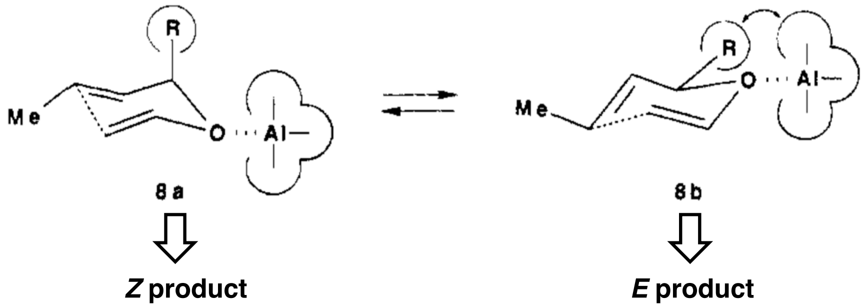
Aluminium derivative catalyst

(1981, Oshima) [2]



(1988, Yamamoto) [3]





1) a) Bryusova. L. Y. *et. al. Zh. Obshch. Khim.* 1941, *11*, 722. b) Barner. R. *Helv. Chim. Acta.* 1973, *56*, 14.
2) Oshima. K. *et. al. Tetrahedron. Lett.* **1981**, *22*, 3985. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 446.
3) Yamamoto. H. *et. al. J. Am. Chem. Soc.* **1988**, *110*, 7922.

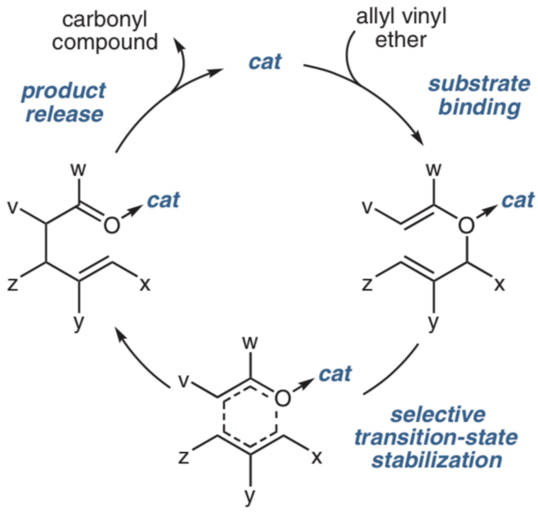
4. Catalyst of Claisen rearrangement

4-2 Lewis acid catalyst

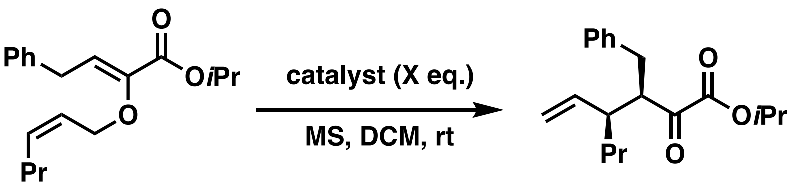
Problem of Alminium promoter
- **need stoichiometric amount of reagent**
- **lack of chemoselectivity (ion-pair formation)**

⇩

Catalyst requires
- **outbalances substrate with product**
- **selectively stabilize the transition state**
- **without inducing ionization**

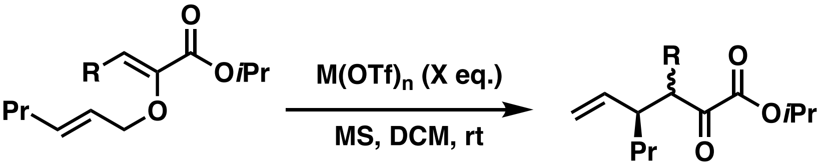


Lewis acid catalyst [1]

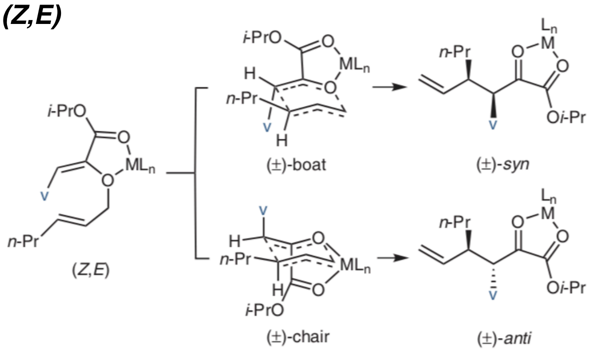


(Z,Z)/(E,Z) = 97 : 3 *syn / anti* = 95 : 5

cat	equiv	*t* (h)	yield (%)
$Sc(OTf)_3$	0.05	0.5	98
$Cu(OTf)_2$	0.1	1	99
$Lu(OTf)_3$	0.1	3	98
$LuCl_3•6H_2O$	0.1	18	98
$YbCl_3•6H_2O$	0.1	18	97

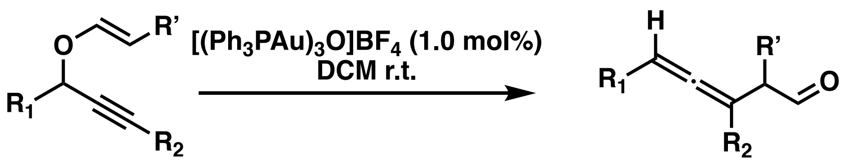


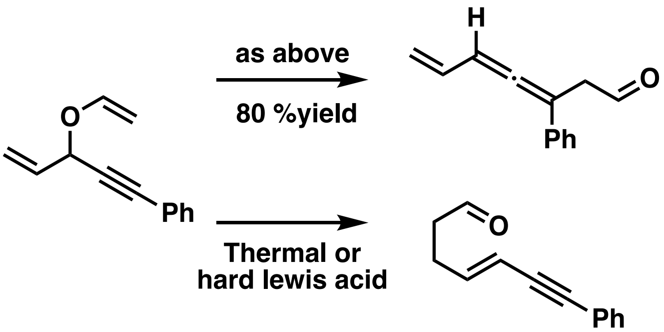
(Z,E)

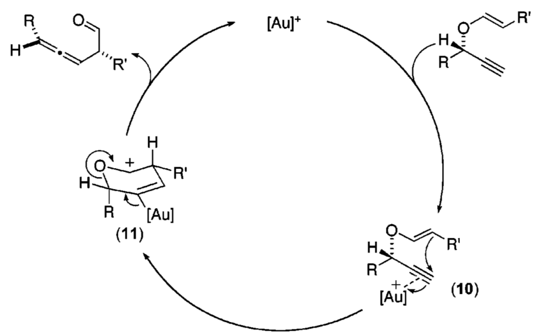


$M(OTf)_n$	equiv	*t* (h)	yield (%)	*syn*/*anti*
R = isopropyl				
$Sc(OTf)_3$	0.025	0.5	98	76:24
$Cu(OTf)_2$	0.025	0.5	98	75:25
$Lu(OTf)_3$	0.1	2	99	74:26
R = isopropenyl				
$Sc(OTf)_3$	0.025	0.5	98	42:58
$Cu(OTf)_2$	0.025	0.5	99	31:69
$Lu(OTf)_3$	0.1	1	95	36:64
R = benzyl				
$Sc(OTf)_3$	0.025	0.5	98	46:54
$Cu(OTf)_2$	0.025	0.5	99	33:67
$Lu(OTf)_3$	0.1	1	99	37:63

Gold catalyst [2]





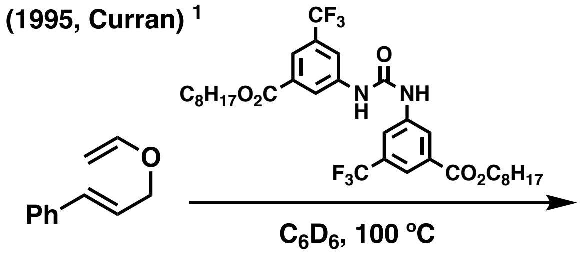


1) Hiersemann. M. *et. al.* *Org. Lett.* **2001**, *3*, 49. *Eur. J. Org. Chem.* **2002**, 1461.
2) Toste. D. *et. al.* *J. Am. Chem. Soc.* **2004**, *126*, 15978.

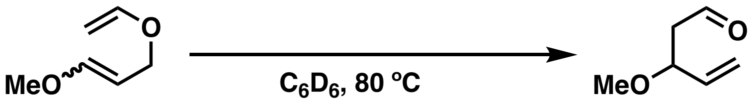
4. Catalyst of Claisen rearrangement

4-3. Organo catalyst

(1995, Curran) [1]



T (°C)	equiv 1a	k (x 10^{-5} s^{-1})	k_{rel}
100	none	0.4	1
100	0.2	0.7	1.7
100	0.5	1.3	3.1
100	1.0	1.8	4.2



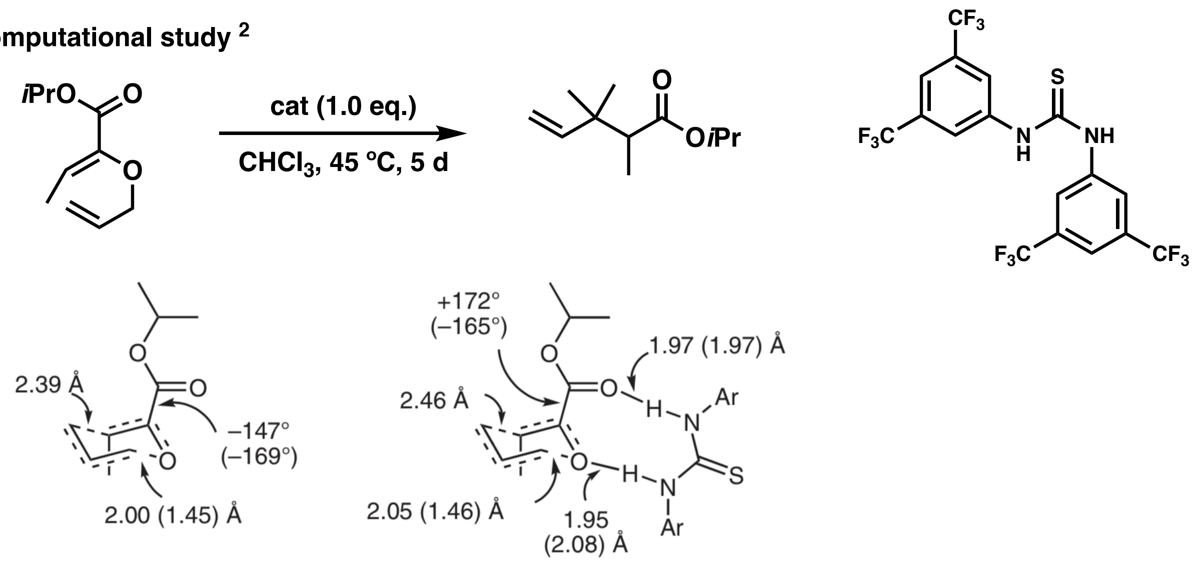
***E/Z* = 73 : 28**

$k_{uncat} = 0.6 \times 10^{-5}\ s^{-1}$

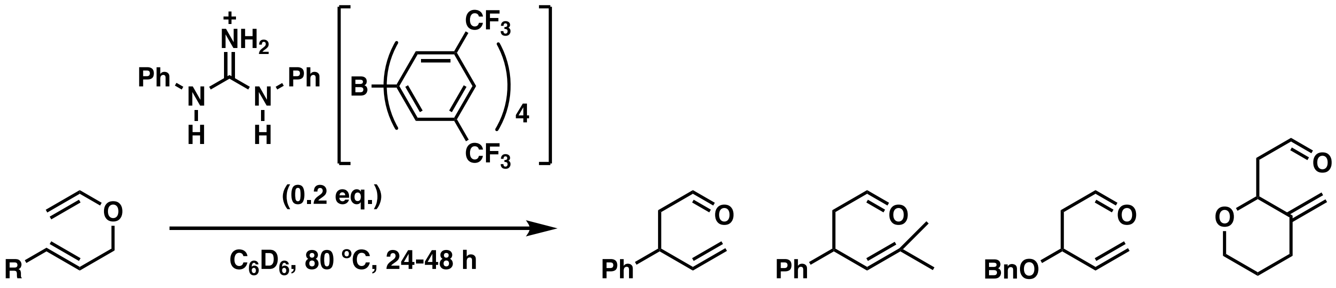
$k_{urea} = 13.7 \times 10^{-5}\ s^{-1}$

×22

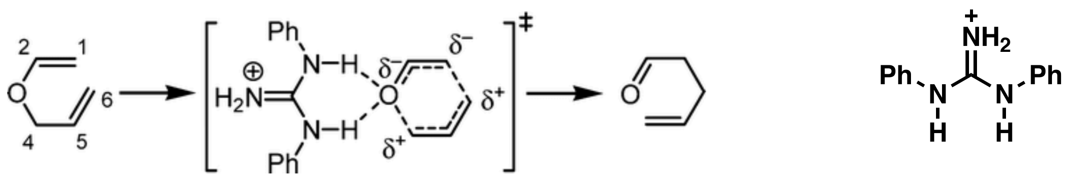
Computational study [2]



(2008, Jacobsen) [3]



	Ph (allyl aldehyde)	Ph (prenyl)	BnO	tetrahydropyran
w cat	15 %	82 %	75 %	72 %
w/o cat	9 %	28 %	0 %	0 %

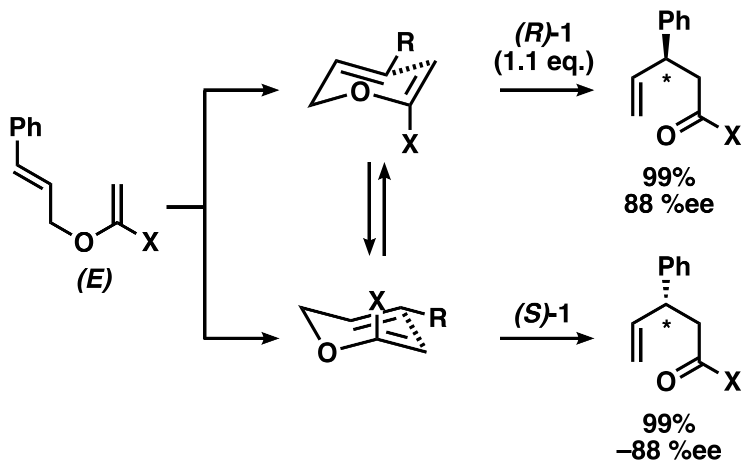


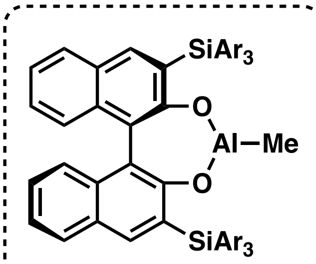
1) Curran. D. P. *et. al.* *Tetrahedron. Lett.* **1995**, *36*, 6647.
2) Strassner. T. *et. al.* *J. Org. Chem.* **2007**, *72*, 4001.
3) Jacobsen. E. N. *et. al.* *J. Am. Chem. Soc.* **2008**, *130*, 9228.

4. Catalyst of Claisen rearrangement

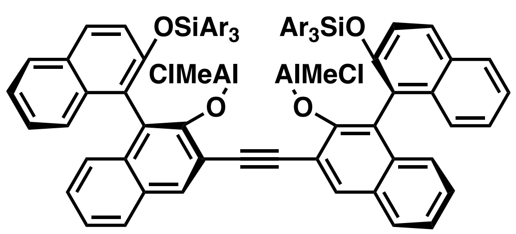
4-4. Enantioselective reaction

First chiral report (1990, Yamamoto) [1a]

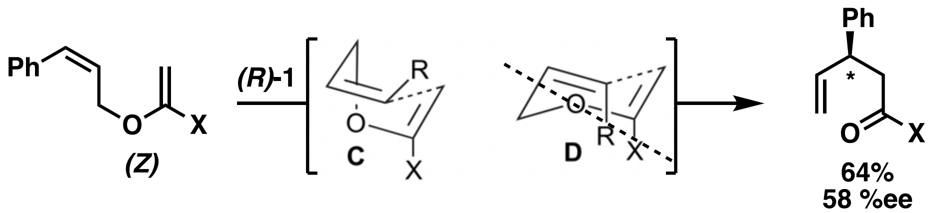




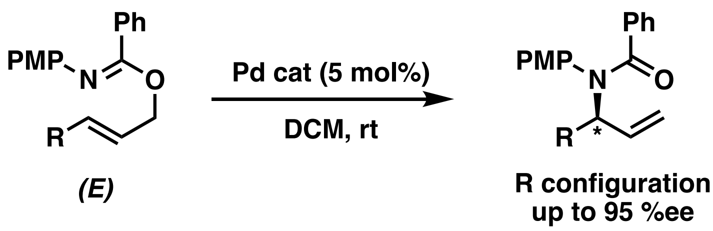
(R)-1 (1990, Yamamoto)

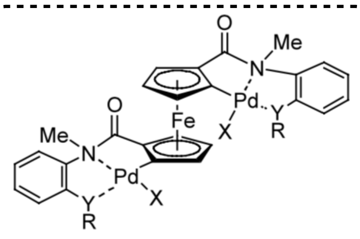


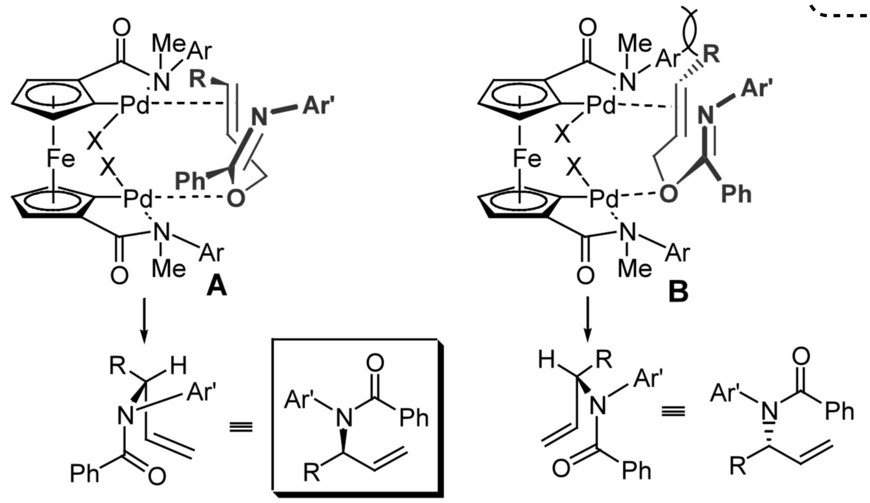
2002, Maruoka [1b]



Pd cat (2002, Kang) [2]



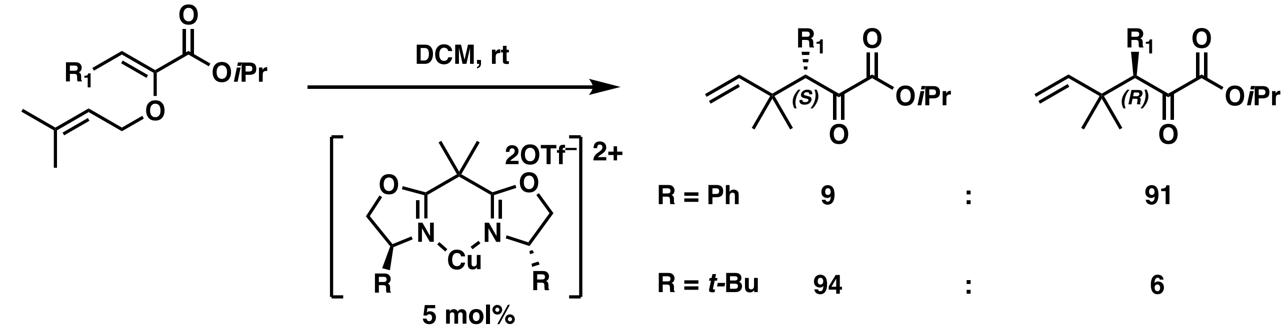


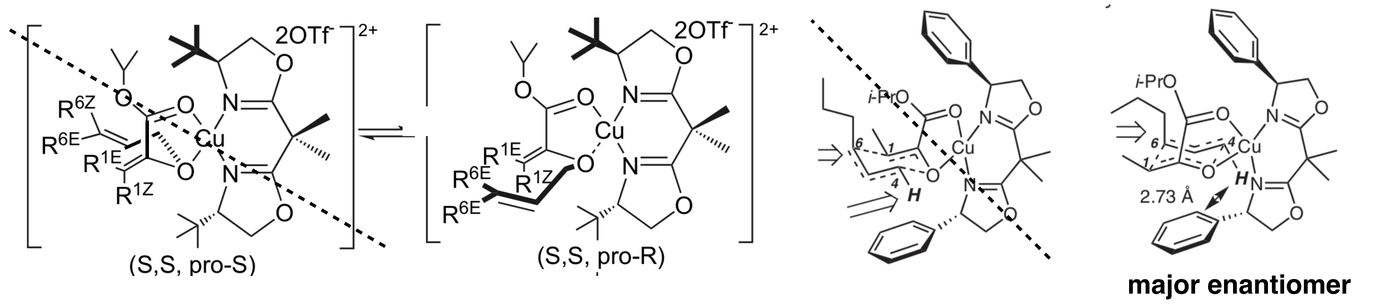


1) a) Yamamoto. H. *et. al. J. Am. Chem. Soc.* **1990**, *112*, 7791. b) Maruoka. K. *et. al. Tetrahedron.* **2002**, *41*, 8307.
2) Kang. J. *et. al. Tetrahedron. Lett.* **2002**, *43*, 9509.

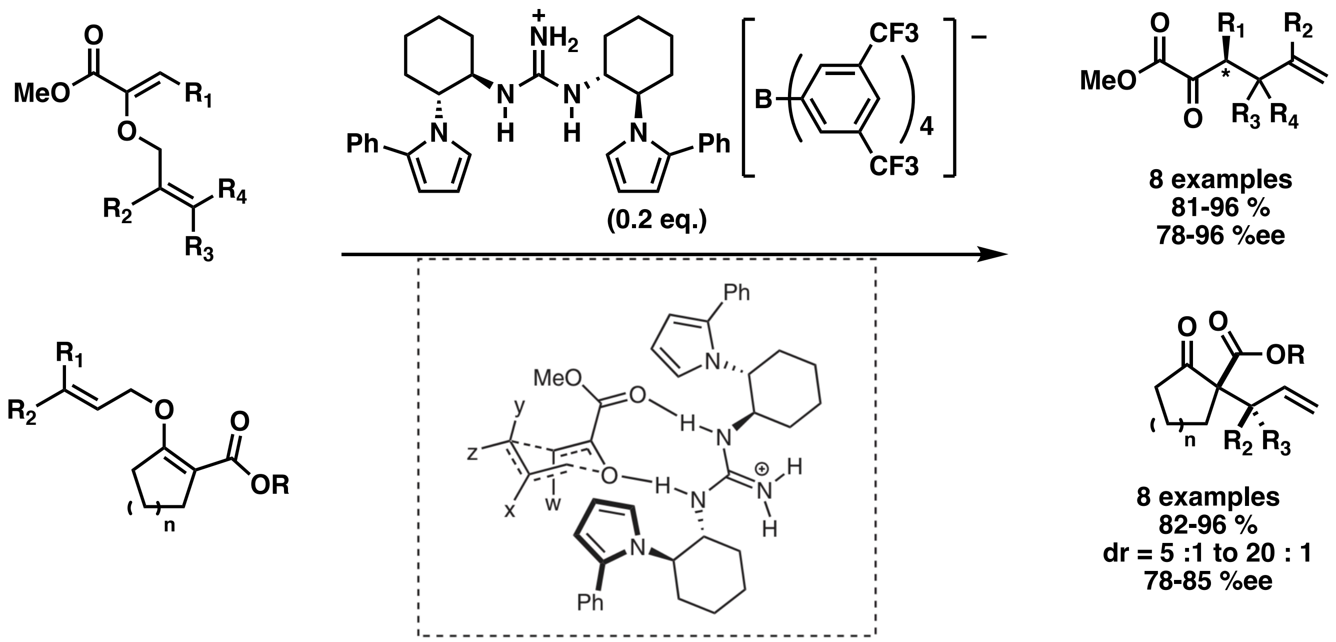
4. Catalyst of Claisen rearrangement

Chiral Copper catalyst (2001, Hiersemann) [1]

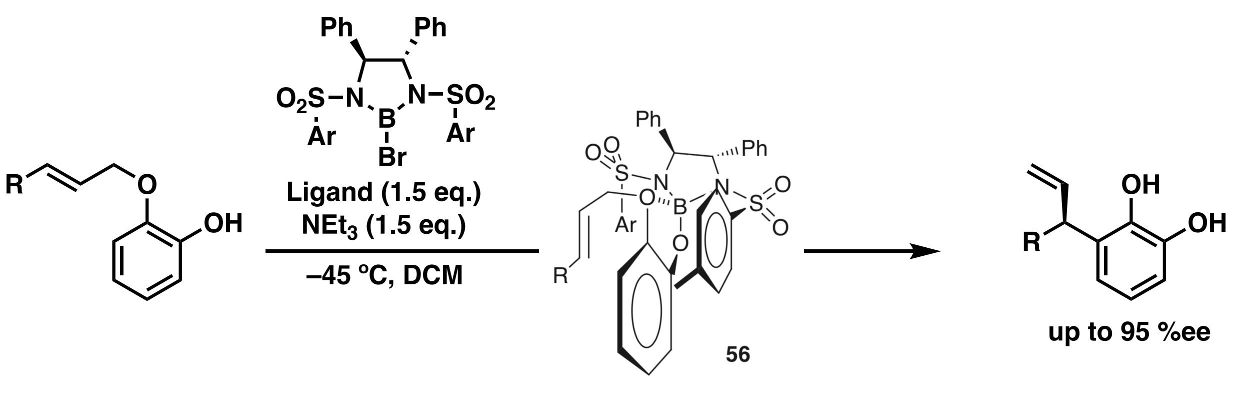




Chiral organo catalyst (2008, Jacobsen) [2]



Enatioselective aromatic Claisen rearrangement (1997, Taguchi) [3]



1) Hiersemann. M. *et. al.* *Angew. Chem. Int. Ed.* **2001**, *40*, 4700.
2) Jacobsen. E-N. *et. al.* *J. Am. Chem. Soc.* **2008**, *130*, 9228. *Angew. Chem. Int. Ed.* **2010**, *49*, 9753.
3) Taguchi. T. *et. al.* *Tetrahedron. Lett.* **1997**, *38*, 4815.