聲明

本檔案之內容僅供下載人自學或推廣化學教育之非營利目的使用。並請於使用時註明出處。[如本頁取材自○○○教授演講內容]。

Recent Advances in Green Catalysis

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2010.05.07

主辦單位
中國化學會環境與化學委員會
國科會化學研究推動中心

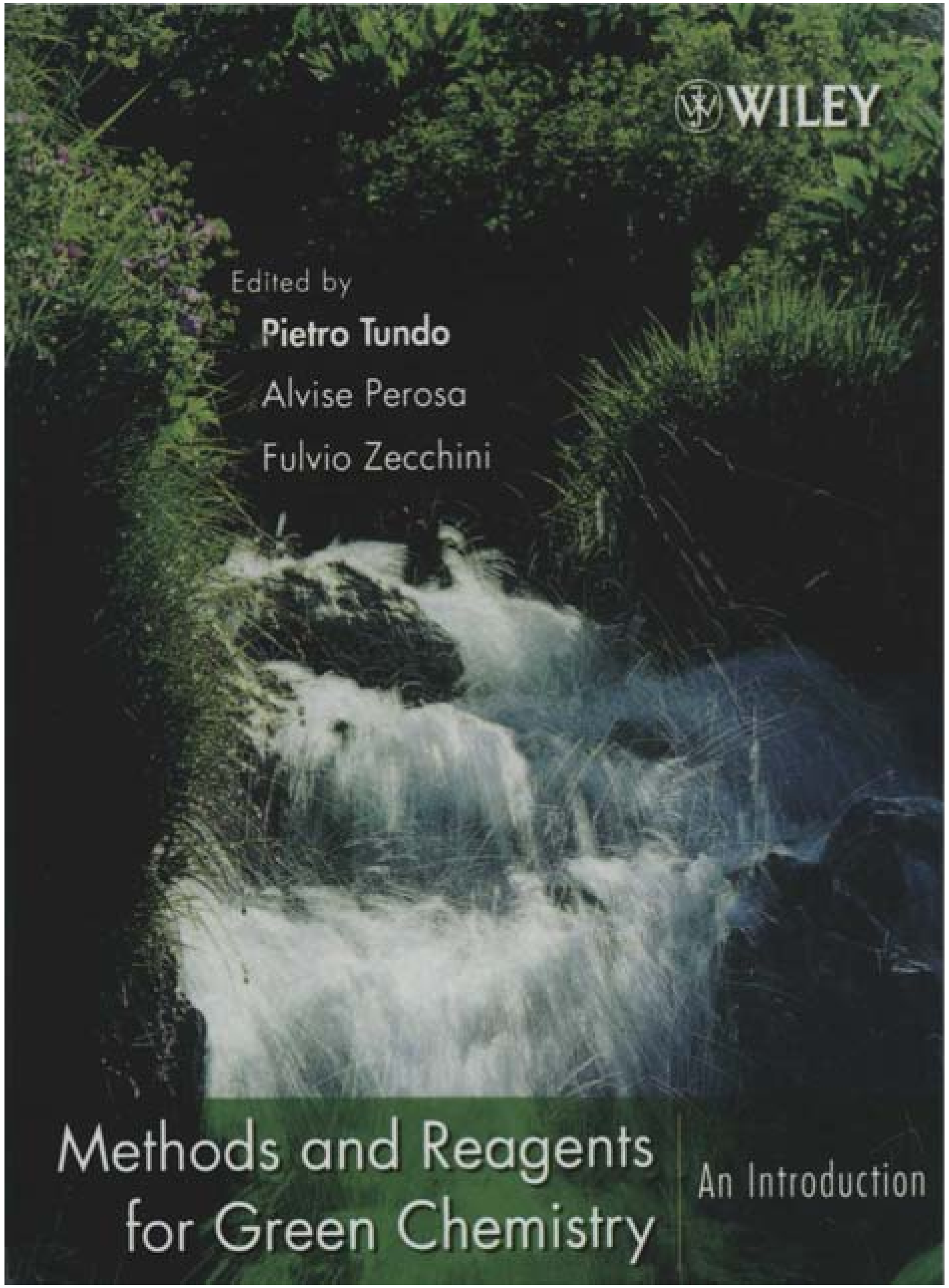
第七次全國科學技術會議

討論議題一：發展特色研究領域

(一) 強化海洋科技研究
(二) 發展綠色科技研究
(三) 強化跨領域尖端研究能力

Green Chemistry

Technologies that efficiently utilize energy and raw materials and reduce, or preferably, eliminate, the generation of waste and avoid the use of toxic and /or hazardous reagents, and solvents.



Condensed Principles of Green Chemistry

Twelve principles of green chemistry written in the form of a mnemonic: PRODUCTIVELY

P – Prevent wastes
R – Renewable materials
O – Omit derivatization steps
D – Degradable chemical products
U – Use safe synthetic methods
C – Catalytic reagents
T – Temperature, Pressure ambient
I – In–Process Monitoring
V – Very few auxiliary substances
E – E-factor, maximize feed in product
L – Low toxicity of chemical products
Y – Yes, it is safe

S. L. Y. Tang, R. L. Smith, M. Poliakoff, *Green Chem.,* 2005, *7*, 761-762

Atom Economy (Atom Efficiency)

% Atom Economy =

$$\left(\frac{\text{molecular weight of desired product}}{\text{molecular weight of all reactants}} \right) \text{ x } 100$$

The E - Factor

A useful measures of the potential environmental impact of chemical processes is the *E*-factor.

E = (Raw materials - Product) / Product

Where do all the wastes originate?

1. **Stoichiometric Brønsted acids and bases:**
   - *Aromatic Nitrations with H_2SO_4 / HNO_3*
   - *Acid promoted rearrangements, e.g. Beckmann (H_2SO_4)*
   - *Base promoted condensations, e.g. Aldol (NaOH, NaOMe)*
2. **Stoichiometric Lewis acids:**
   - *Friedel-Crafts acylation ($AlCl_3$, $ZnCl_2$, BF_3)*
3. **Stoichiometric oxidants and reductants:**
   - *$Na_2Cr_2O_7$, $KMnO_4$, MnO_2*
   - *$LiAlH_4$, $NaBH_4$, Zn, Fe/HCl*
4. **Halogenation and Halogen replacement:**
   - *Nucleophilic substitutions*
5. **Solvent losses:**
   - *Air emissions and aqueous effluent*

Water as a Solvent

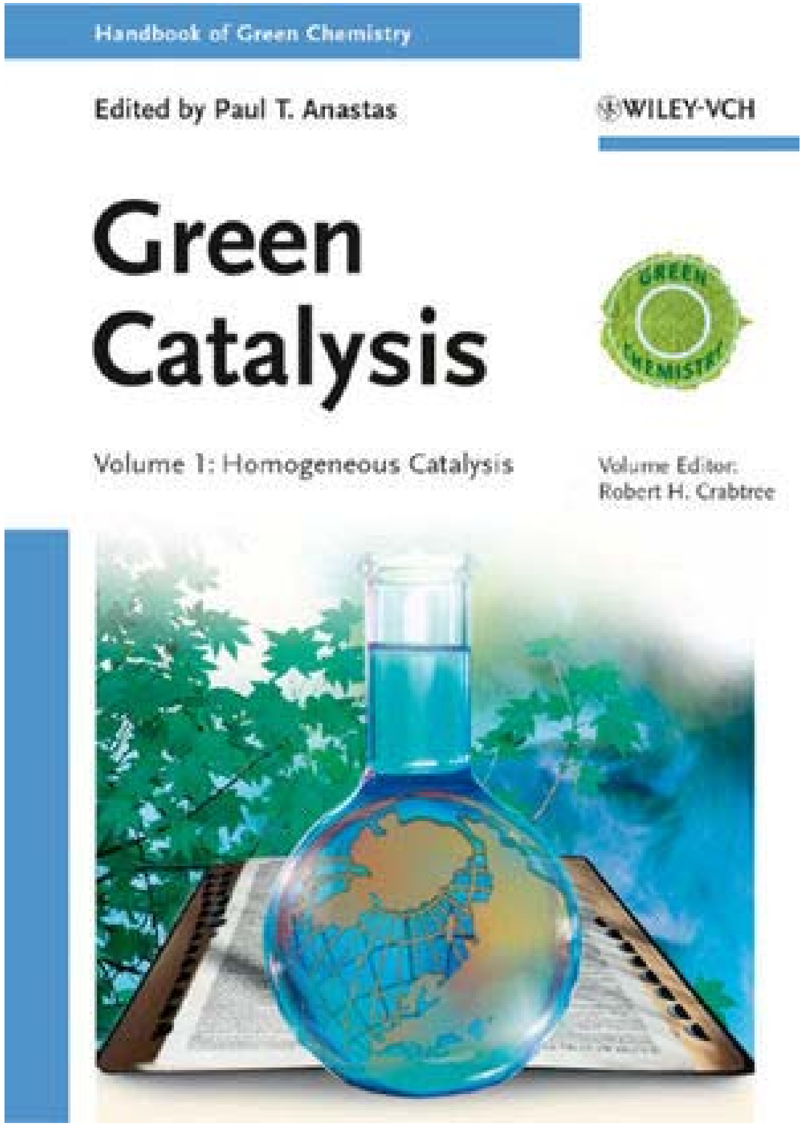
Advantages

- **Economically & Environmentally attractive**
- **Inexpensive and abundantly available**
- **Non-inflammable and non-toxic**
- **Odorless & colorless**
- **Highly polar reaction medium**
- **Novel reactivity of organometallic complexes**
- **Facile product separation/catalyst recycling**
- **Reduced product contamination**

I. T. Horvath, *Green Chem.*, 2008, *10*, 1024-1028.

Catalysis

Brønsted Acid-Base Catalysis
Lewis Acid-Base Catalysis
Transition-metal catalysis
Organocatalysis
Photocatalysis
Asymmetric Catalysis
Biocatalysis



Handbook of Green Chemistry

Edited by Paul T. Anastas

WILEY-VCH

Green
Catalysis

Volume 1: Homogeneous Catalysis

Volume Editor:
Robert H. Crabtree

Catalysis in Organic Reactions

- It can provide a new reaction route.
- It can increase the stability of a transition state.
- It can increase the reactivity of a nucleophile.
- It can increase the susceptibility of an electrophile to nucleophilic attack.
- It can increase the leaving ability of a group by converting it into a weaker base.

Homogeneous vs. Heterogeneous Catalysis

	Homogeneous	Heterogeneous
Advantages	- Mild reaction conditions - High reactivity and selectivity - Efficient heat transfer	- Facile separation of catalyst and products - Continuous processing
Disadvantages	- Cumbersome separation and recycling of catalyst - Product contamination	- Heat transfer problems - Low reactivity and selectivity

The Role of Green Catalysis

The increasing use of catalytic processes can substantially reduce waste at the source, resulting in primary pollution prevention.

Stoichiometric vs. Catalytic Oxidation

Stoichiometric: (The Jones oxidation)

$$3\ PhCH(OH)CH_3 + 2\ CrO_3 + 3\ H_2SO_4 \longrightarrow 3\ PhCOCH_3 + Cr_2(SO_4)_3 + 6\ H_2O$$

Atom efficiency = 120 x 3/122 x 3 + 100 x 2 + 98 x 3 = 360 / 860 = 42 %

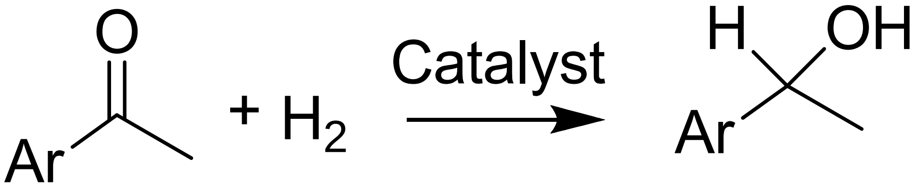
Catalytic:

$$PhCH(OH)CH_3 + 1/2\ O_2 \longrightarrow PhCOCH_3 + H_2O$$

Atom efficiency = 120 / 122 + 16 = 120 / 138 = 87%

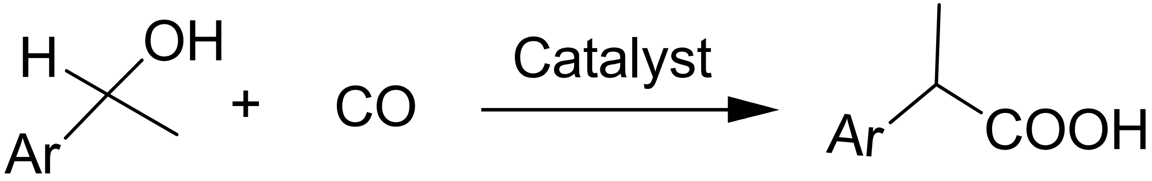
Atom-efficient Catalytic Processes

Hydrogenation:



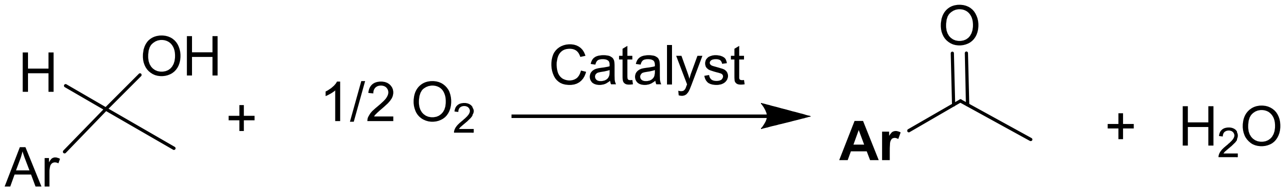
100 % atom efficient

Carbonylation:



100 % atom efficient

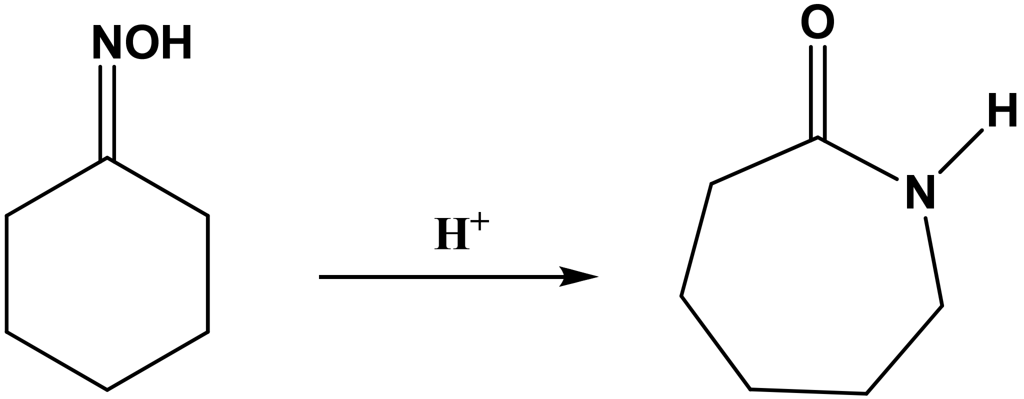
Oxidation:



87 % atom efficient

Ar = Phenyl

Caprolactam Formation



Brønsted Acid Catalysis

Lewis Acid Catalysis

Initial coordination of a Lewis acid occurs to the basic site of the substrate.

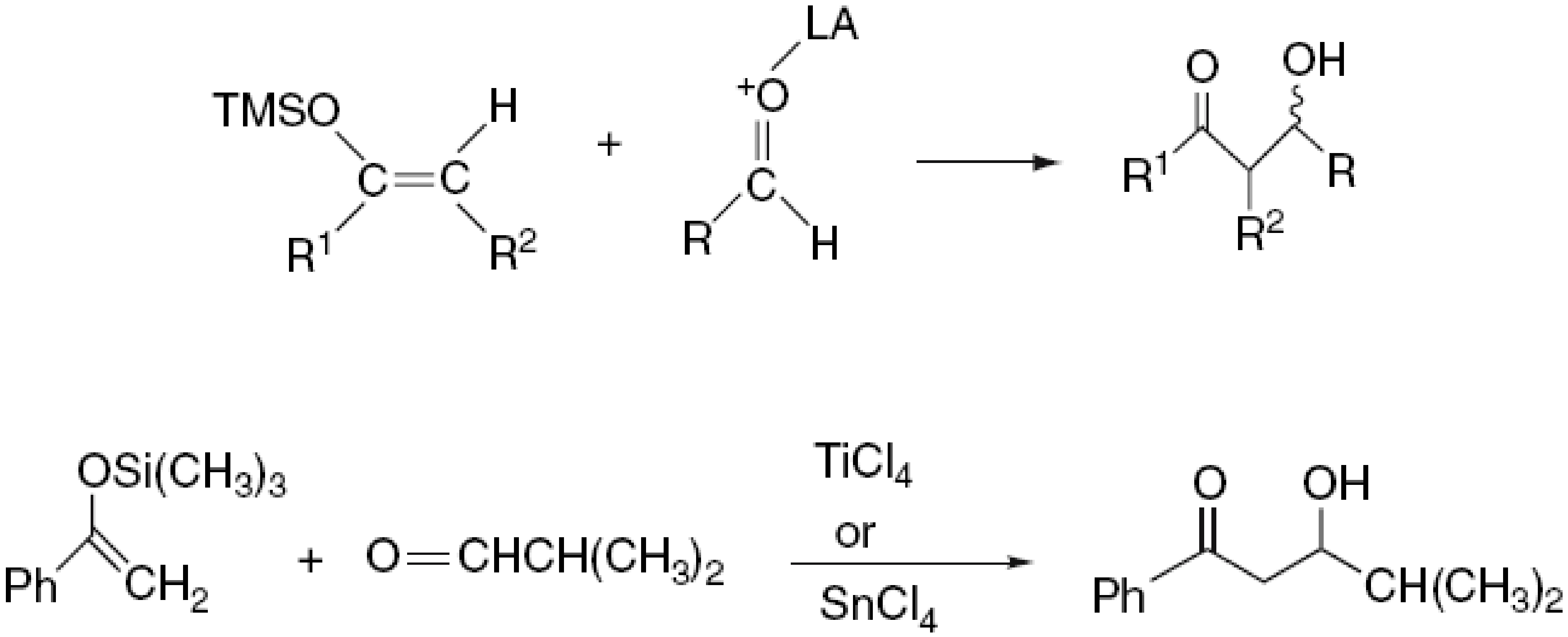
The Lewis acid plays the key role to determine the overall reaction path by controlling the generation and trapping of the cationic species.

The Lewis acid decides also the nature of the cationic species generated, an ion pair or a loosely bound covalent species or somewhere in-between.

Lewis acid-base catalysis reactions are becoming of increasing importance in current organic synthesis

http://www.organic-chemistry.org/topics/lewis acid-base catalysis.shtm

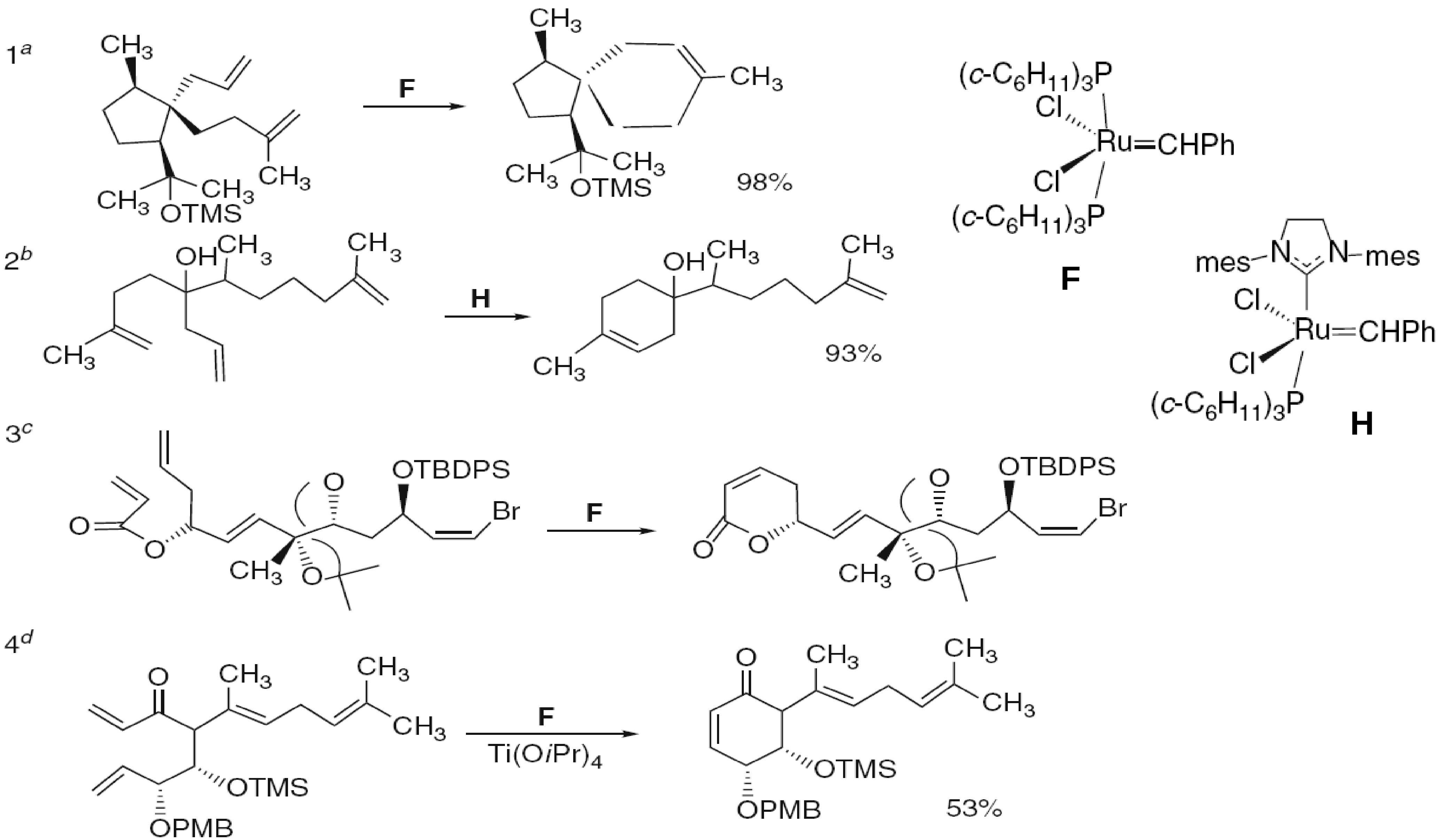
The Mukaiyama Aldol Reaction



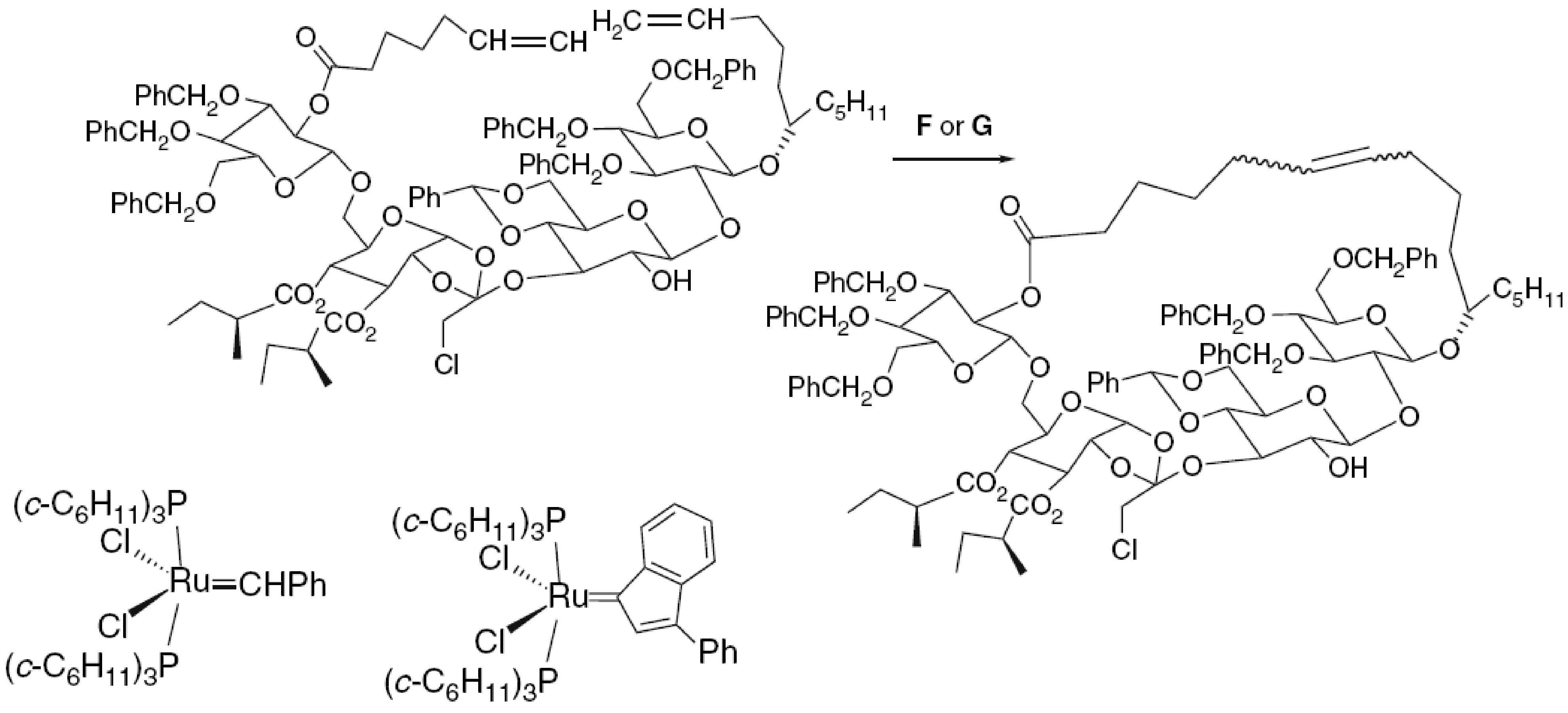
Metathesis

- **Yves Chauvin, Richard Schrock, and Robert Grubbs**
- more efficient (fewer reaction steps, fewer resources required, less wastage),
- simpler to use (stable in air, at normal temperatures and pressures) and
- environmentally friendlier (non-injurious solvents, less hazardous waste products).
- This represents a great step forward for "green chemistry", reducing potentially hazardous waste through smarter production. Metathesis is an example of how important basic science has been applied for the benefit of man, society and the environment.

The Olefin Metathesis Reaction



The Olefin Metathesis Reaction

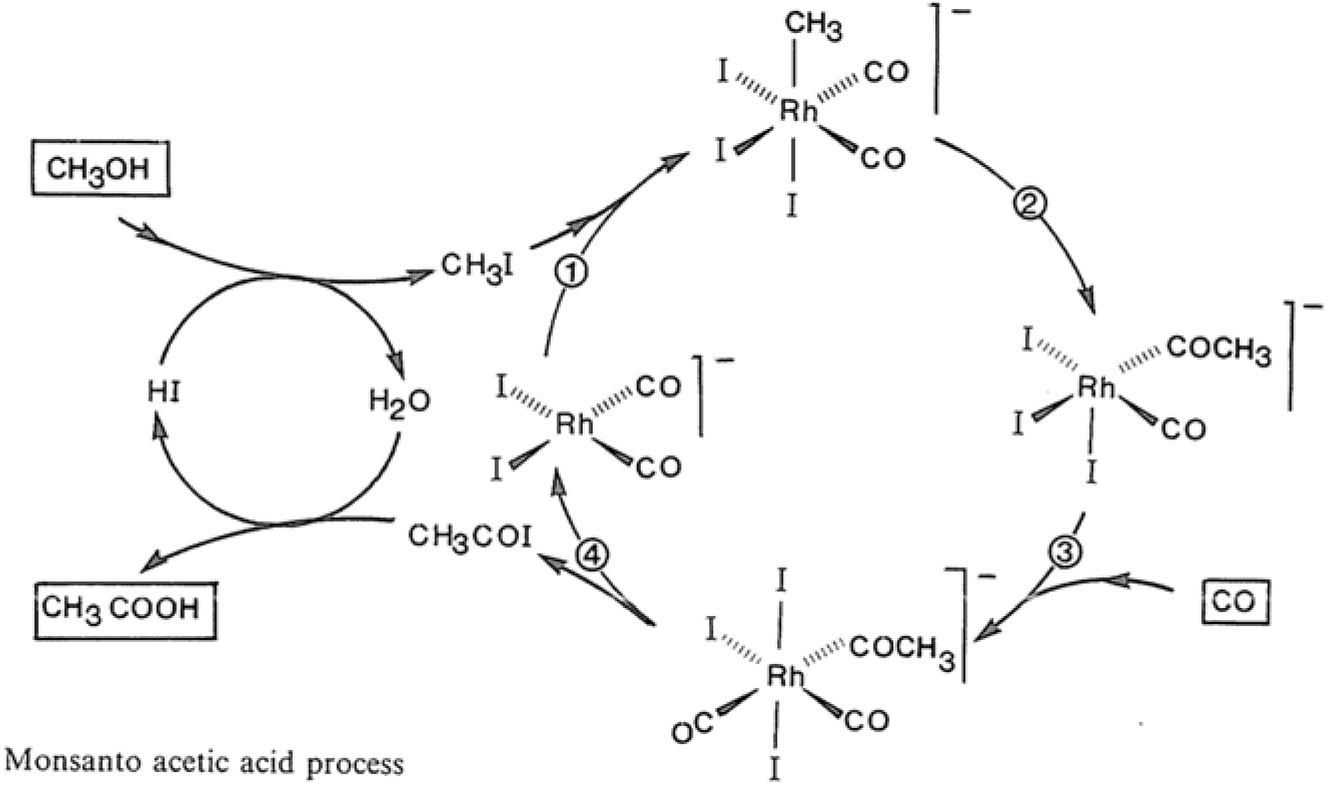


F

G

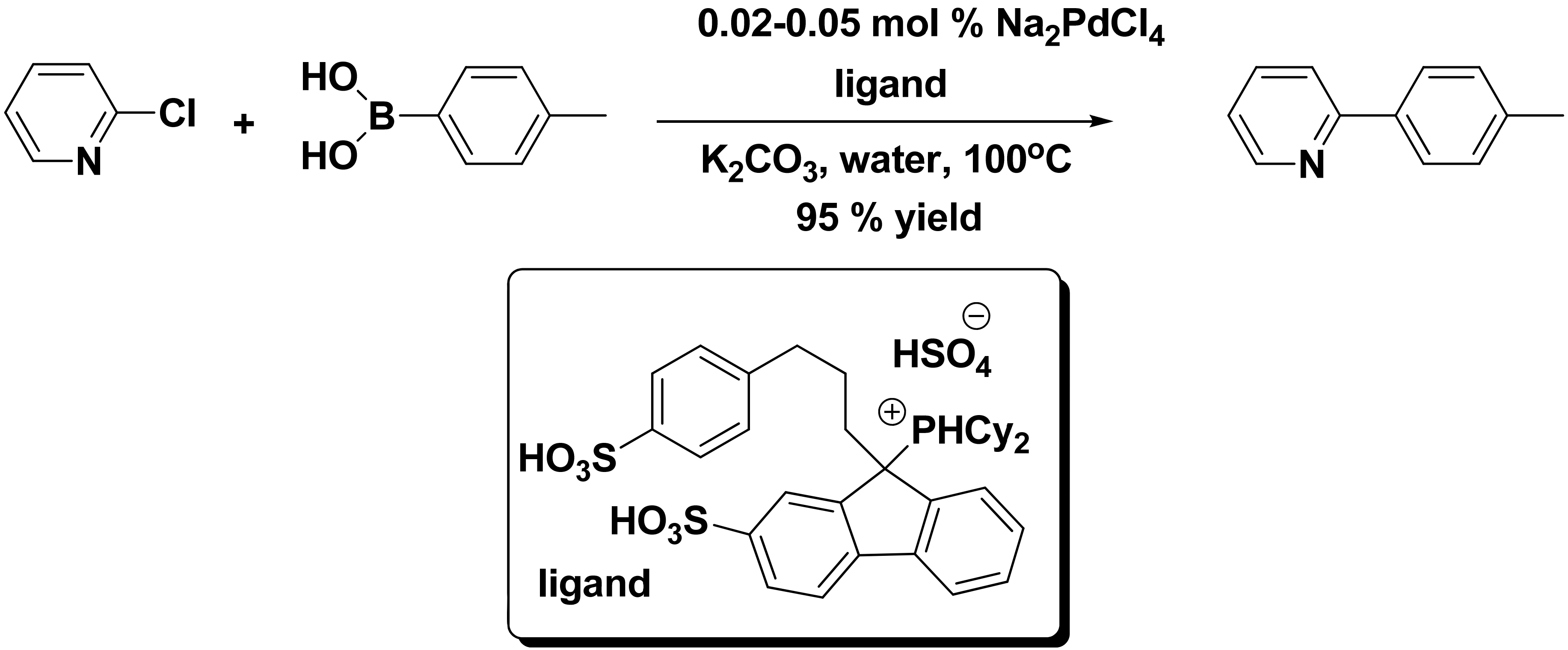
Monsanto Acetic Acid Process

$CH_3OH + CO \rightarrow CH_3COOH$ $\Delta H^o = -136.6$ kJ/mol



Monsanto acetic acid process

Suzuki-Miyaura Coupling in Water



0.02-0.05 mol % Na_2PdCl_4

ligand

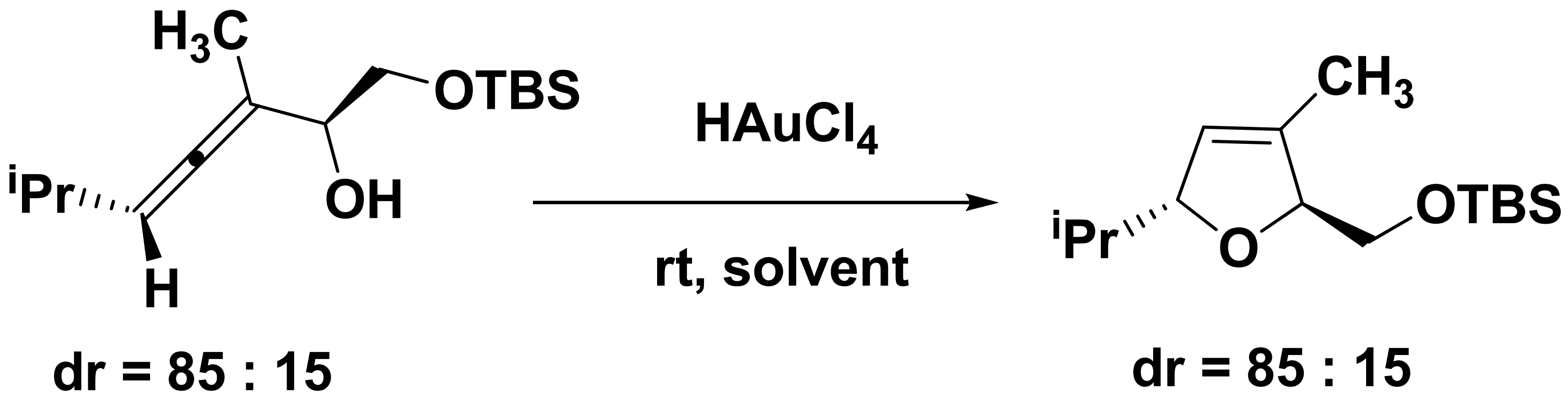
K_2CO_3, water, 100°C

95 % yield

ligand

C. A. Fleckenstien, H. plenio, *Green Chem.*, 2007, *9*, 1287-1291.

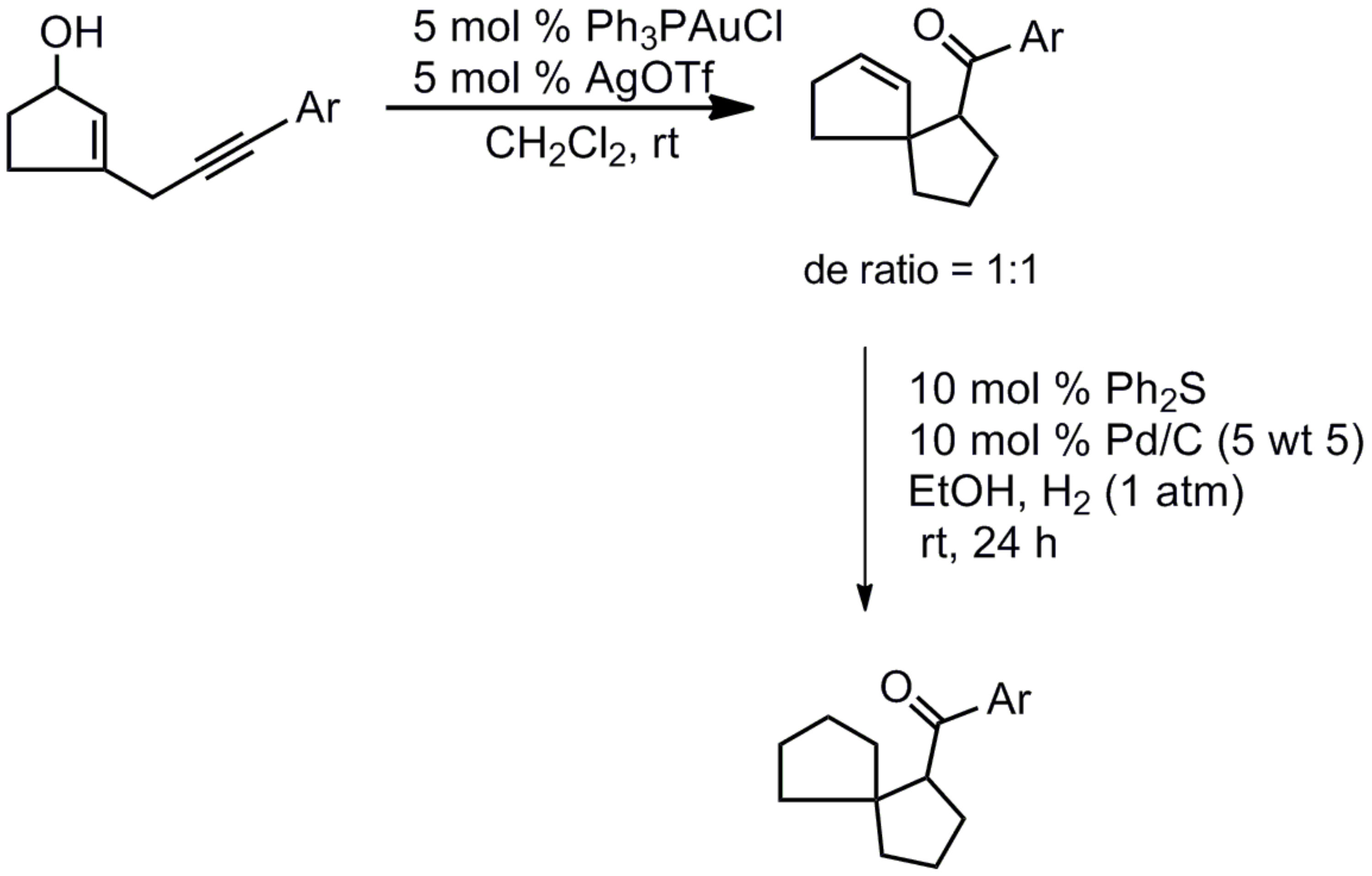
Chloroauric Acid ($HAuCl_4$)-catalyzed Reaction in Water



solvent	catalyst loading (mol %)	time	yield %
water (10 mL)	5	2.5 h	78
water (10 mL)	10	1 h	58
water (10 mL)	1	5 h	43

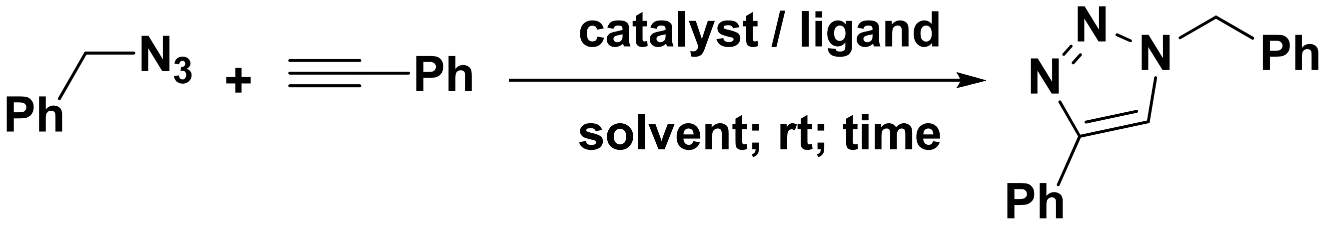
C. Winter, N. Krause, *Green Chem.*, 2009, *11*, 1309-1312.

Gold(I)-Catalyzed Synthesis



M. C.. Yeh, H. F. Pai, C.Y. Hsiow, Y. R. Wang *Organometallics*, 2010, *29*, 160.

Click Reaction in Water



catalyst / ligand	solvent	time	yield %
5 mol % CuBr / 30 mol % PhSMe	t- BuOH	1 h	< 5
5 mol % CuBr / 30 mol % PhSMe	t- BuOH / H_2O (1:2)	10 min	50
5 mol % CuBr / 30 mol % PhSMe	H_2O	5 min	96
10 mol % CuBr / 30 mol % PhSMe	H_2O	5 min	97

F. Wang, H. Fu, Y. Jiang, Y. Zhao, *Green Chem.*, 2008, *10*, 452-456.

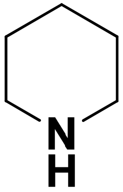
What is Organocatalysis?

- A concatenation of the terms “organic” and “catalyst”

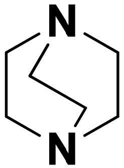
- In organic chemistry the term Organocatalysis refers to a form of catalysis, whereby the rate of a chemical reaction is increased by an organic catalyst consisting (mainly) of carbon, hydrogen, sulfur, nitrogen, oxygen, and phosphorus.

- Metal-free catalysis

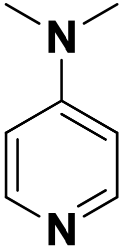
Achiral and Chiral Organocatalysts



Piperidine



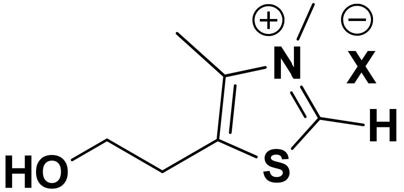
DABCO



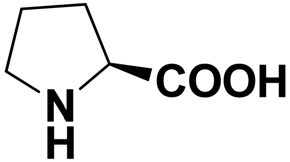
DMAP

$H\text{-}C\equiv N$

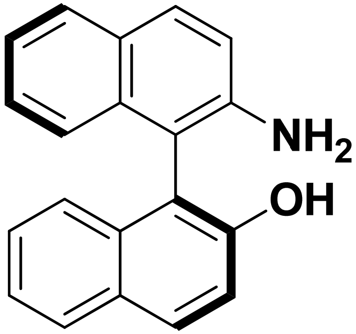
hydroen cynide



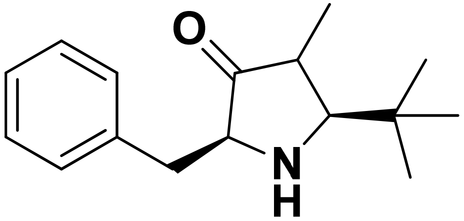
thiazolium salts



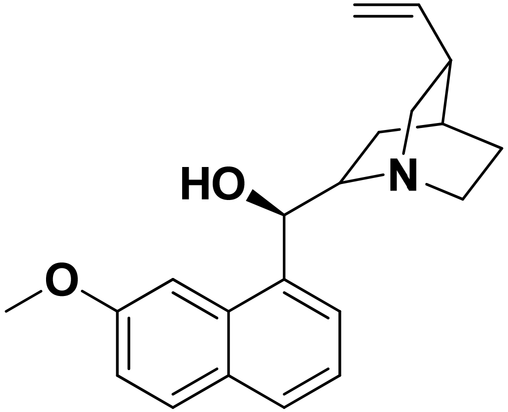
L-Proline



Nobin



Macmillan's catalyst



Quinine

Primary Attractions of Organocatalysis

- Readily available

- Non-toxic (environmentally benign)

- Inexpensive compared to Metal-based catalysts

- Inertness towards moisture and oxygen

Primary Attractions of Organocatalysis (continued)

- Demanding reaction conditions (inert atmosphere, low temperatures, absolute solvents, etc,.) are usually not required

- Absence of transition metals, attractive for synthesis of nontoxic pharmaceutical and agrochemical products

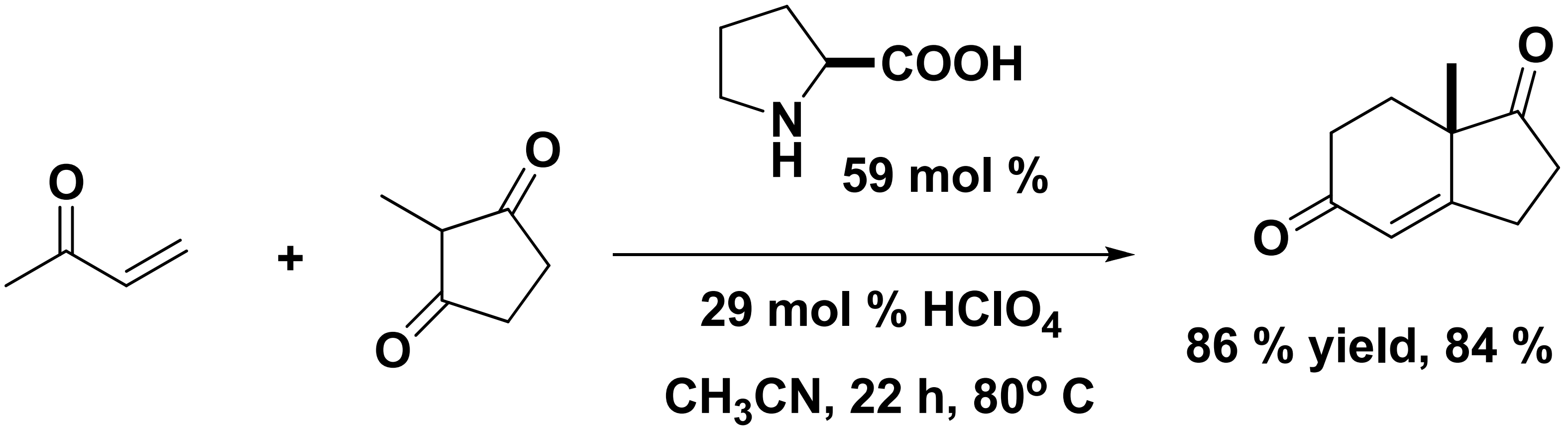
- Biomimetic-induced cascade reactions

Comparison with Conventional Catalysis

Type	Advantages	Disadvantages
Organometallic Catalysis	Wide substrate scope high catalytic activity	Tedious process, potential heavy metal pollution
Enzyme Catalysis	High selectivity and catalytic activity	Limited substrate scope usually single enantiomer
Organocatalysis	Simple structure, inexpensive, natural molecules, nontoxic	No

Robinson Annulation

Early Organocatalysis:



59 mol %

29 mol % $HClO_4$

CH_3CN, 22 h, 80° C

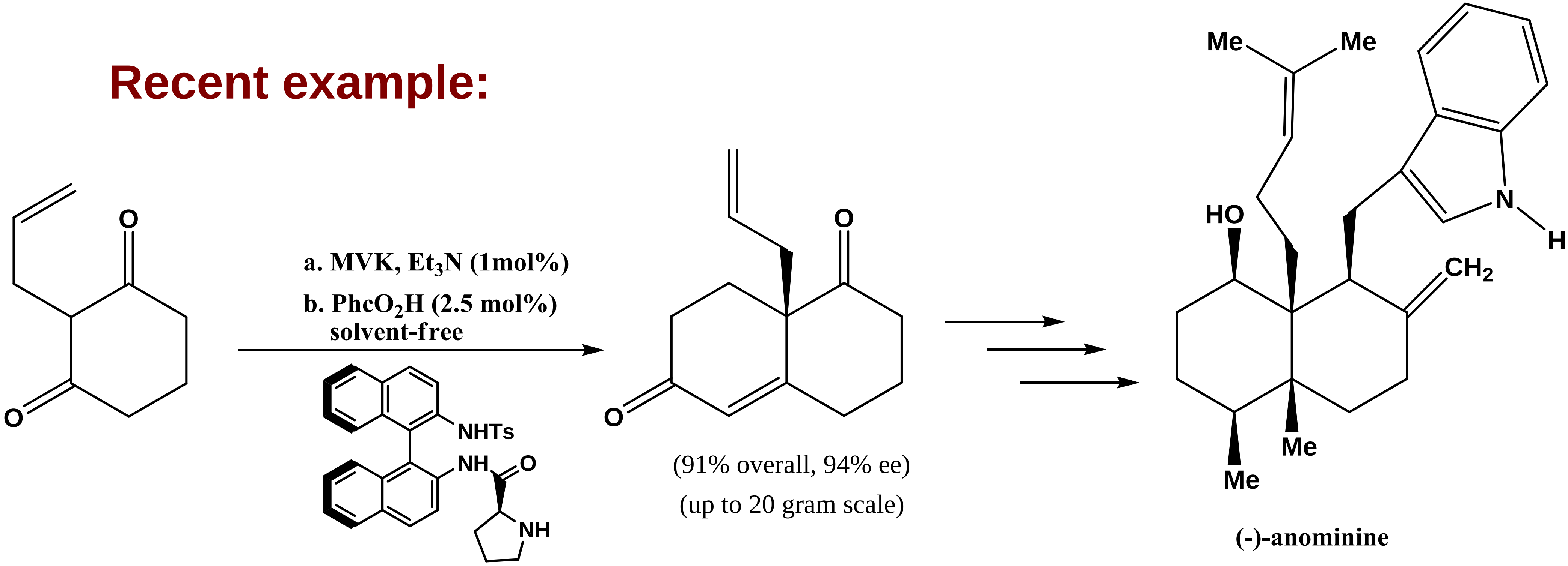
86 % yield, 84 % ee

Eder et al. *Angew. Chem. Int. Ed.* 1971, *10*, 496-497

Z. Hajos, D. Parrish, *J. Org. Chem.* 1974, *39*, 1615-1621

Robinson Annulation

Recent example:



a. MVK, Et_3N (1mol%)

b. $PhcO_2H$ (2.5 mol%)
solvent-free

(91% overall, 94% ee)
(up to 20 gram scale)

(-)-anominine

Bradshaw, B.; Etxebarria-Jardi, G.; Bonjoch, J,
J. Am. Chem. Soc. ASAP 2010.

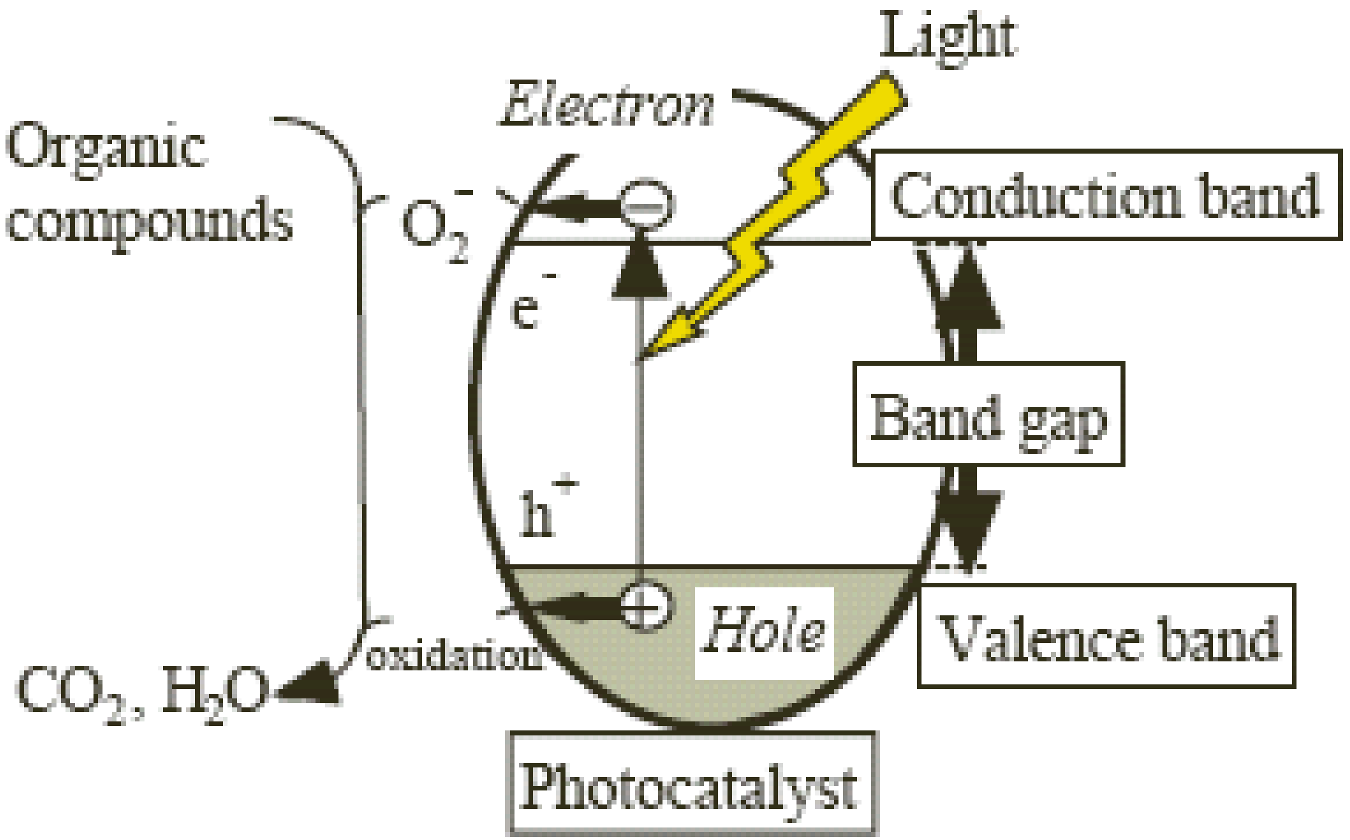
Photocatalysis

The phenomenon by which a relatively small amount of light-absorbing material, called a photocatalyst, changes the rate of chemical reaction without itself being consumed.

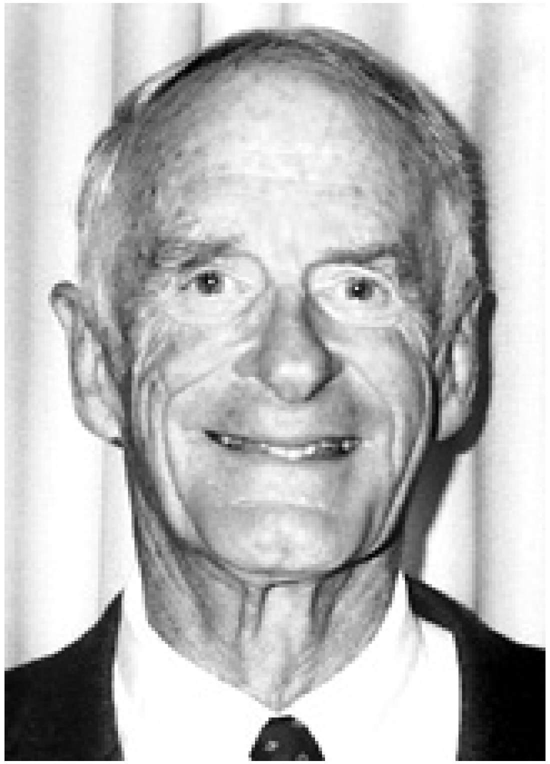
Photocatalysis by TiO_2 has been investigated for decades since the first report by Fujishma and Honda in 1972.

A. Fujishima, K.Honda, *Nature*, 1972, 238, 37-38.

Mechanism of Photocatalysis

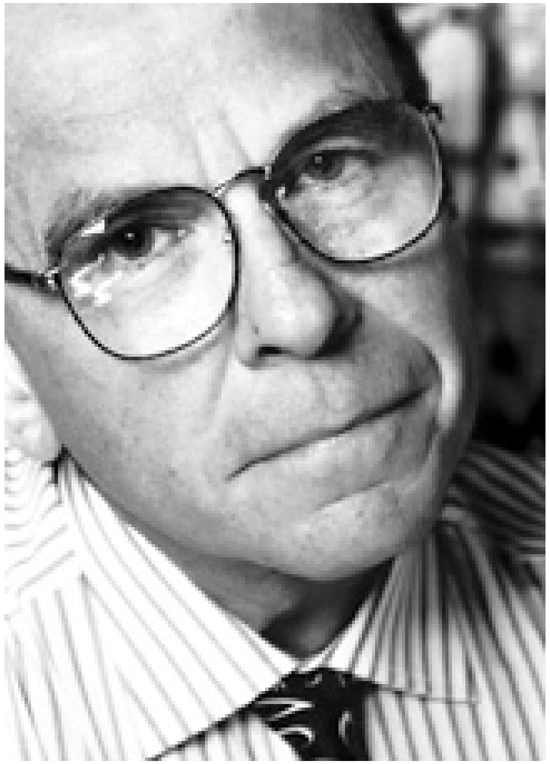


Asymmetric Catalysis



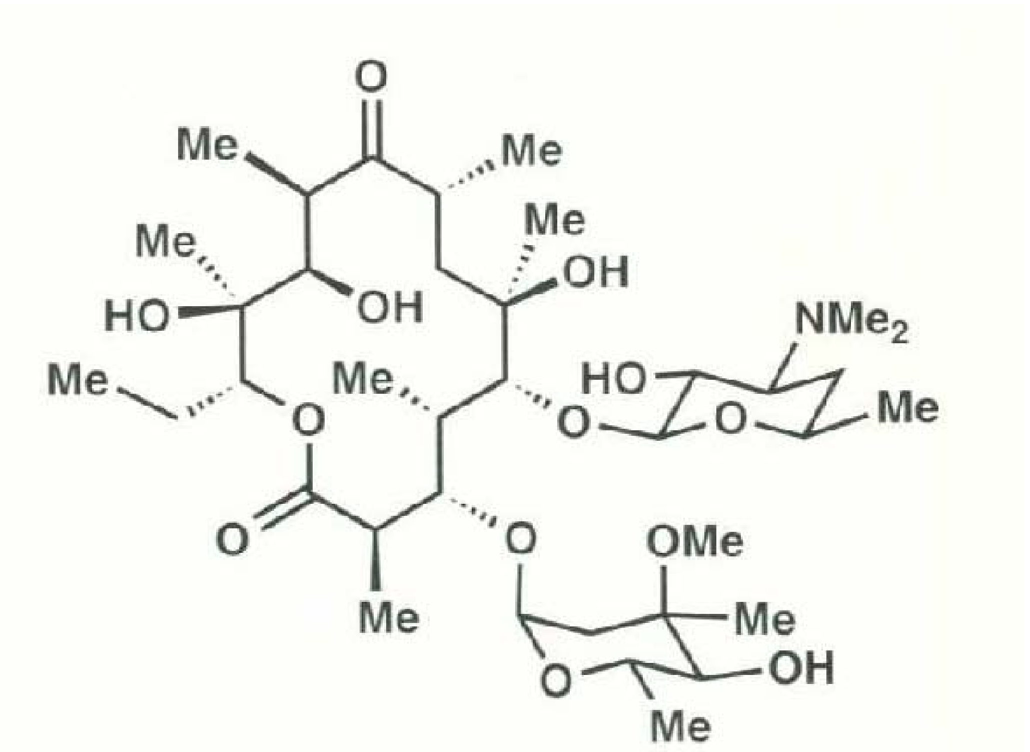
William S. Knowles

Ryoji Noyori



K. Barry Sharpless

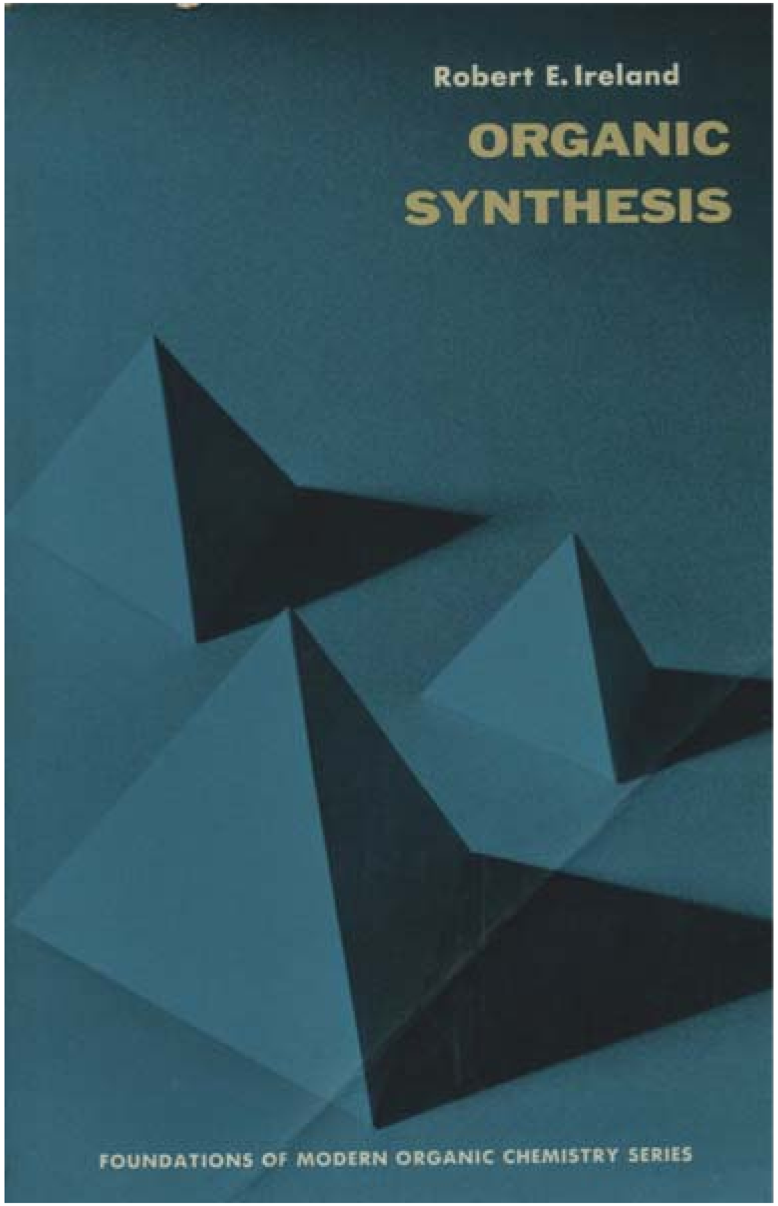
Stereochemistry raises its ugly head



Erythromycin A

Stereocenters = 18

Stereoisomers = 262,144



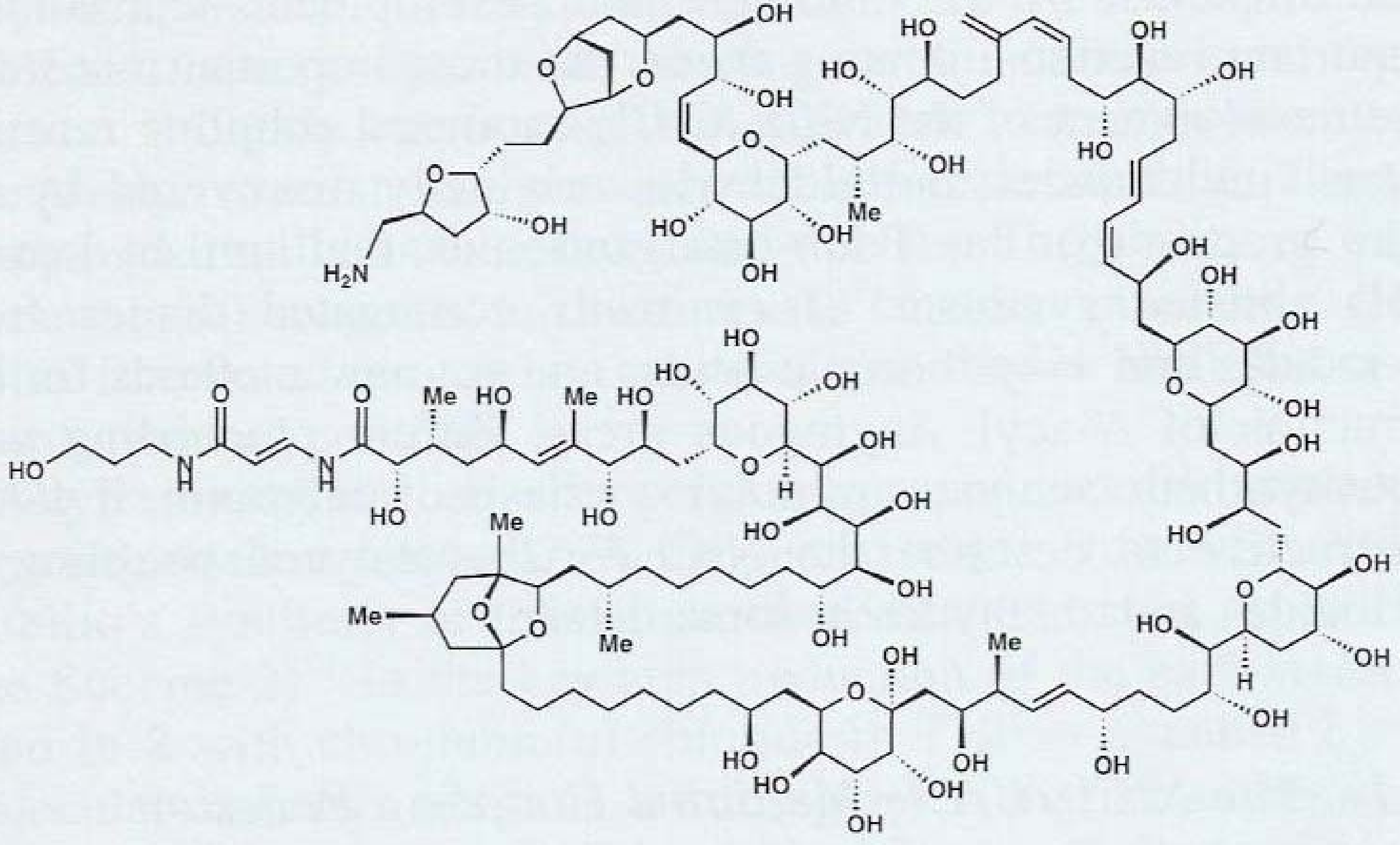
Robert E. Ireland

ORGANIC SYNTHESIS

FOUNDATIONS OF MODERN ORGANIC CHEMISTRY SERIES

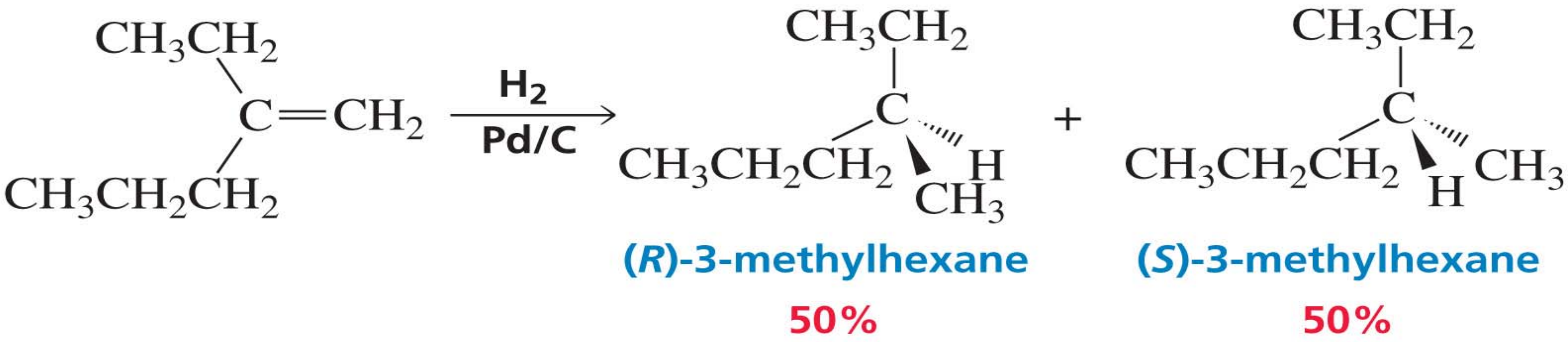
Palytoxin

- **with 64 Chiral Centers and 7 C=C Stereocenters**



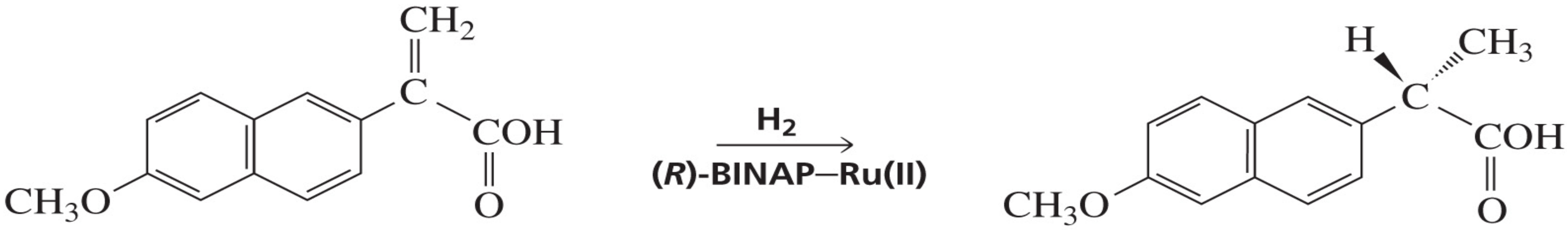
1: palytoxin

Catalytic Hydrogenation



The transition states are enantiomers.

Enantioselective Hydrogenation



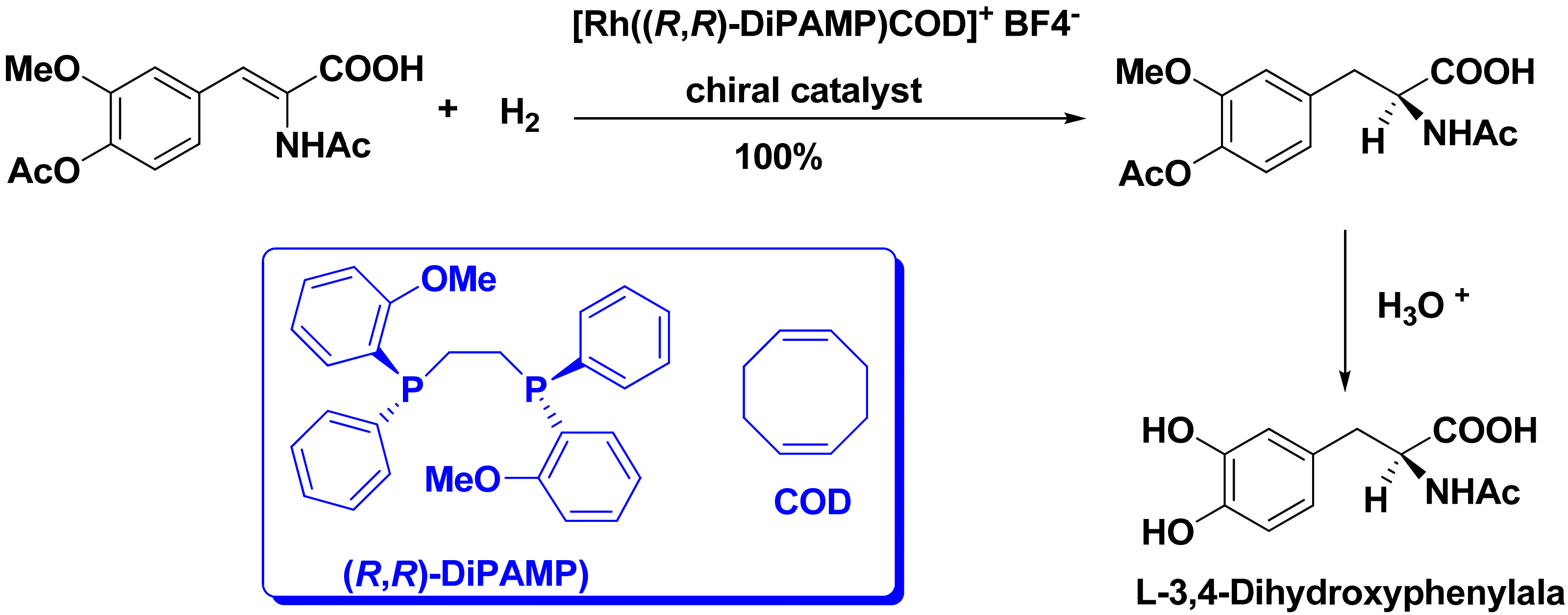
(*S*)-naproxen

>98% ee

The transition states are diastereomers.

MONOSANTO L-DOPA PROCESS

The first industrial catalytic asymmetric synthesis



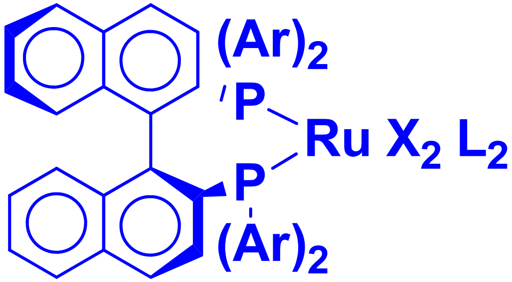
L-3,4-Dihydroxyphenylalanine

(L-DOPA)

W. S. Knowles, Acc. Chem. Res., 1983, 16, 106-112; J. Chem. Edu., 1986, 63, 222-225

(*R*)-BINAP-Ru-catalyzed Hydrogenation

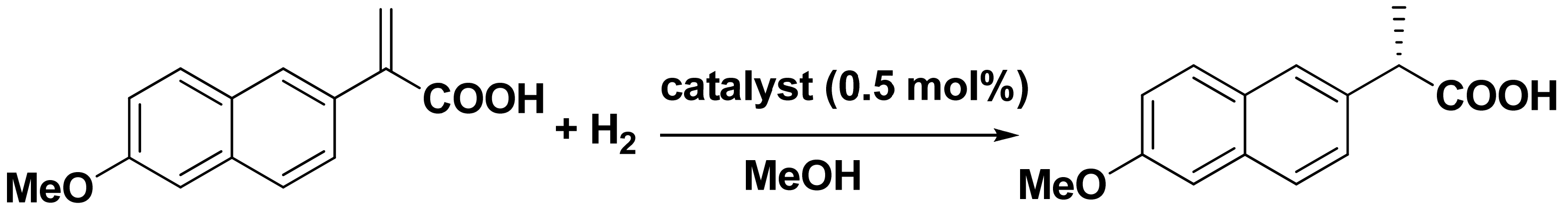
Ar = aryl, L = ligand, X = Cl, Br, I



The (*R*)- BINAP-Ru-catalyzed hydrogenation of acetol to (*R*)-1,2-propanediol is currently used for the industrial synthesis of antibacterial levofloxacin

M. Kitamura, T. Ohkuma, S. Inoue, N. Sayo, H. Kumobayashi, S. Akutagawa, T. Otha, H.Takaya, R. Noyori, *J. Am. Chem. Soc.*, 1988, *110*, 629.

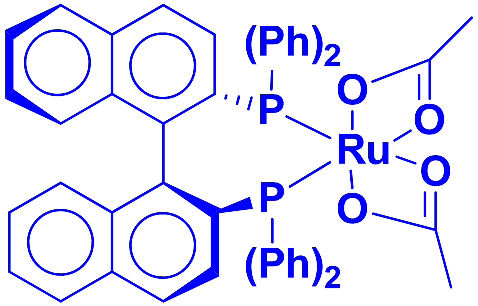
Catalytic Asymmetric Synthesis of (S)-Naproxen



92 % yield, 97 % ee

(*S*)-Naproxen
an anti-inflammatory agent

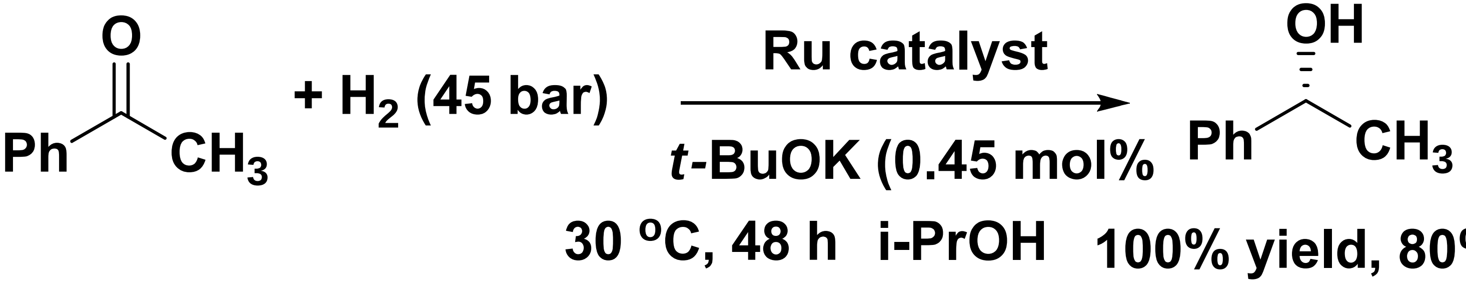
catalyst



(*S*)-BINAP-Ru$(OCOCH_3)_2$

T. Ohta, H. Takaya, R. Noyori, *Inorg. Chem.,* 1988, 27, 566

Asymmetric Hydrogenation of Ketones



+ H_2 (45 bar)

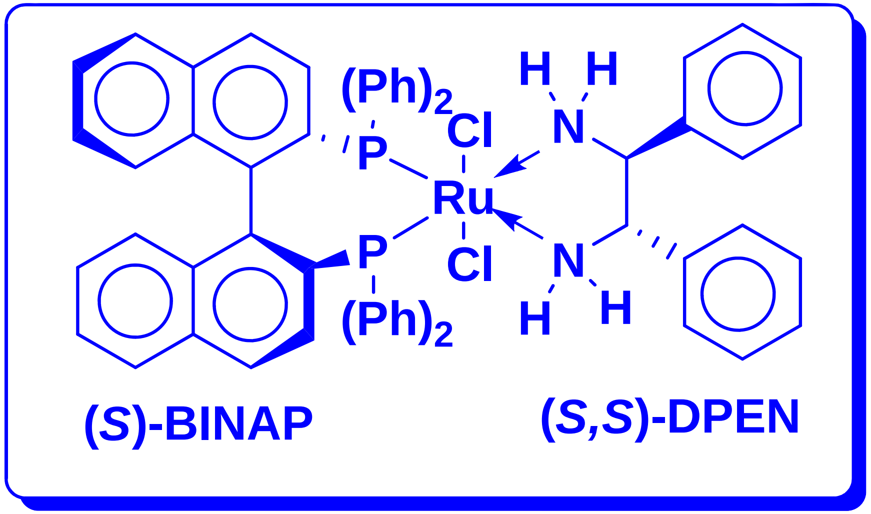
Ru catalyst

t-BuOK (0.45 mol%

30 °C, 48 h i-PrOH

100% yield, 80% ee

Turnover number (TON) = 2400000

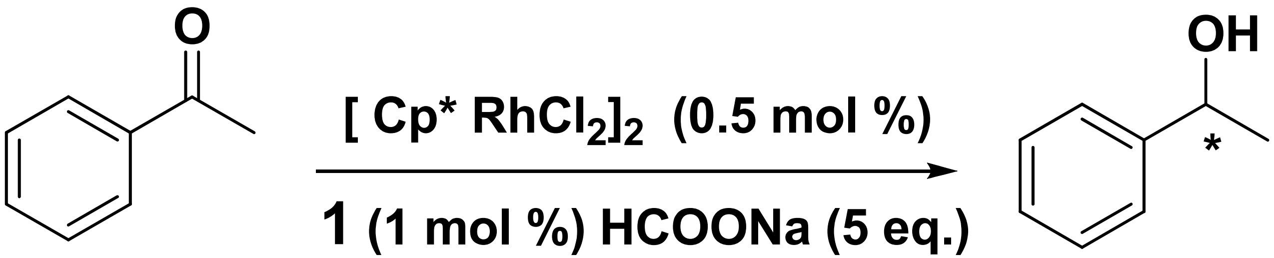


(*S*)-BINAP

(*S*,*S*)-DPEN

R. Noyori et al., *Angew. Chem. Int. Ed.*, 1998, *37*, 1703-1707.

Rhodium-catalyzed Asymmetric Hydrogenation in Water

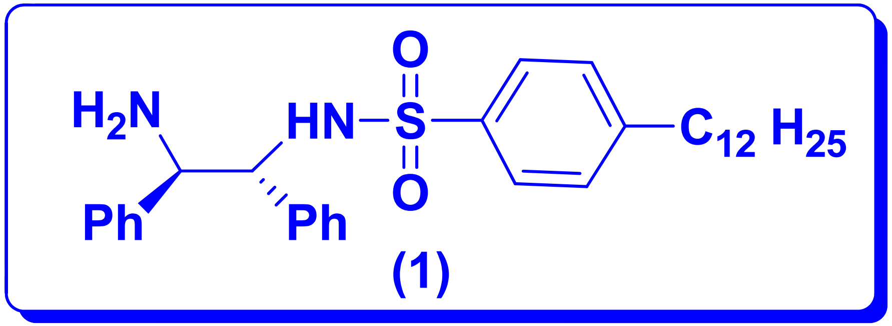


[Cp* RhCl$_2$]$_2$ (0.5 mol %)

1 (1 mol %) HCOONa (5 eq.)

H_2O, 28 °C, 17 h

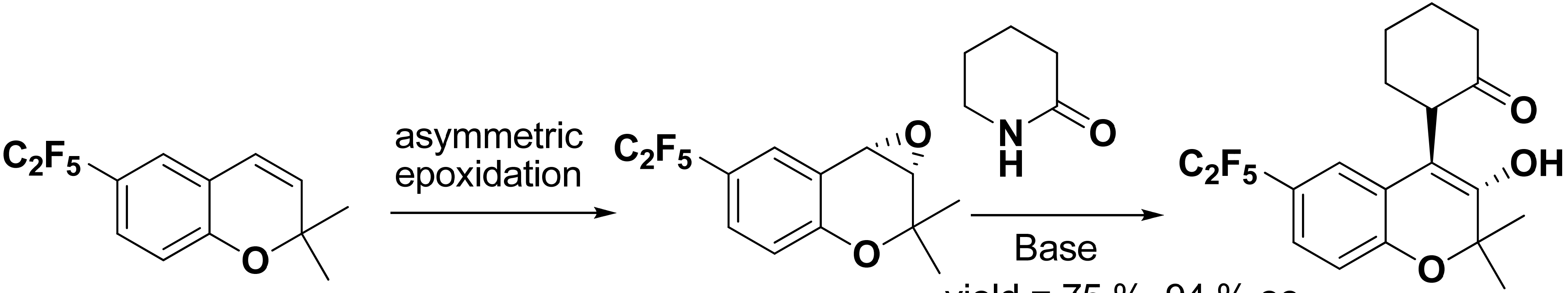
conversion = 97 %;
ee = 97 % (*R*)



(1)

K. Ahlford, J. Lind, L. Maler, H. Adolfsson, *Green Chem.,* 2008, *10*, 832-835.

Asymmetric Epoxidation of Alkenes



asymmetric
epoxidation

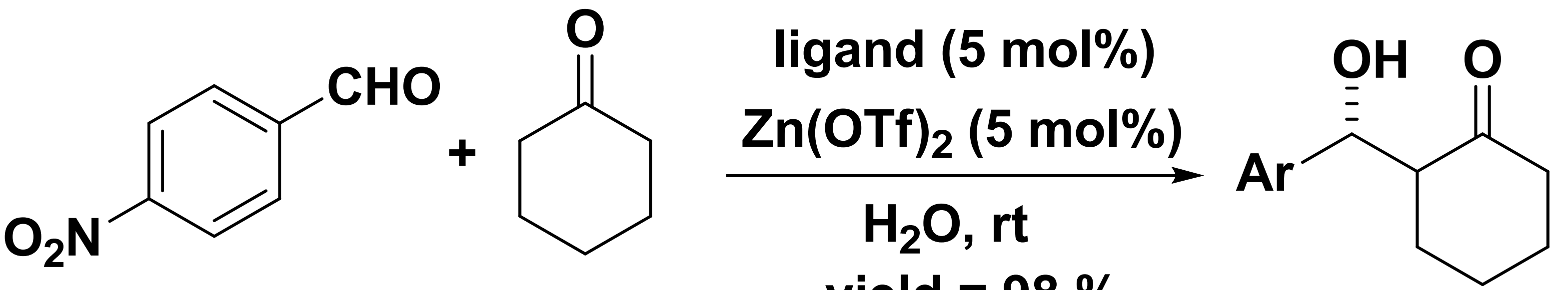
Base

yield = 75 %, 94 % ee

BRL 55834
K channel activator

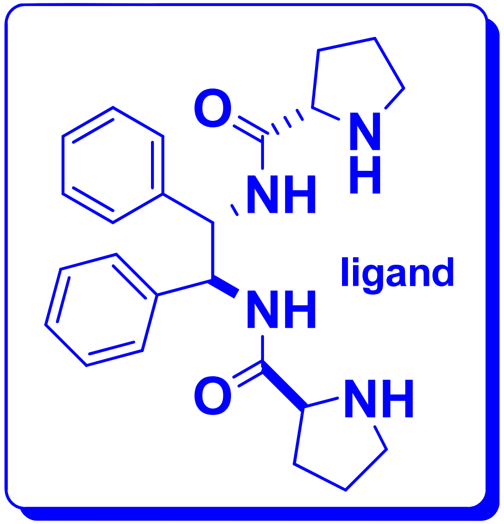
N. H. Lee, A. R. Muci, E. N. Jacobsen, *Tetrahedron Lett.,* 1991, 32, 5055-5058.
D. Bell, M. R. Davies, F. J. L. Finney, *Tetrahedron Lett.,* 1996, 37, 3895-3898.

Asymmetric Aldol Reaction in Water



yield = 98 %

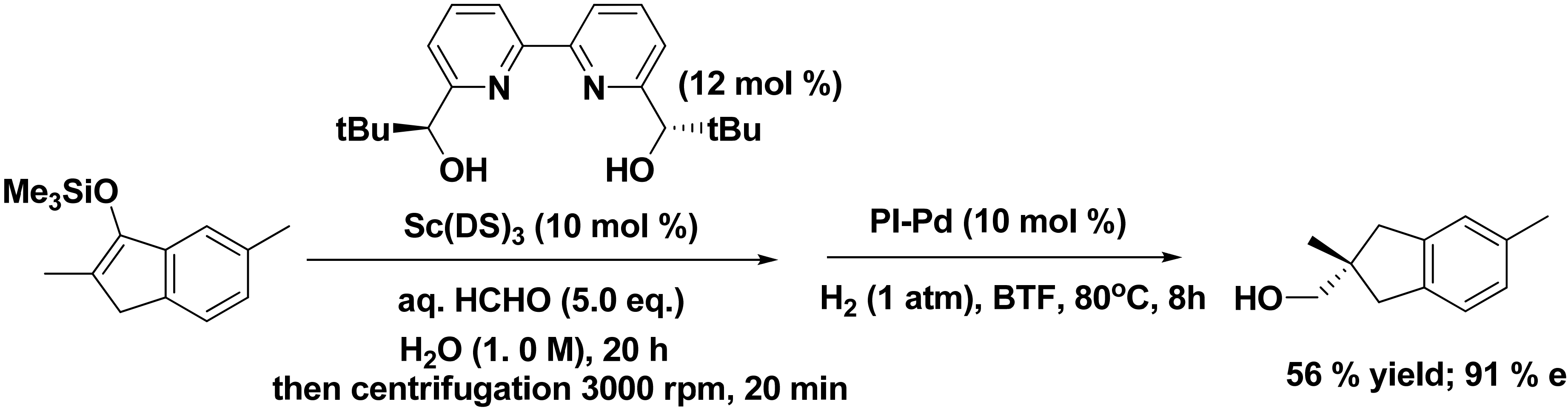
de = 90%, ee = 94%



ligand

J. Paradowska, M. Stodulski, J. Mlynarski, *Adv. Synth. Catal.*, 2007, 349,1041

Asymmetric Aldol Reaction in Water



(12 mol %)

Sc(DS)$_3$ (10 mol %)

aq. HCHO (5.0 eq.)
H_2O (1. 0 M), 20 h
then centrifugation 3000 rpm, 20 min

PI-Pd (10 mol %)

H_2 (1 atm), BTF, 80°C, 8h

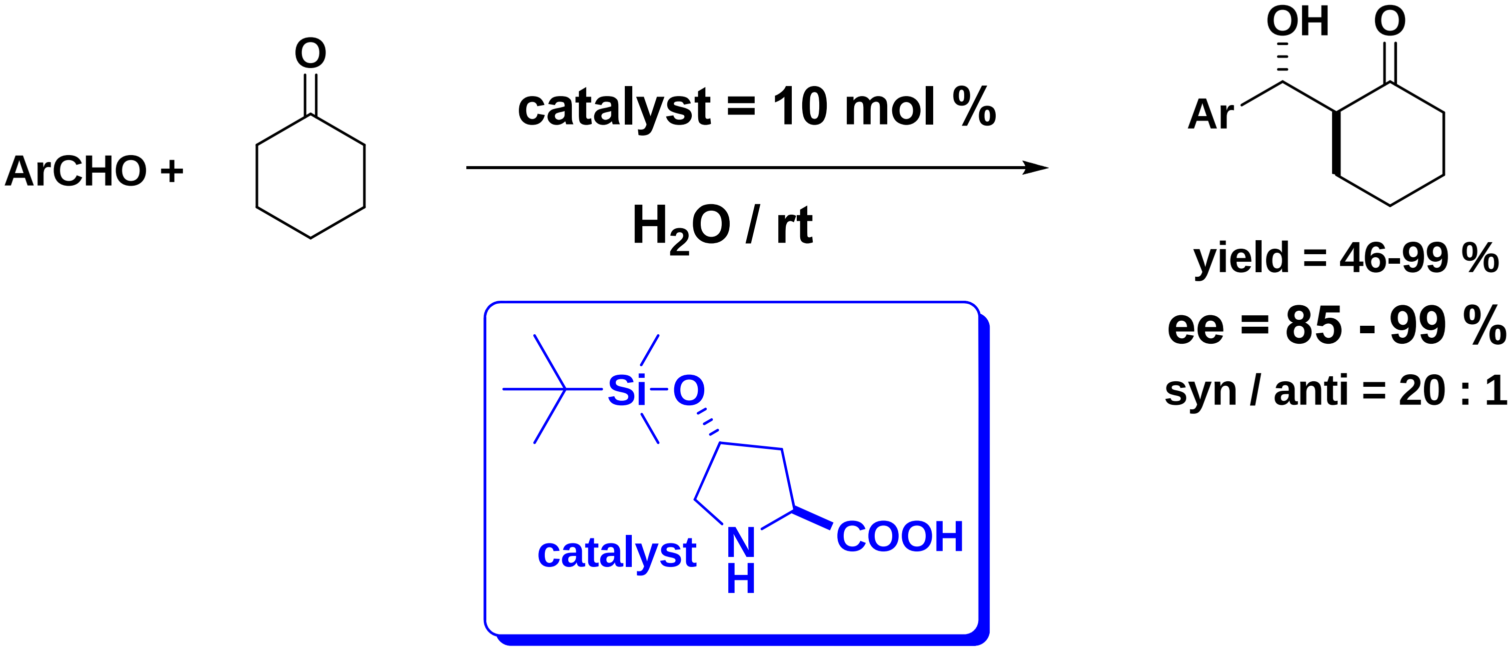
56 % yield; 91 % ee

This reaction does not require any organic solvent

Sc(DS)$_3$ = Sc[$O_3S(CH_2)_{10}$ CH_3]$_3$
PI-Pd = polymer incarcerated palladium; BTF = benzo triffluoride

M. Kokubo, C. Ogawa, S. Kobayashi, *Angew. Chem. Int. Ed*. 2008, *47*, 6909-6911.

Asymmetric Aldol Reaction with Homochiral Organocatalyst in Water



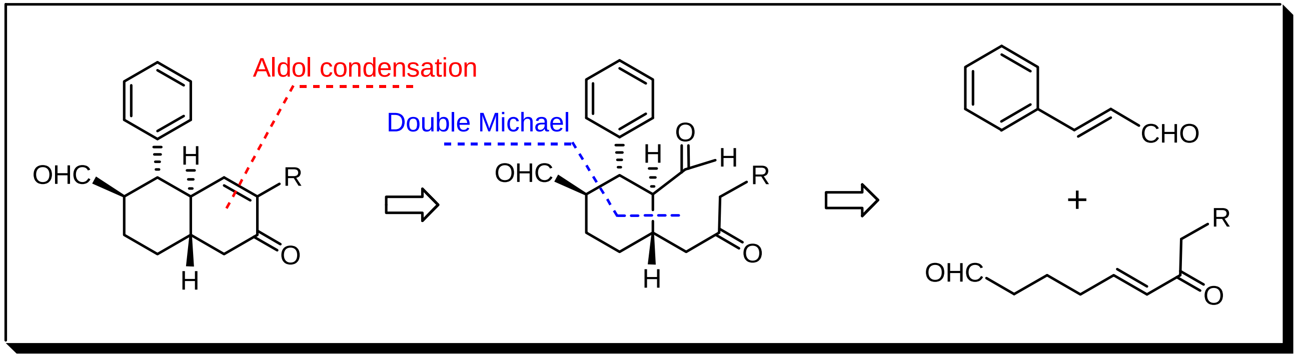
yield = 46-99 %

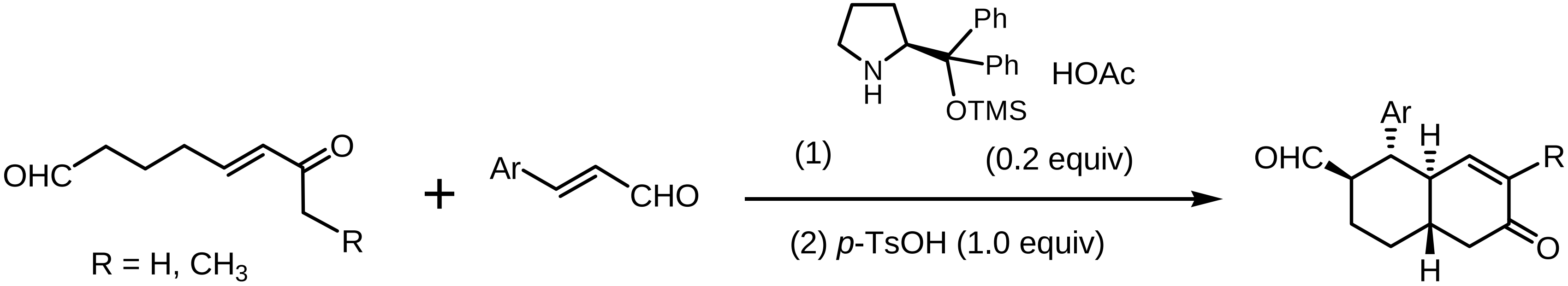
ee = 85 - 99 %

syn / anti = 20 : 1

N. Mase, Y. Nakai, N. Ohara, H. Yoda, K. Takabe, F. Tanaka, C. F. Barbas III, *J. Am. Chem. Soc.*, 2006, *128*, 734.

Enantioselective Synthesis of Highly Functionalized Octahydro-6-oxo-1-phenylnaphthalene-2-carbaldehydes via Organocatalytic Domino Reactions

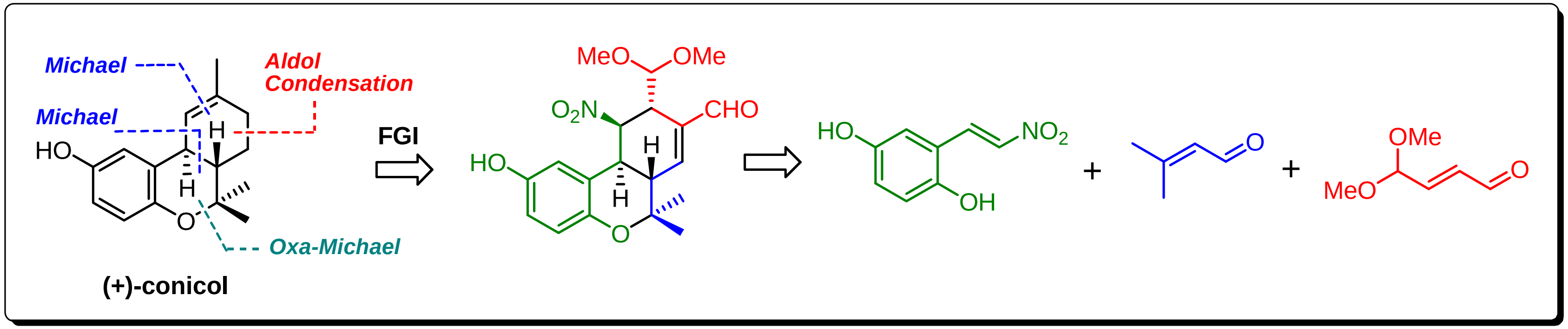




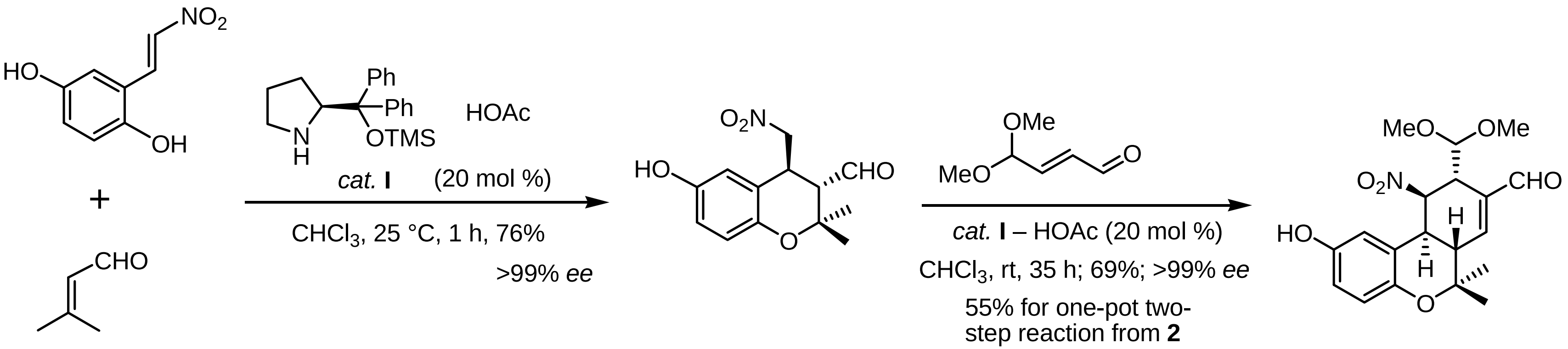
63-86% yield
>99% *ee*

B.-C. Hong,* R. Y. Nimje, J.-H. Liao, *Org. Biomol. Chem.* 2009, 3095–3101.

Enantioselective Total Synthesis of (+)-Conicol via Cascade Three-Component Organocatalysis



(+)-conicol



cat. **I** (20 mol %)

$CHCl_3$, 25 °C, 1 h, 76%

>99% *ee*

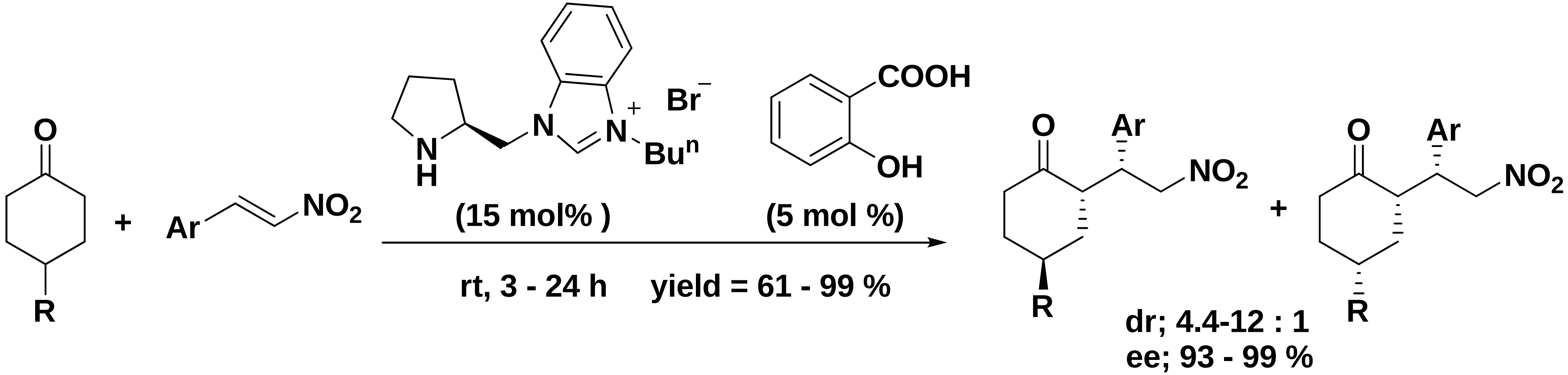
cat. **I** – HOAc (20 mol %)

$CHCl_3$, rt, 35 h; 69%; >99% *ee*

55% for one-pot two-step reaction from **2**

B.-C. Hong,* P. Kotame, C.-W. Tsai, J.-H. Liao *Org. Lett.* 2010, ASAP, DOI: 10.1021/ol902840x

Michael Addition Reactions in Chiral Ionic Liquids



(15 mol%) (5 mol %)

rt, 3 - 24 h yield = 61 - 99 %

dr; 4.4-12 : 1

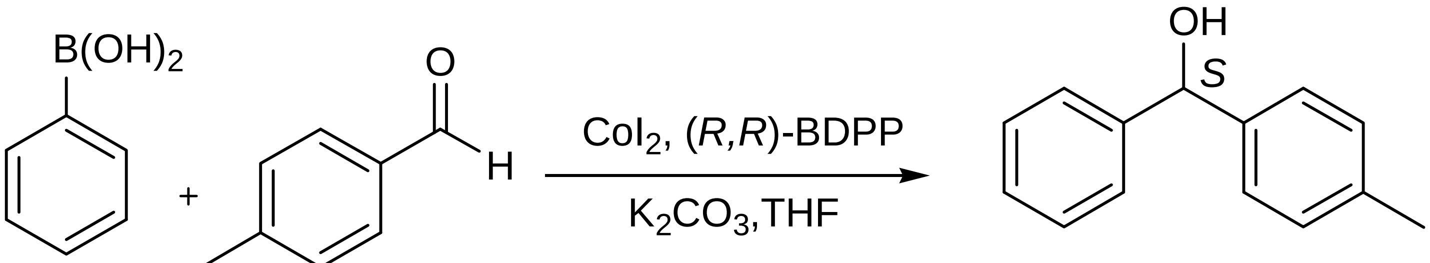
ee; 93 - 99 %

R = Me, Et, t-Bu, Ph, N_3, SAc, OH, Br, CN

Ar = Ph, 4-ClPh, 2-ClPh, 4-MePh, 4-PhPh, 4-MeOPh, 4-NO_2Ph, 2-NO_2Ph, 1-Naph, Piperal

S. Luo, L. Zhang, X. Mi, Y. Qiao, J. –P. Cheng, *J. Org. Chem.,* 2007, 72, 9350-9352.

Cobalt-Catalyzed Addition Reaction of Organoboronic Acids with Aldehydes

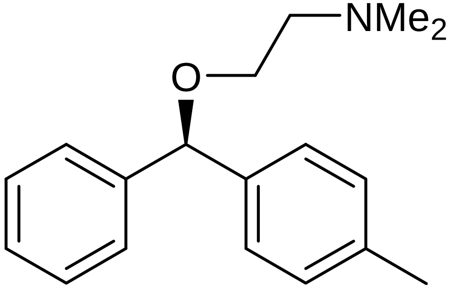


1 **2** **3**

93% ee
90% yield

18 examples, 86-99% ee
77-99% yield

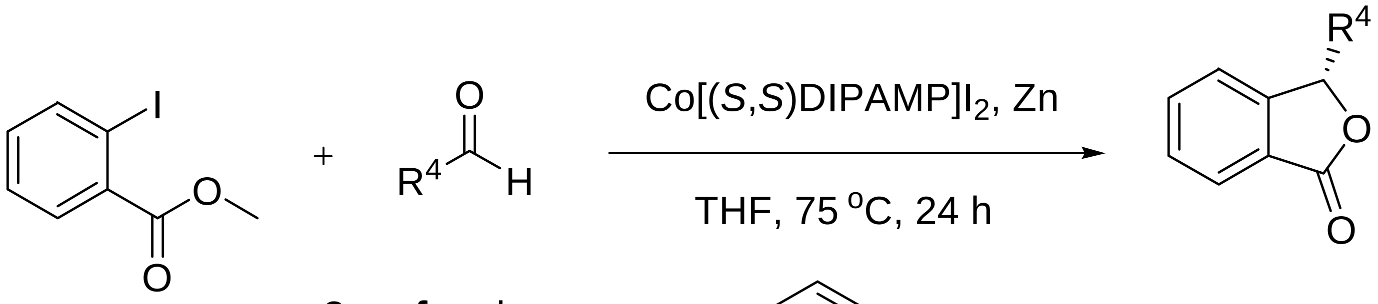
3-R can be used as the precursor for the synthesis of bioactive (R)-neobenodine



(R)-neobenodine

By Karthickeyan J. and C.-H. Cheng

Asymmetric Cyclization of *o*-Iodobenzoates with Aldehydes Catalyzed by Cobalt Complexes

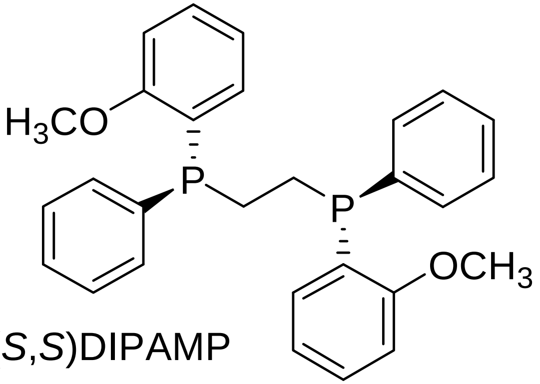


1a

2a-c,f and **g**

4a-e

2a: R^4 = Ph
2b: R^4 = p-CH_3-C_6H_4
2c: R4 = p-t-butyl-C_6H_4
2f: R^4 = p-Cl-C_6H_4
2g: R^4 = p-CF_3-C_6H_4

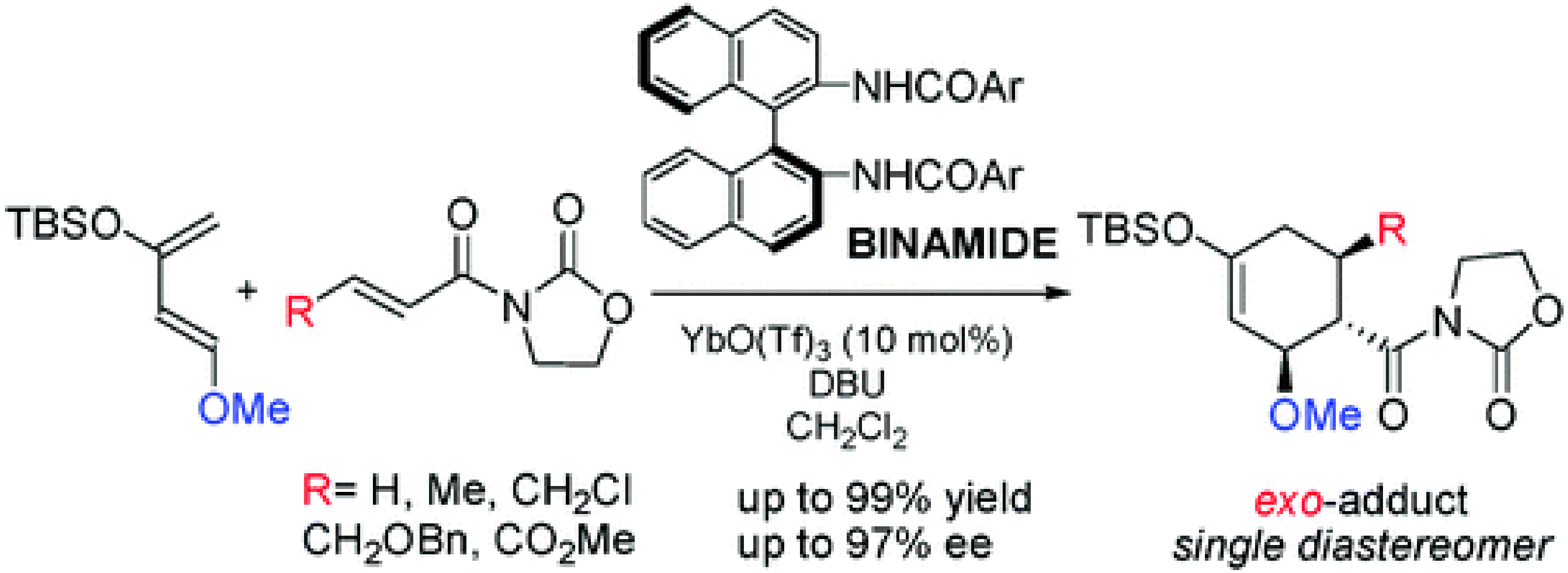


(*S*,*S*)DIPAMP

4a: 89%, 84% ee
4b:80%, 79% ee
4c: 85%, 91% ee
4d: 83%, 98% ee
4e: 81%, 70% ee

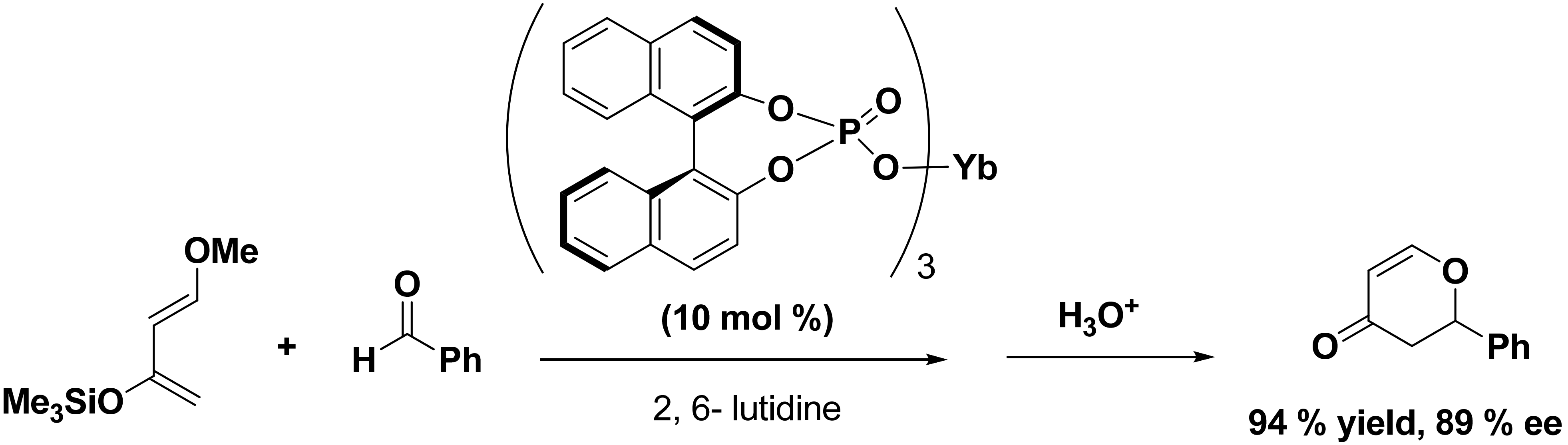
Chang, H.T.; Jeganmohan M.; Cheng C.H. *Chem. Eur. J.,* 2007, *15*, 4356.

Asymmetric Diels-Alder Reaction



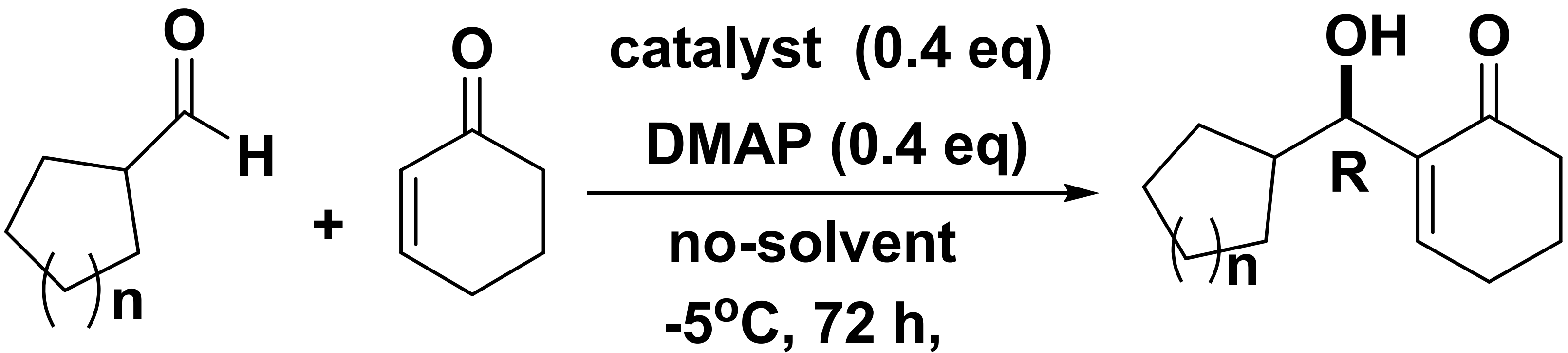
Y. Sudo, D. Shirasaki, S. Harada, A. Nishida
***J. Am. Chem. Soc.*, 2008, *130*, 12588-12589.**

Asymmetric Hetero-Diels-Alder Reaction



H. Furuno, T. Hanamoto, Y. Sugimoto, J. Inanaga, *Org. Lett*. 2000, *2*, 49-52

Baylis-Hillman Reaction



catalyst (0.4 eq)

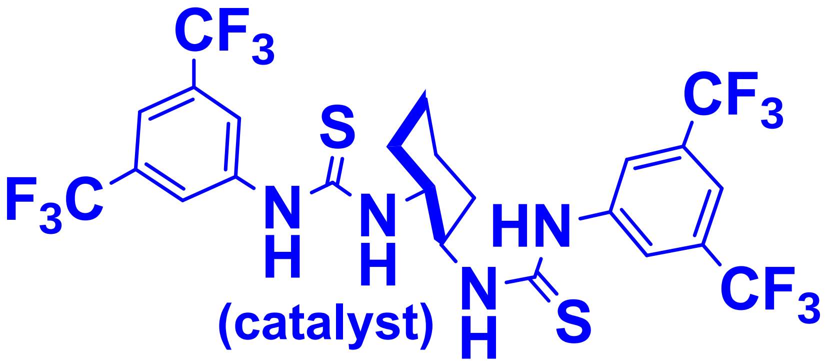
DMAP (0.4 eq)

no-solvent

-5^{o}C, 72 h,

n = 1= 55%, 86%ee

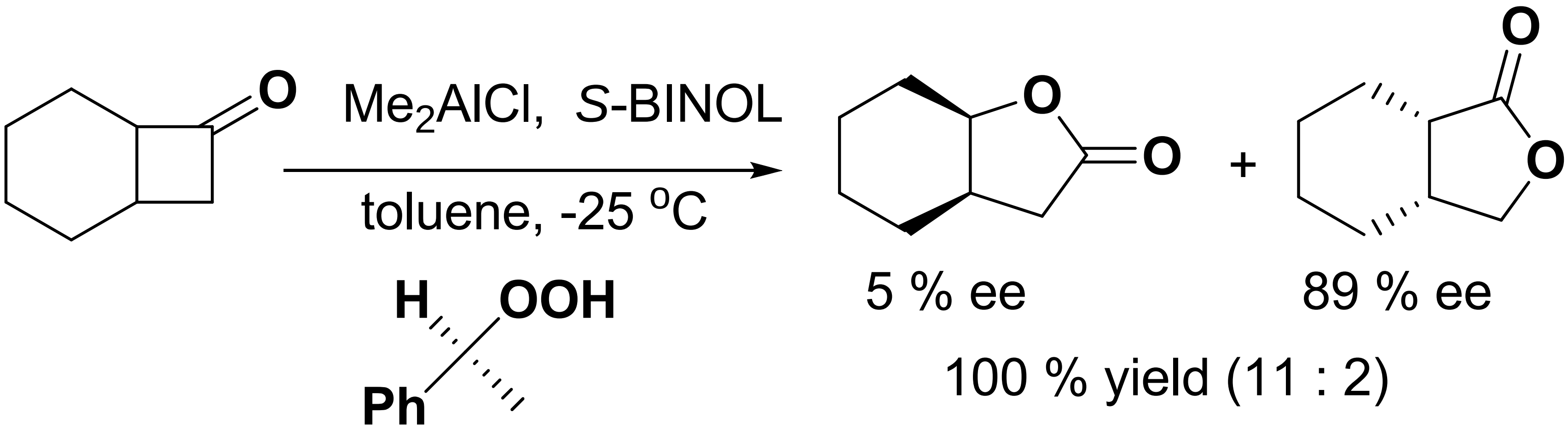
n = 2 = 72%, 90%ee



(catalyst)

Sohtome, Y.; Tanatani, A.; Hashimoto, Y.; Nagasawa, K. *Tetrahedron Lett.* 2004, *45*, 5589.

Baeyer-Villiger Oxidation



Me_2AlCl, *S*-BINOL

toluene, -25 °C

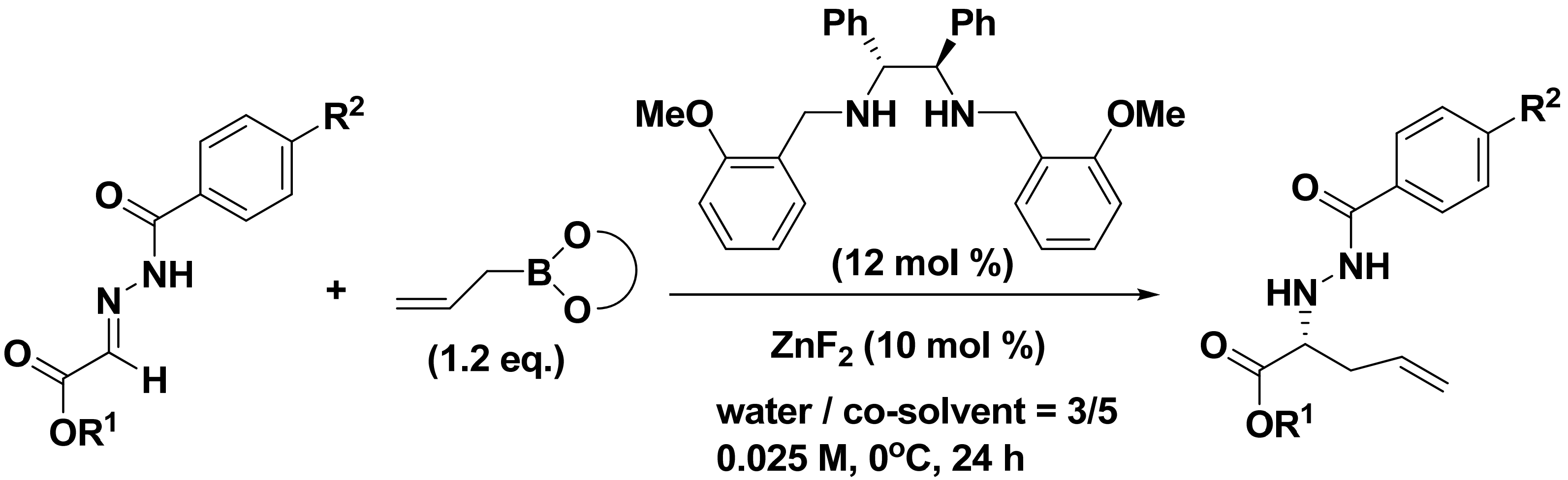
5 % ee

89 % ee

100 % yield (11 : 2)

C. Bolm, O. Beckmann, T. Kuhn, *Tetrahedron: Asymmetry*, 2001, *12*, 2441-2446.

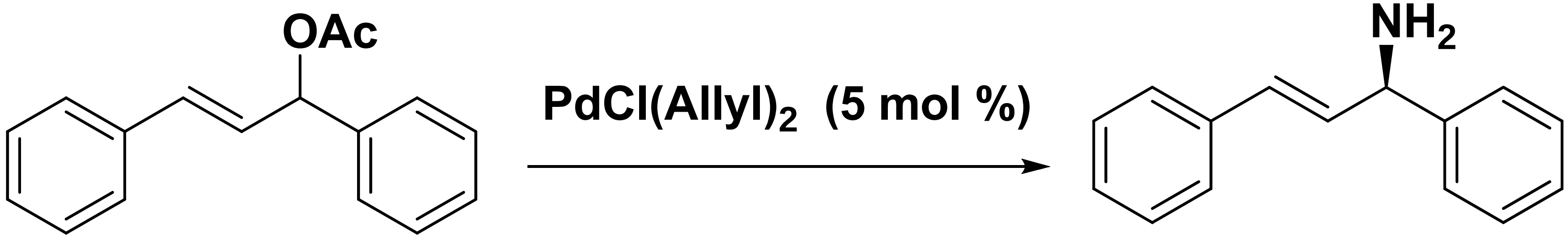
Asymmetric Allylation of Hydrazono Esters with Allylboronates in Aqueous Media



R^1	R^2	co-solvent	yield %	ee %
Et	H	acetone	quant.	79
Et	H	DMSO	71	71
Et	H	CH_3CN	76	62
Me	NMe_2	acetone	quant.	90

M. Fujita, T. Nagano, U. Schnieder, T. Hamada, C. Ogawa, S. Kobayashi, *J. Am. Chem. Soc*. 2008, *130*, 2914-2915

Palladium-catalalized Asymmetric Allylic Amination

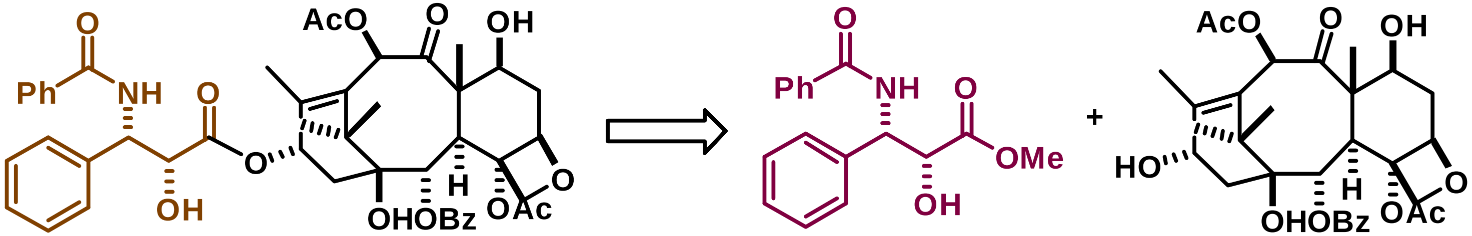


$PdCl(Allyl)_2$ (5 mol %)

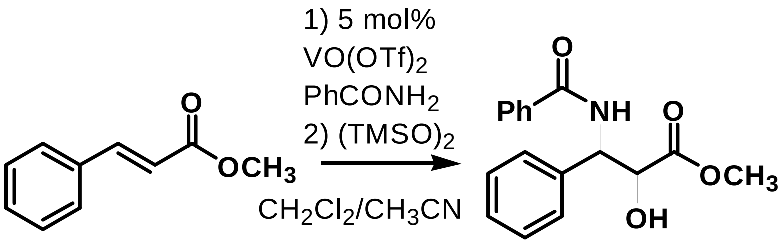
R-Binap (20 mol%)
aqueous NH_3 / 1, 4-Dioxane (1/2) 0.04 M,
rt, 18h
71 % yield; 87 % ee

T. Nagano, S. Kobayashi, *J. Am. Chem. Soc*. 2009, *131*, 4200-4201

以綠色奈米手性觸媒合成具殺死黑色素瘤細胞活性之紫杉醇〔Taxol〕側鏈

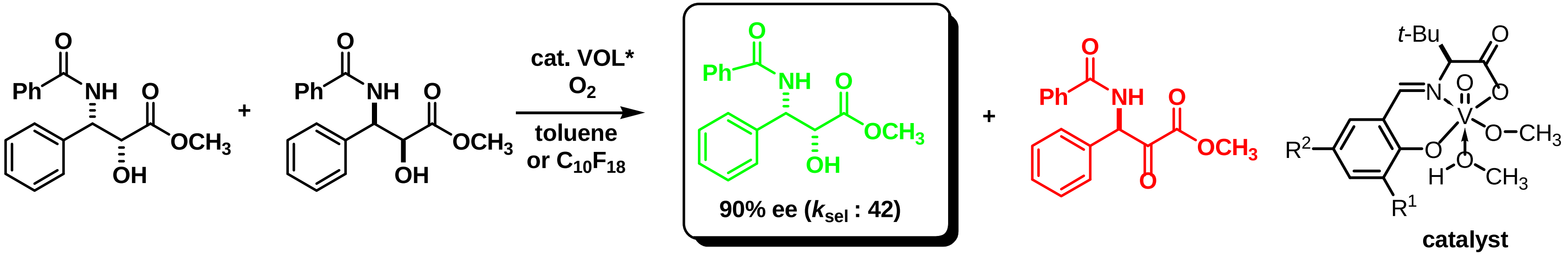


Taxol
(Antitumor drug)



syn-product

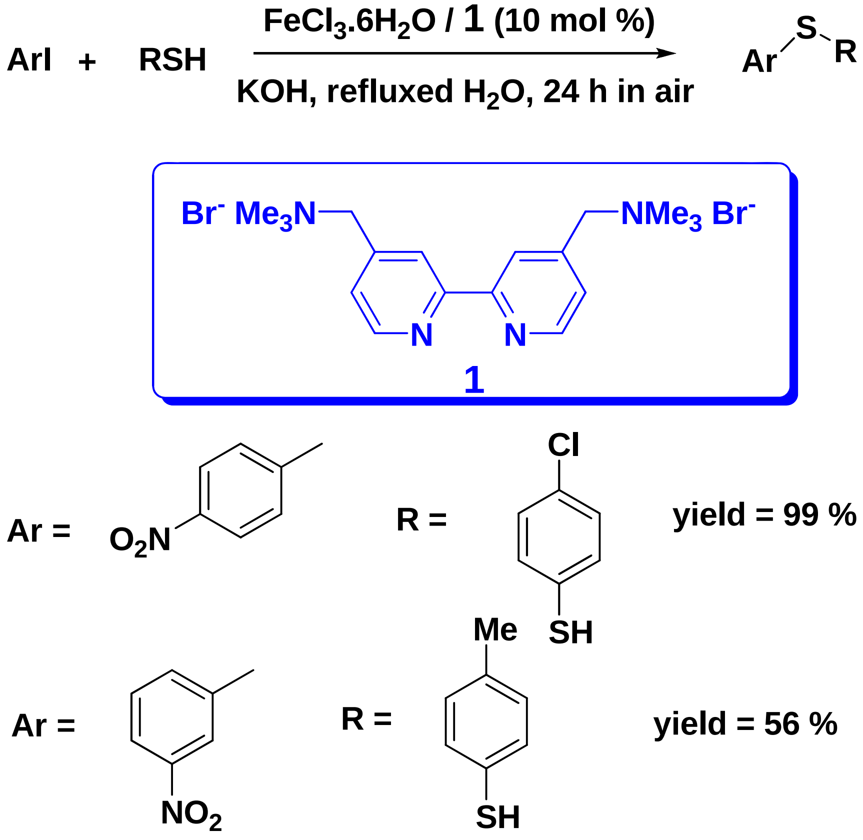
Chen, C.-T et al. *OL* 2007, *9*, 5195.



catalyst

C.-T. Chen, S.-S. Weng, et al. *Proc. Natl. Acad. Sci. USA* 2006,*103(10)*, 3522.

A Reusable $FeCl_3.6H_2O$/Cationic 2,2-Bipyridyl System as a Catalyst in Water under Aerobic Conditions



$FeCl_3.6H_2O$ / **1** (10 mol %)

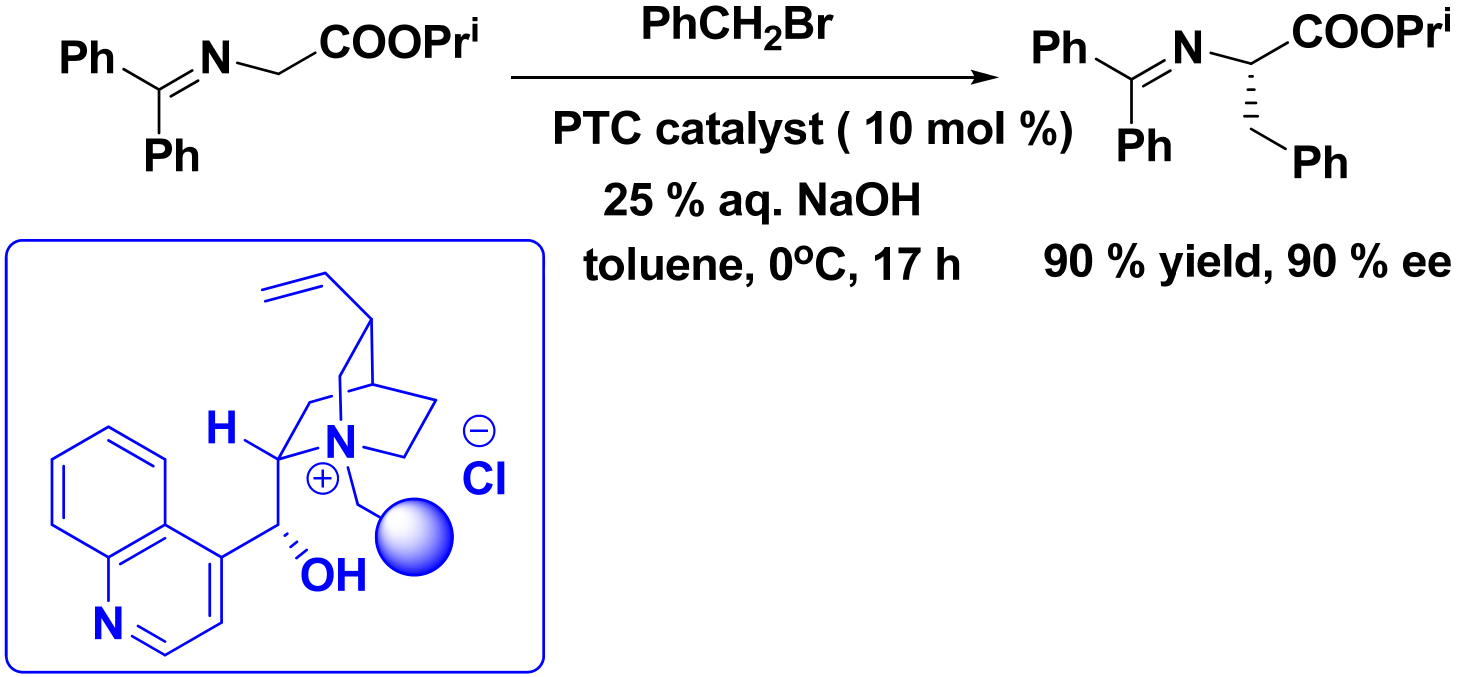
KOH, refluxed H_2O, 24 h in air

yield = 99 %

yield = 56 %

W-Y. Wu, J-C. Wang, F-Y. Tsai, *Green Chem.*, 2009, *11*, 326-329.

Easily Recoverable Phase-Transfer Catalysts for the Asymmetric Synthesis of α-Amino Acids



$PhCH_2Br$

PTC catalyst (10 mol %)

25 % aq. NaOH

toluene, 0°C, 17 h

90 % yield, 90 % ee

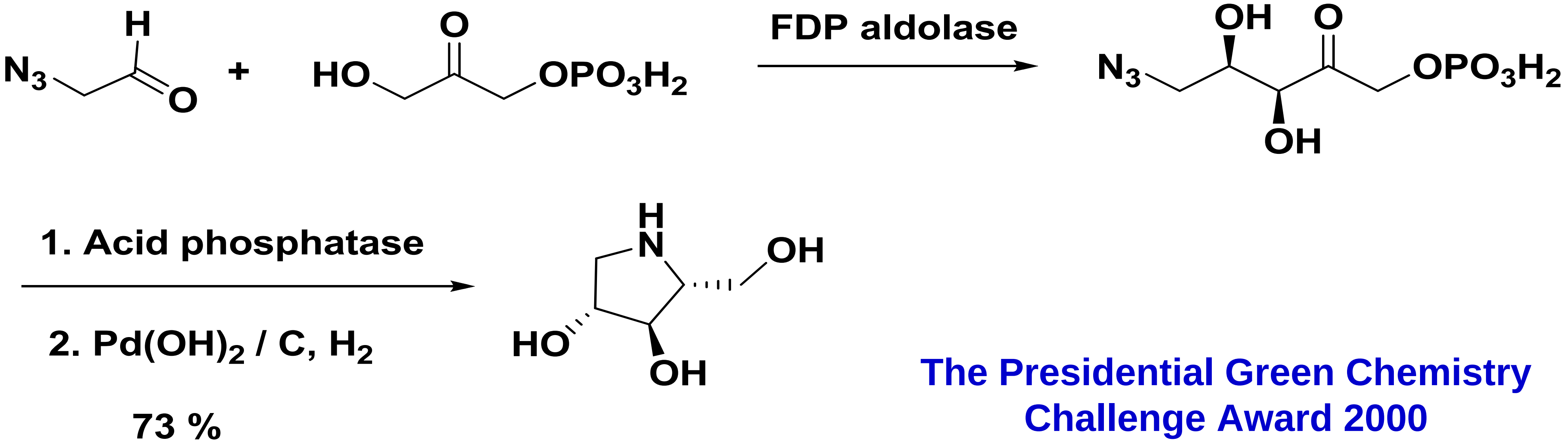
R. Chinchilla, P. Mazon, C. Najera, *Adv. Synth. Catal*.,2004, *346*, 1186-1194;
A. F. Trindade, P. M. P. Gois, C. A. M. Afonso, *Chem. Rev.,* 2009, *109*, 418-514

Industrial Applications of Biocatalysts

Why Biocatalysis….?

- **Mild conditions**
- **Ambient temperature**
- **Pressure and physiological pH**
- **Fewer steps (avoids protection/deprotection steps)**
- **Largely avoids toxic/hazardous reagents & solvents**
- **High chemo-, regio-, and stereoselectivities**

D-Fructose-6-phosphate Aldolase-Catalyzed One-Pot Synthesis of Iminocyclitols

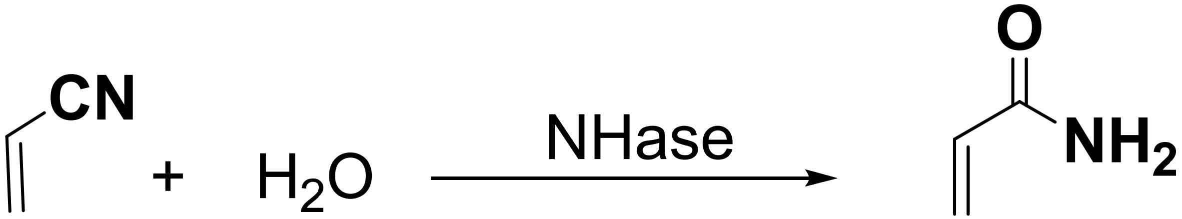


The Presidential Green Chemistry Challenge Award 2000
Academic Award
Enzymes in Large-Scale Organic Synthesis

M. Sugiyama, Z. Hong, P. H. Liang, S. M. Dean, L. J. Whalen, W. A. Greenberg, C. -H. Wong, *J. Am. Chem. Soc.*, 2007, *129*, 14811-14817

Biocatalytic production of Acrylamide

Mitsubishi



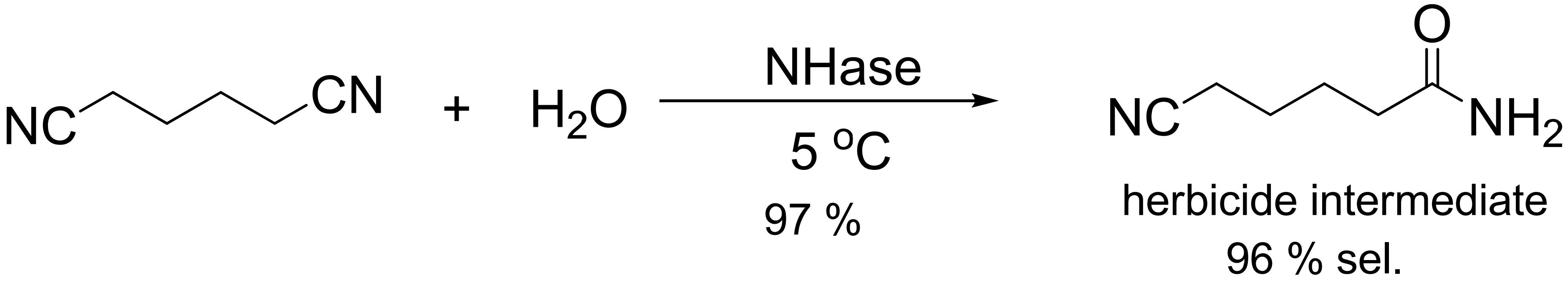
conv. > 99.99 %

sel. 99.99 %

- **100,000 tons per annum and still increasing**
- **Simpler than chemical process (Cu-catalyst)**
- **Immobilized whole cells of *Rh. rhodocrous* J1**
- **Mild conditions (5 °C); no polymerization inhibitor needed**
- **high product quality.**

A. Liese, K. Seelbach, C. Wandrey, *Industrial Biotransformations,* Wiley-VCH, 2000

Biocatalytic Hydrolysis of Nitriles



Immobilized whole cells of *P. chlororaphis* B23

Catalyst consumption 0.006 kg/kg product

Higher conversion/selectivity than chemical process (MnO_2 cat. / 130 °C)

R. Dicosimo et al., *Bioorg. Med. Chem*. 1999, 7. 2239.

Conclusion

Acknoledgements

劉廣定教授
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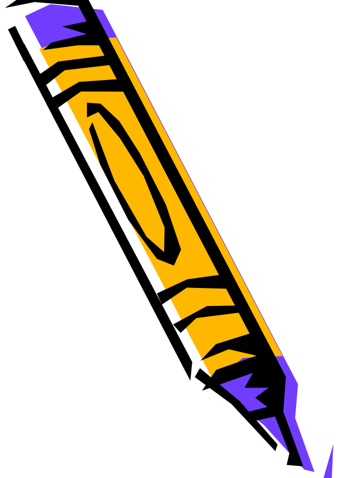
葉名倉教授
陳建添教授
洪伯誠教授



Thank You for Your Attention

敬請指正