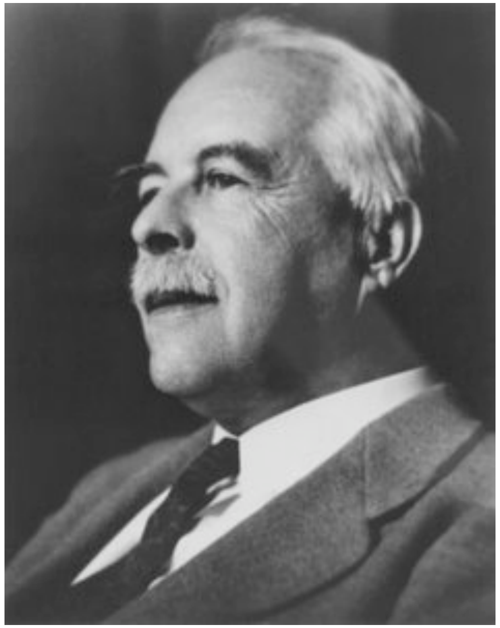
Current Organic Chemistry (year of 2017)

Lewis Acid and Base, Chemistry of Group 13 Element

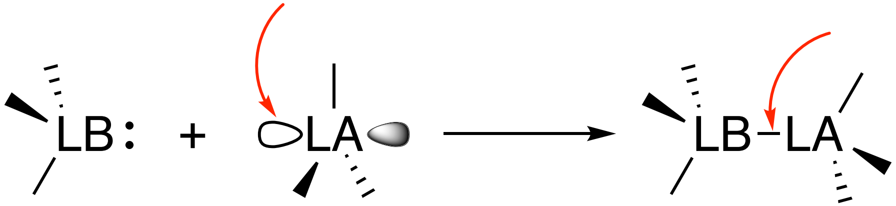
May 30, 2017, #8, Makoto Yamashita (room 1031)
makoto@oec.chembio.nagoya-u.ac.jp

Lewis Acid and Base

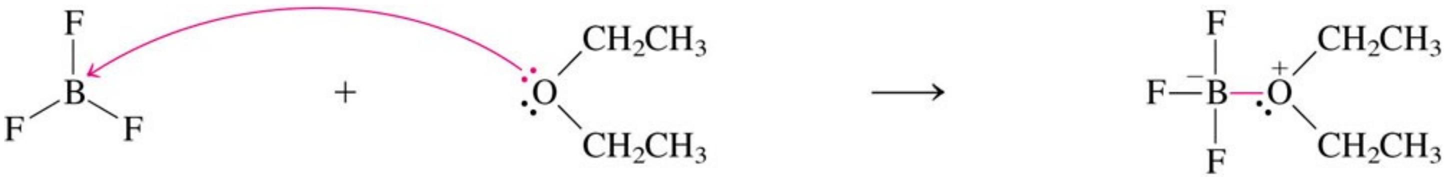
Lewis acid:
Lewis base:



Gilbert Lewis
“Octet rule”



Lewis base Lewis acid Lewis acid-base adduct



Lewis, G. N., Valence and the Structure of Atoms and Molecules. Chemical Catalogue Company, Inc.: New York, 1923.

Collecting Literatures

Classification of literatures and their citation format

(1)

(2)

ex. Tsukahara, N.; Asakawa, H.; Lee, K.-H.; Lin, Z.; Yamashita, M., *J. Am. Chem. Soc.* **2017**, *139*, 2593-2596.

name of authors — abbreviated joural name — year — volume — pages

For full-name of journal, google with a word of "abbreviation" and abbreviated journal name

→ *J. Am. Chem. Soc.* = *the Journal of the American Chemical Society* (sometimes further abbreviated as *JACS*)

(3)

place of publisher

ex. Pauling, L., *The Nature of The Chemical Bond*. 3 ed.; Cornell University Press: Ithaca, 1960.

name of author — title of the book (italicized) — edition — name of publisher — published year

name of authors — title of chapter — title of the book (italicized)

ex. Yamashita, M.; Nozaki, K., Boryl Anions. In *Synthesis and Application of Organoboron Compounds*, Fernández, E.; Whiting, A., Eds. Springer International Publishing: 2015; pp 1-37.

name of editors — name of publisher — published year — page of chapter

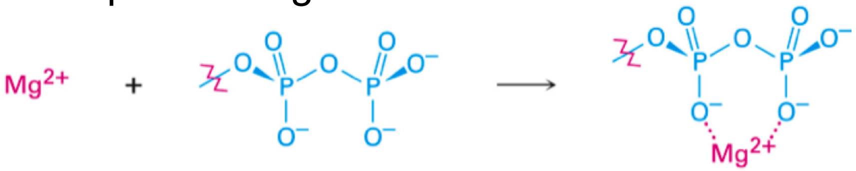
How to find the paper

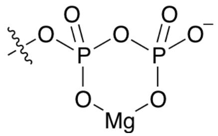
(1) go to http://sfx.nul.nagoya-u.ac.jp/nagoya/az/?lang=eng on browser of your PC
(2) type the journal name into the textbox of "title" and hit "Go"
(3) you will find the title of the journal on the bottom, then click it
(4) type year, vol, and start page, then hit "go"
(5) click PDF in somewhere of the website

Examples of Lewis Acids & Bases

Lewis acids

metals possessing vacant orbitals





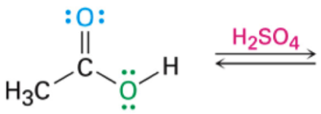
can also be drawn with
O-Mg covalent bond
(no formal charge)

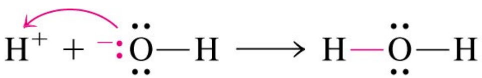
group 13 element compounds

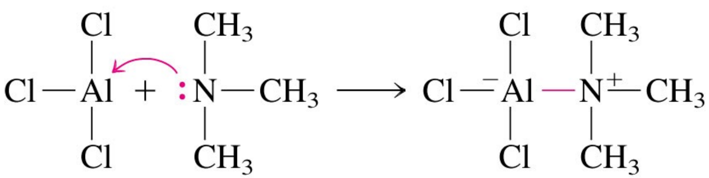
heavy main group element compounds
possessing a low-energy σ* orbital

Lewis bases

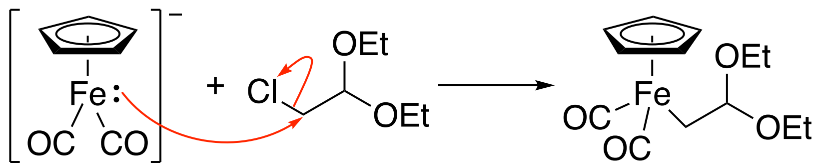
heteroatoms having lone pair(s)







transition metals having a filled d-orbital



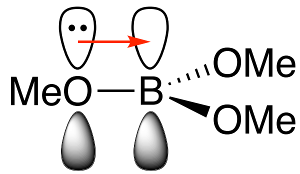
Org. Synth. **1988,** 66, 95.

Strength of Lewis Acids

Donation of π-electron weakens Lewis acidity

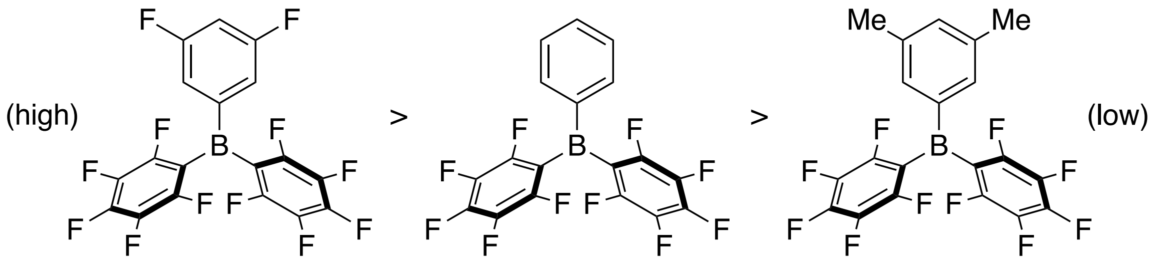
Lewis acidity of boron compounds

(high) BPh_3 > $B(OMe)_3$ > $B(NMe_2)_3$ (low)



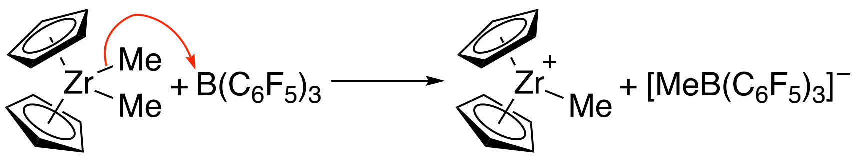
Enhancement of Lewis acidity by electron-withdrawing groups

Lewis acidity of boron compounds

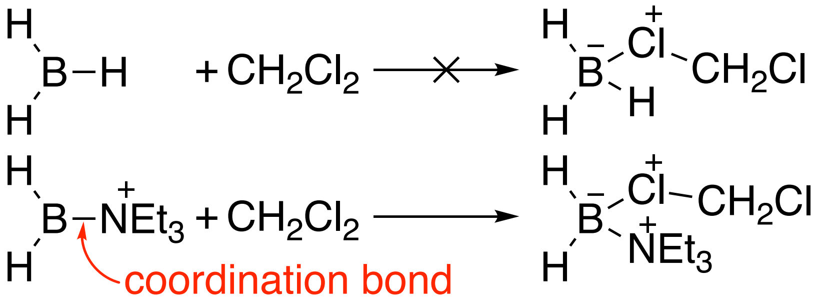


JACS **1998,** *120*, 1772.

application of strong Lewis acid

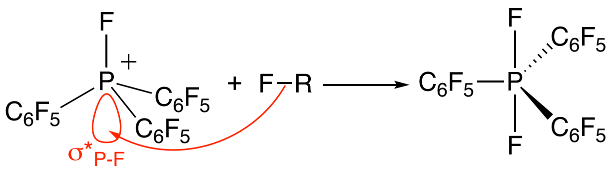


Enhancement of Lewis acidity by formal positive charge



cationic boron binds
a lone pair of CH_2Cl_2

application of strong Lewis acid



Science **2013,** *341*, 1374.

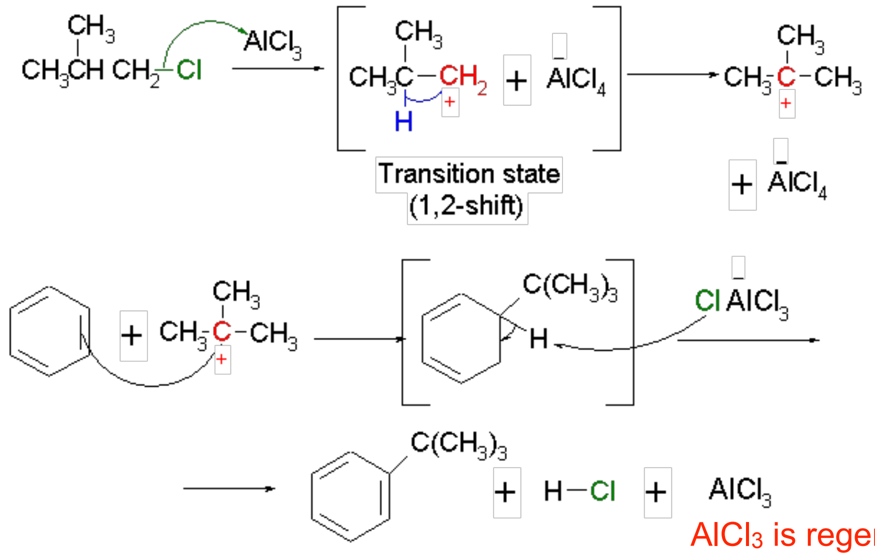
fluorophosphonium could absorb fluoride
even from alkyl fluoride to form alkyl cation

homework (1):
Design your own Lewis acid
having cationic charge and draw its structure

Lewis Acid Catalyst (1)

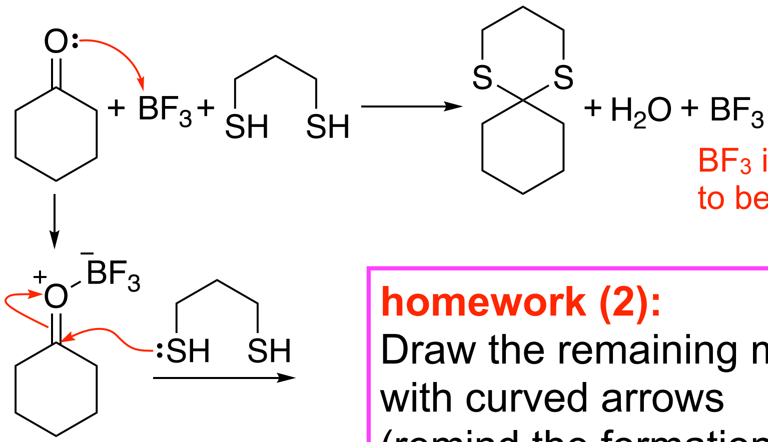
Basic concept:

remind Friedel-Crafts alkylation



AlCl₃ is regenerated
to be used as catalyst

coordination of carbonyl to Lewis acid
to enhance the reactivity

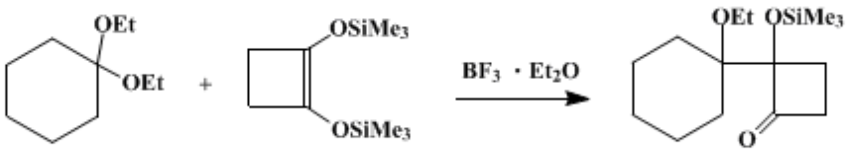


BF_3 is regenerated
to be used as catalyst

homework (2):
Draw the remaining mechanism
with curved arrows
(remind the formation of acetal)

Application

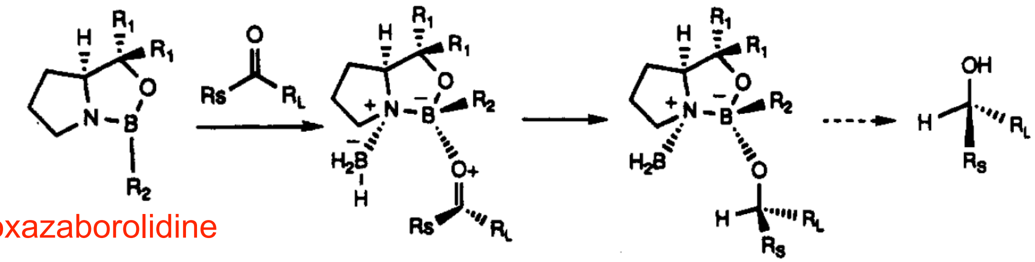
(1) Mukaiyama aldol reaction



Organic Syntheses, **1993,** *Coll. Vol. 8,* 578.

BF_3 absorbes OEt anion to form
an oxonium intermediate

(2) CBS (Corey-Bakshi-Shibata) reduction



oxazaborolidine

JACS **1987**, *109*, 5551.

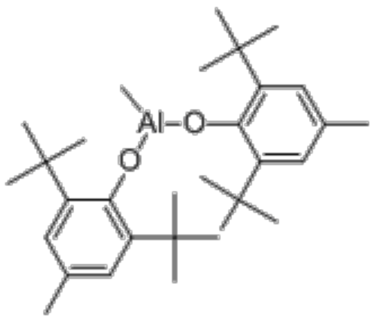
Double activation:
(a) N to BH_3, (b) carbonyl to B

Stoichiometric amount of borane (BH_3)
+ catalytic amount of oxazaborolidine

Lewis Acid Catalyst (2)

Application

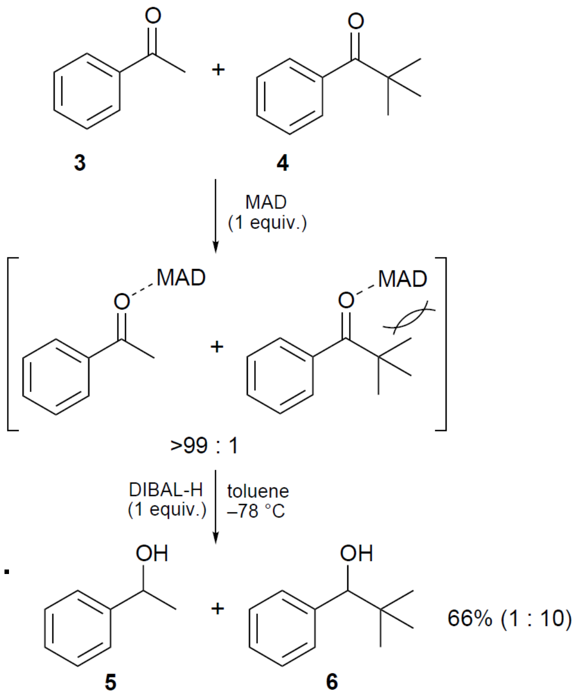
Chemoselective reduction



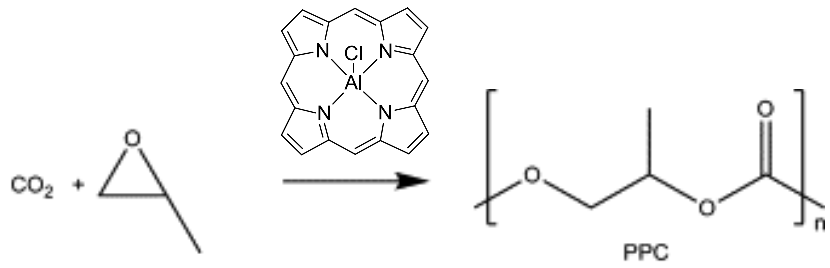
MAD: methylaluminium bis(2,6-di-*tert*-butyl-4-methylphenoxide)

"bulky" Lewis acid

JACS **1988,** *110,* 2650.



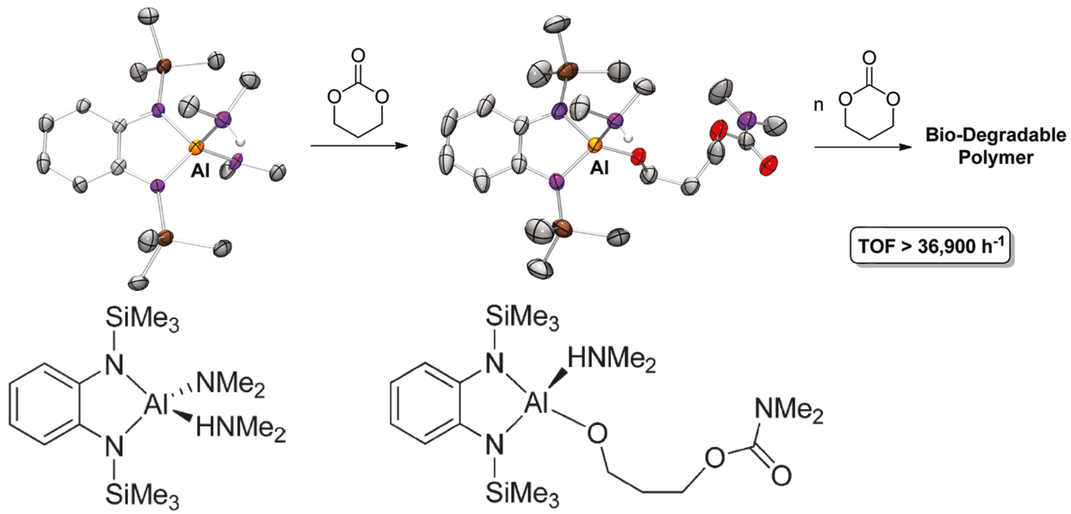
Ring-opening alternating co-polymerization of epoxide and CO_2 to produce biodegradable polymer



polymer from CO_2
recently industrialized

Makromol. Chem. **1969,** *130*, 210.

Ring-opening polymerization of cyclic carbonate ester generated from CO_2 to produce biodegradable polymer

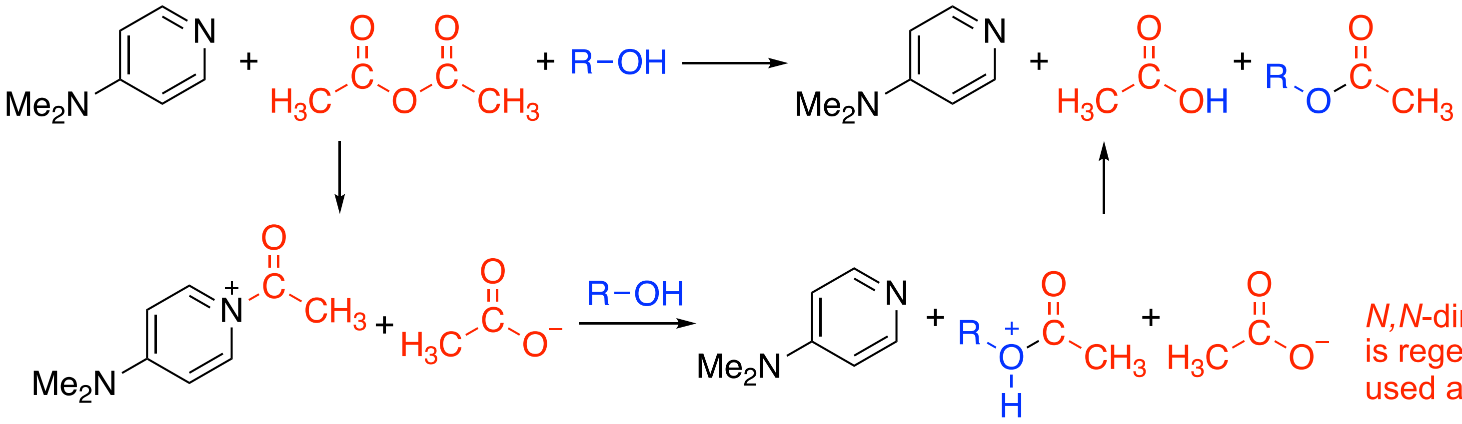


Organometallics **2011,** *30,* 3217.

Lewis Base Catalyst

Basic concept:

acceleration of nucleophilic acyl substitution by cationic charge

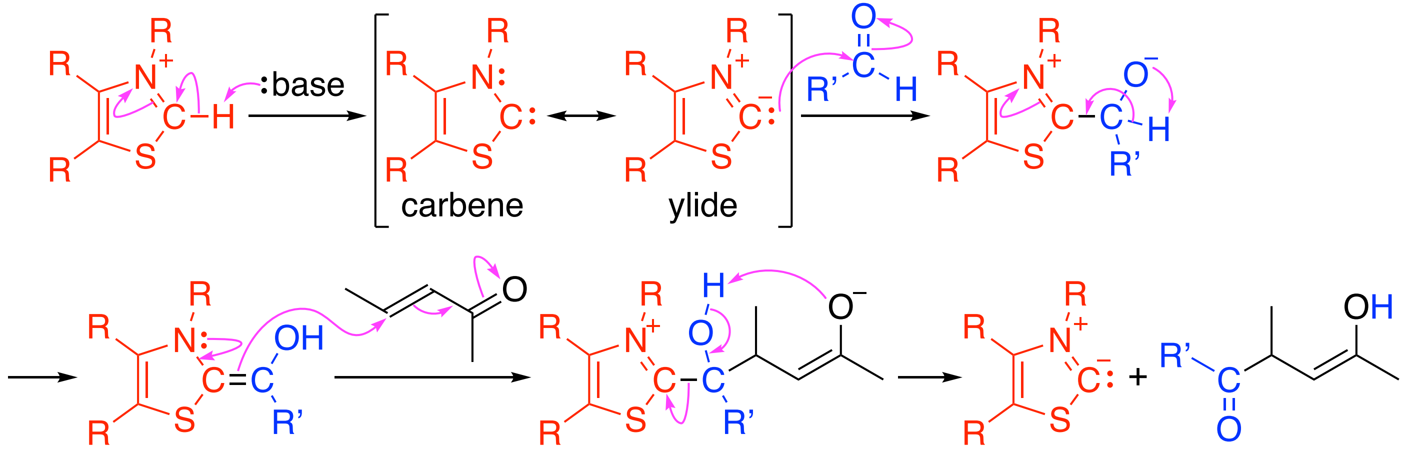


N,N-dimethylpyridine is regenerated to be used as catalyst

homework (3):
Draw resonance hybrid of the first intermediate with four resonance structures

Application

Stetter reaction by using nucleophilic carbene catalyst: umpolung reaction of aldehyde



aldehyde can be considered as

=

carbene (ylide) is regenerated to be used as catalyst

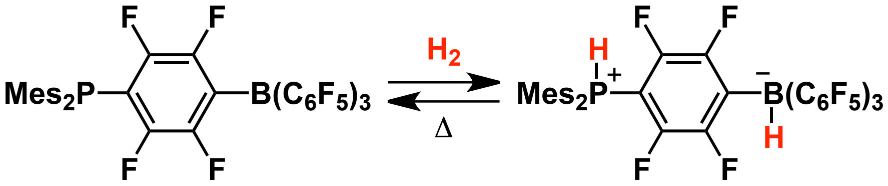
ACIE **1976,** *15,* 639.

Frustrated Lewis Pair (FLP)

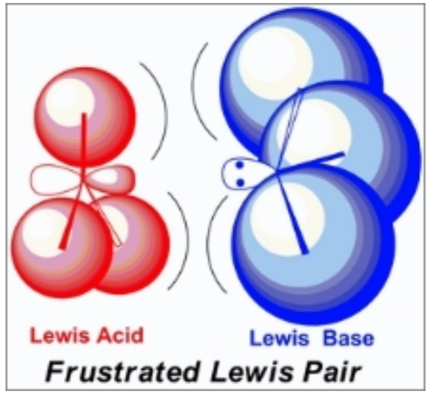
Basic concept:

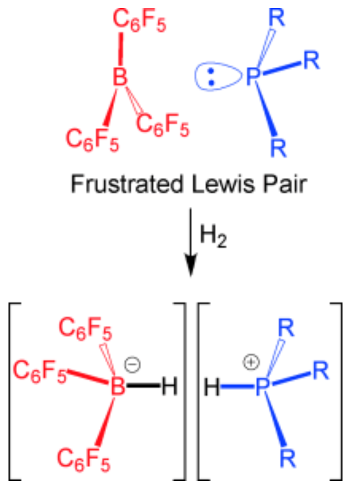
If Lewis acid and base can not form adduct due to steric hindrance,
they show unique reactivity toward organic molecules

heterolytic cleavage of hydrogen



Science **2006,** *314*, 1124.

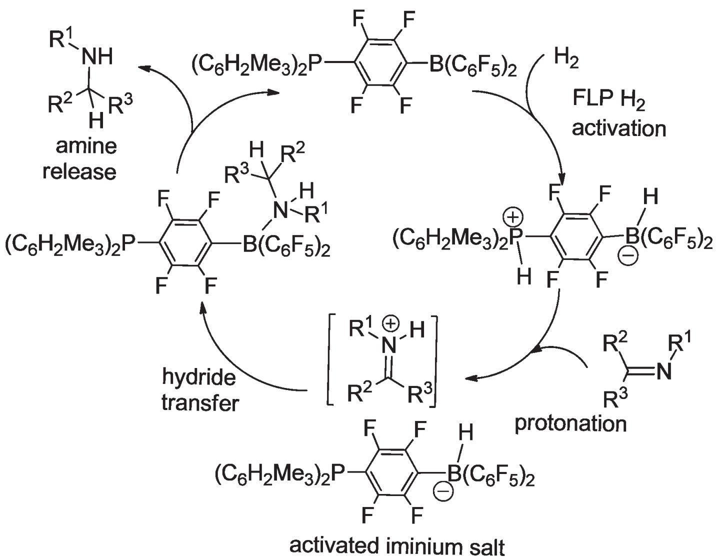




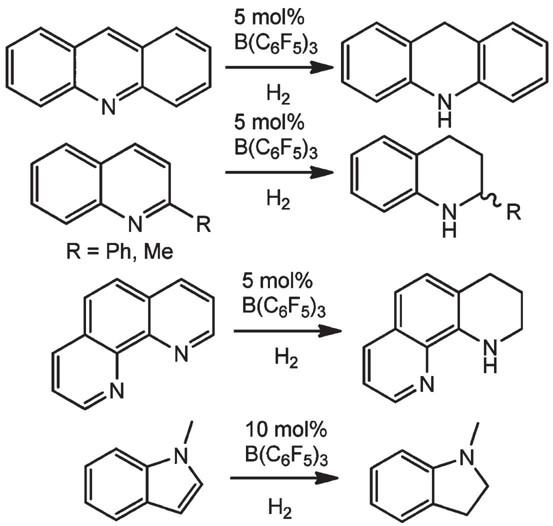
ACIE **2010,** *49*, 46.

Application

Catalytic hydrogenation of imine, nitrile, aziridine, aromatic hydrocarbons, alkenes, and ketones



ACIE **2007,** *46,* 8050.

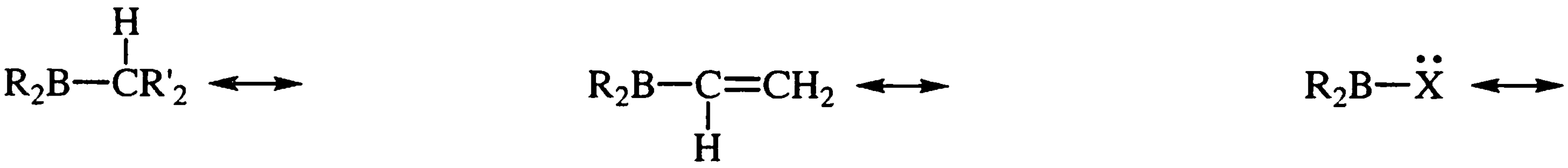


Chem. Commun. **2012,** *48,* 11963.

Prof. Doug Stephan
@U of Toronto, Canada

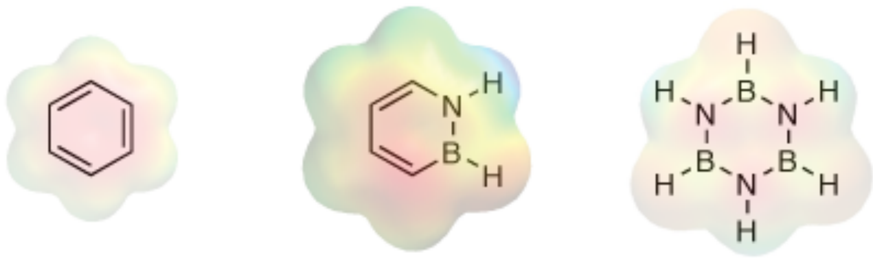
Organic Molecules Containing Group 13 Element

Electronic effect of boryl substituent

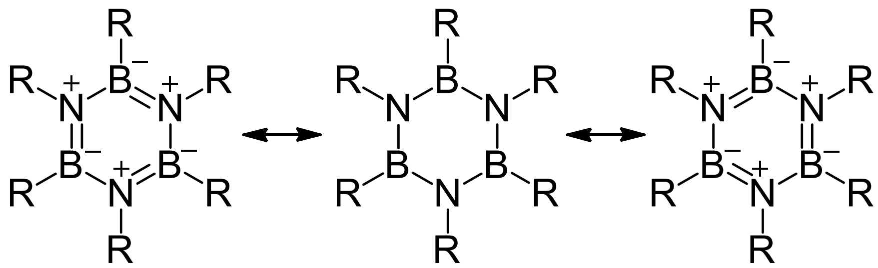


In all cases, a vacant p-orbital of B atom accept an electron pair to form a negatively charged “borate” having four bonds

“Inorganic benzene”: Borazine

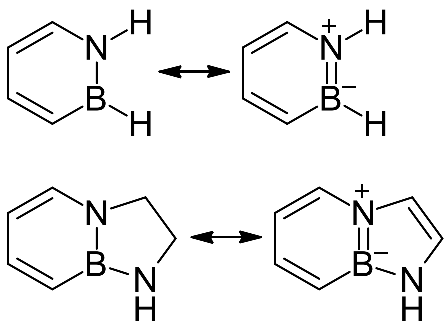


benzene 1,2-dihydro-1,2-azaborine borazine

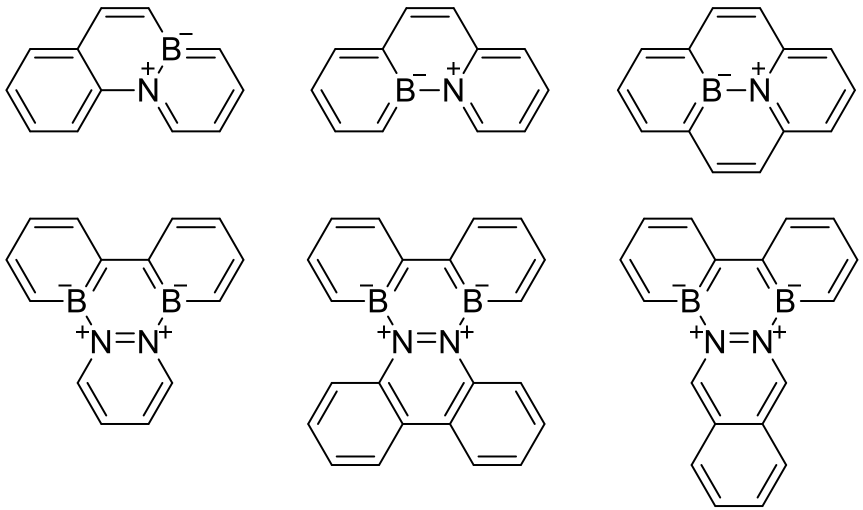


Due to B=N double bond character, borazine is similar to benzene

BN-Containing aromatic molecules



ACIE **2009,** *48,* 973.
JACS **2011,** *133,* 11508.



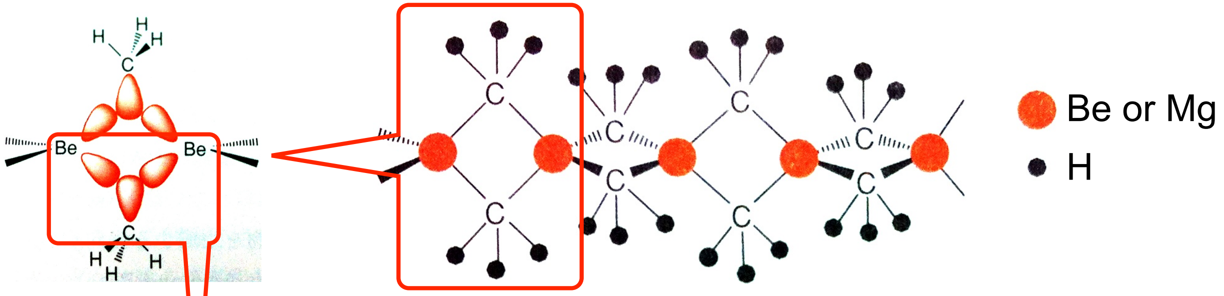
Prof. Warren Piers
@U of Calgary, Canada

general review:
Can. J. Chem. **2009,** *87,* 8.

Polarity of B=N double bond gives unique photophysical properties

3-Center-2-Electron Bond

Structure of $Be(CH_3)_2$

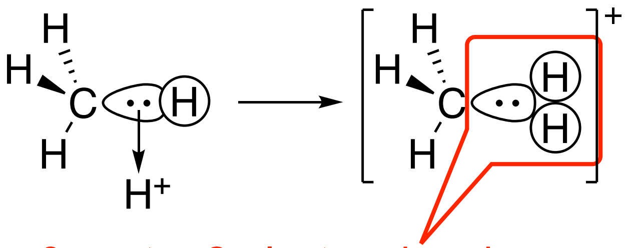


William Lipscomb
Nobel Prize 1976

3-center-2-electron bond

Electron deficient group 1, 2, and 13 element compounds easily aggregate by sharing bonding electrons into vacant orbital(s)

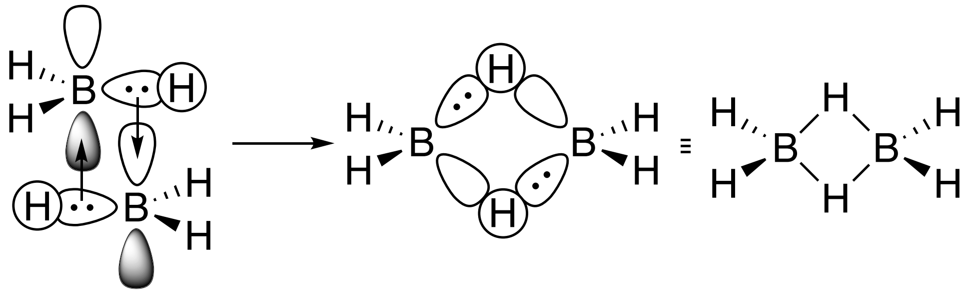
Structures of CH_5^+ and B_2H_6



3-center-2-electron bond

Important intermediate in acid-catalyzed cracking process of oil

George Olah
Nobel Prize 1994



hydride (H^-) reagent in organic synthesis

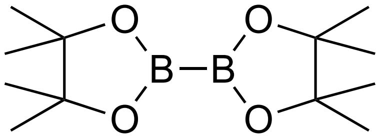
homework (4):
Draw the structure of $(AlMe_3)_2$ with 3c-2e bond with description of orbitals and electrons

Diborane(4): Strong Lewis Acid & Reductant

B–B bond in diborane(4)

diborane(6) diborane(4)

Cf. Nomenclature of Inorganic Chemistry
IUPAC Recommendations 2005

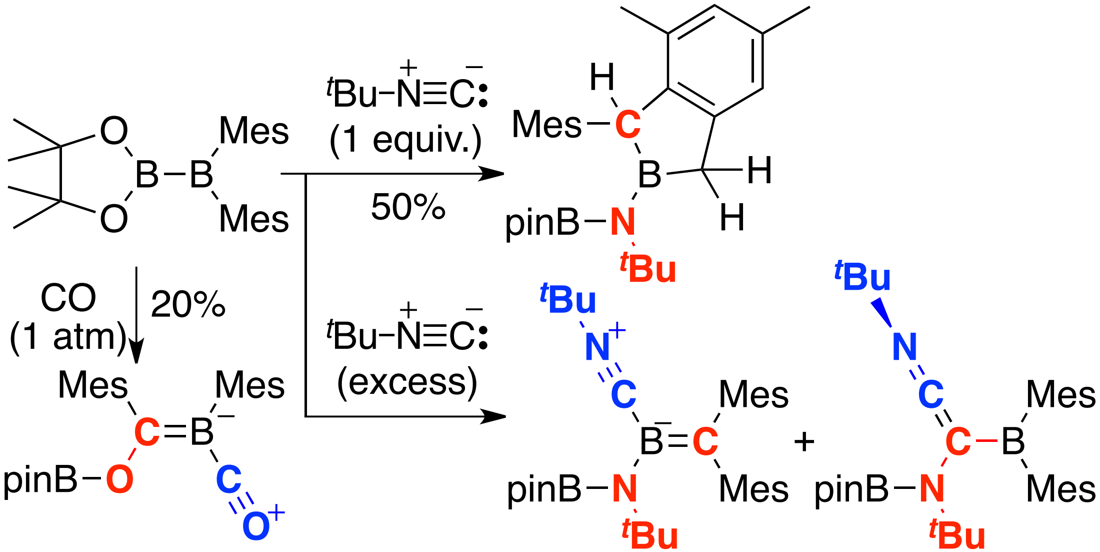


B_2pin_2 **1**

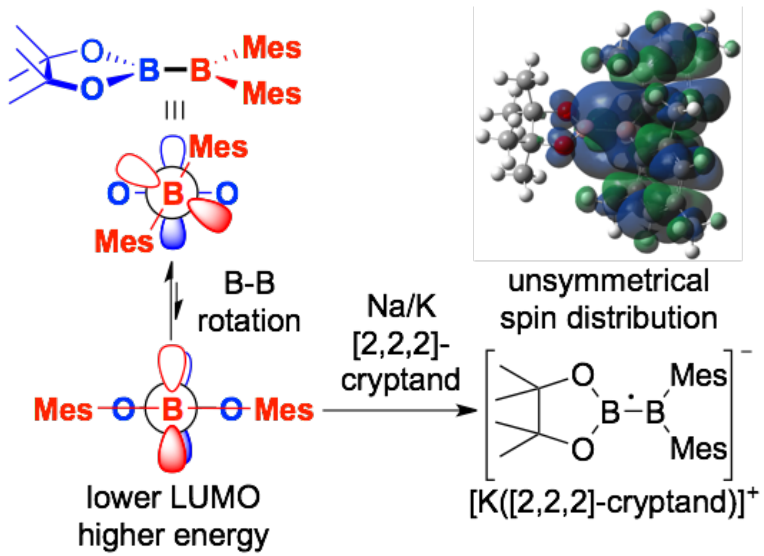
	bond length (Å)	BDE (kJ/mol)
B–B	1.75	293
B–C	1.65	372
B–O	1.36	536

J. Emsley, *The Elements*, 3rd ed.,
Oxford University Press, New York, **1998**.

Diborane(4) can reduce C≡N triple bond



The unsymmetrical diborane(4) compound reacted
with isocyanide to cleave C≡N triple bond

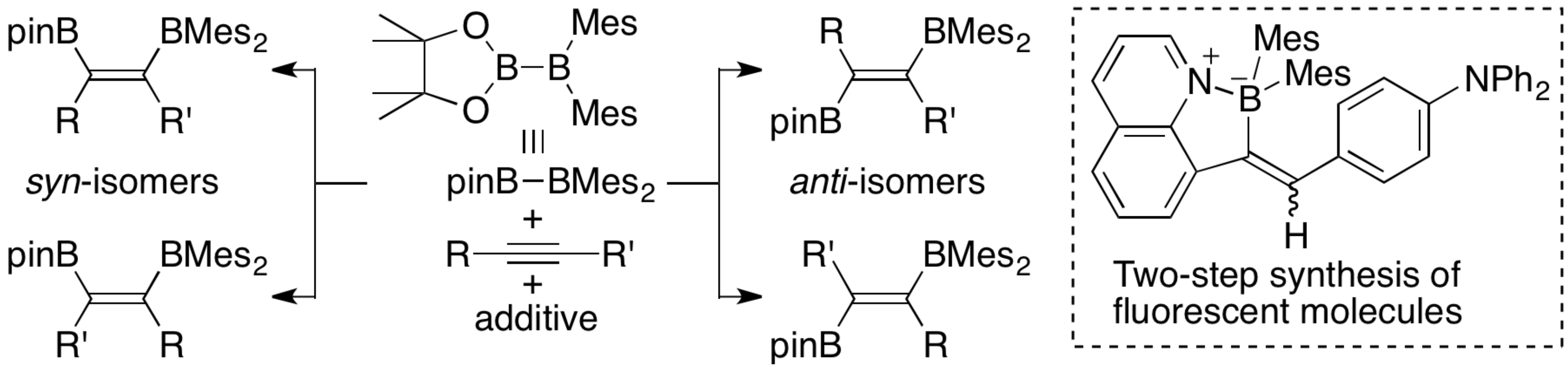


overlapping of two vacant orbitals
lead to higher Lewis acidity

Asakawa, H.; Lee, K.-H.; Lin, Z.; Yamashita, M., *Nat. Commun.* **2014,** *5*, 4245.
Asakawa, H.; Lee, K.-H.; Furukawa, K.; Lin, Z.; Yamashita, M., *Chem. Eur. J.* **2015,** *21*, 4267.

Diborane(4): Strong Lewis Acid & Reductant

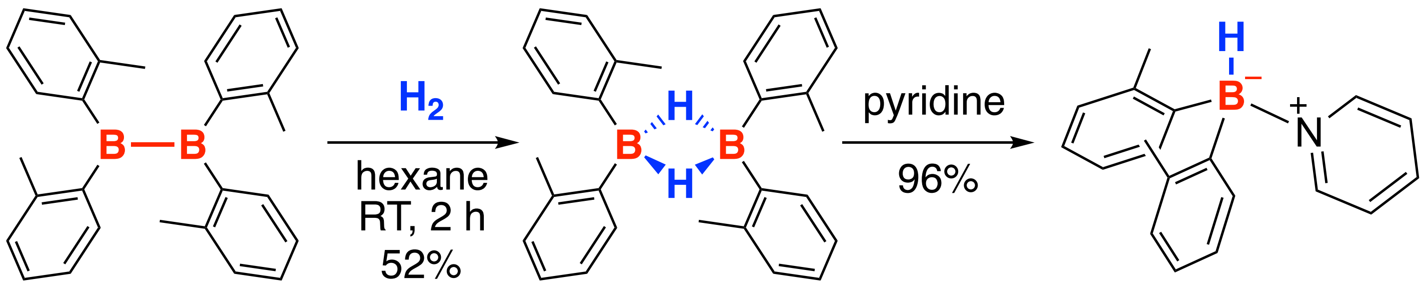
Highly Lewis acidic diborane(4) reacted with alkyne



Direct diboration of alkyne with controlled selectivity

Kojima, C.; Lee, K.-H.; Lin, Z.; Yamashita, M., *J. Am. Chem. Soc.* **2016,** *138,* 6662.

Further higher Lewis acidity leads direct reaction with H_2



The first example of direct metathesis between B–B and H–H bonds
H–H bond was reduced by reductive B–B bond

Tsukahara, N.; Asakawa, H.; Lee, K.-H.; Lin, Z.; Yamashita, M., *J. Am. Chem. Soc.* **2017,** *139*, 2593.

Boron Clusters *via* Accumulation of 3c-2e Bonds

Wade rule: Nomenclature for cluster compounds

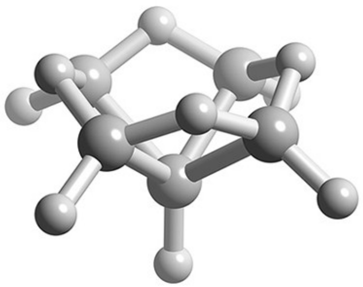
Kenneth Wade

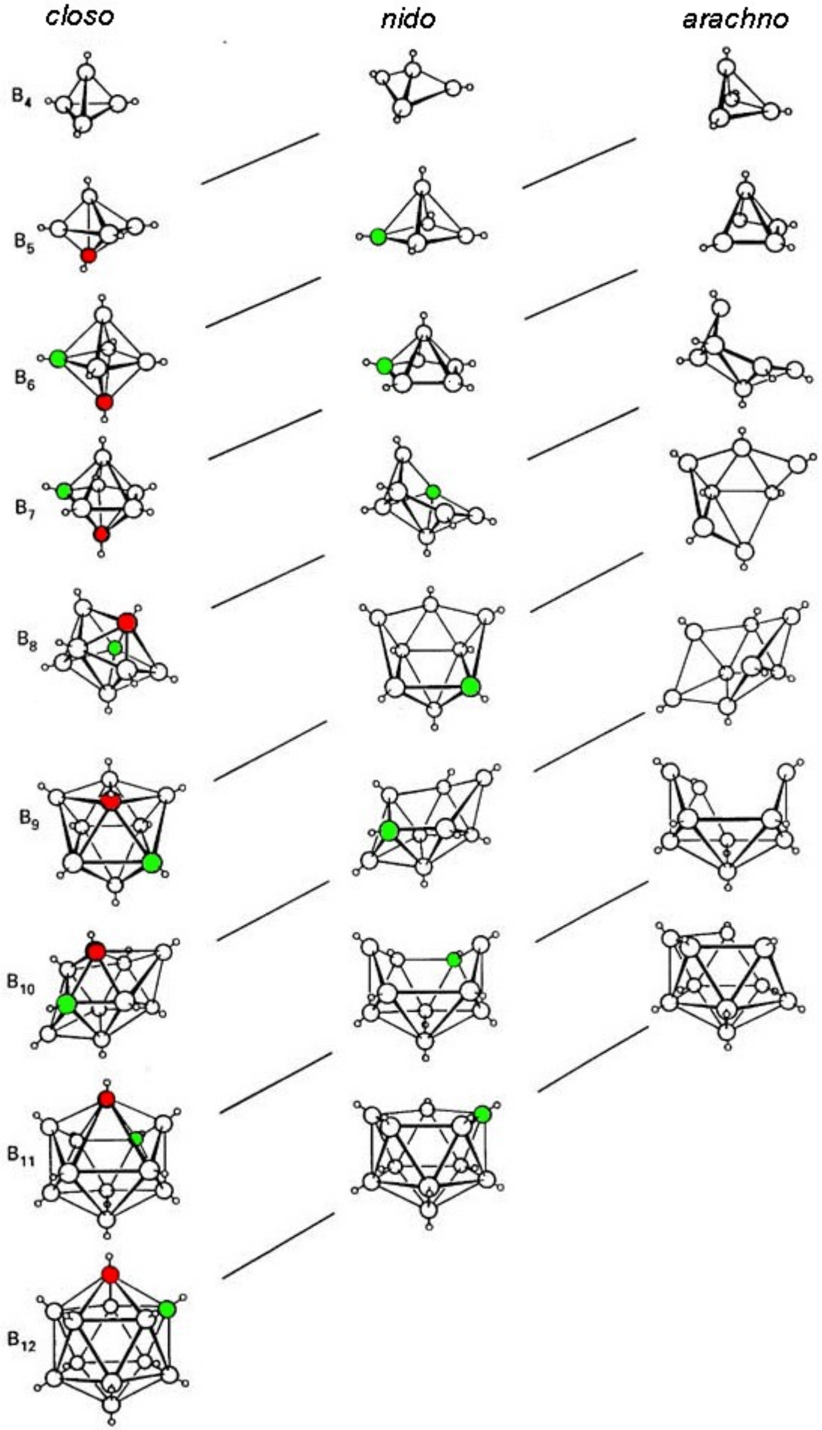
Accumulation of

Counting in Wade rule

(1) counting all electrons from formula of the cluster
ex. B: 3, H: 1, charges change the # of electrons
(2) SEP (skeletal electron pair) is defined as
[(total electrons) – 2×(B-H unit)]/2
(3) all borane clusters can be classified by
n = SEP – (# of B atoms)
n = 1: *closo*-, *n* = 2: *nido*-, *n* = 3: *arachno*-
(4) determining the # of vertices
closo-, SEP–1; *nido*-, SEP–2; *arachno*-, SEP–3
(5) # of vertices can give the structure

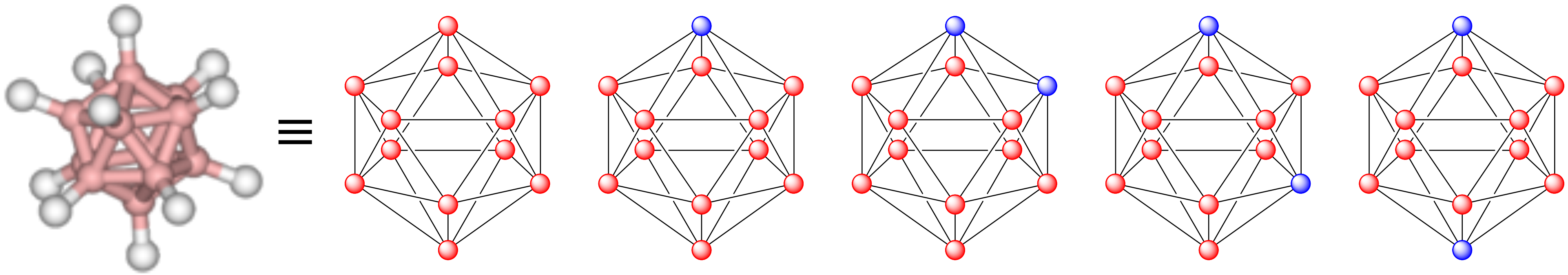
ex. B_5H_9
all electrons = 5 x 3 (B) + 9 x 1 (H) = 24
SEP = [24 – 2×5]2 = 7
n = SEP – 5 = 2, can be considered as *nido*-borane
# of vertices = SEP–2 = 5





Boron Clusters (2)

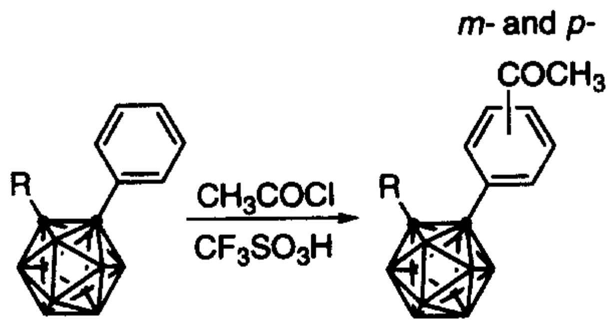
Carborane: carbon-incorporated boron cluster



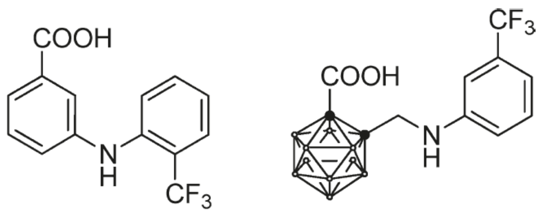
$[B_{12}H_{12}]^{2-}$ $[CB_{11}H_{12}]^{-}$ *ortho*- $[C_2B_{10}H_{12}]$ *meta*- $[C_2B_{10}H_{12}]$ *para*- $[C_2B_{10}H_{12}]$

Applications of carborane

use $[C_2B_{10}H_{12}]$ as a surrogate of benzene ring in medicinal chemistry

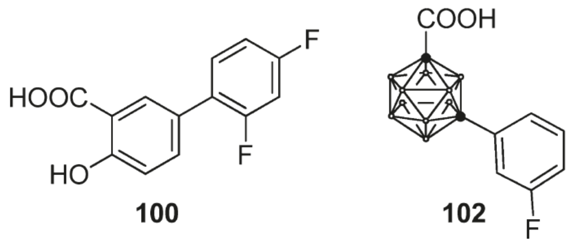


application in pharma (1)



99 **101**

anti-inflammatory

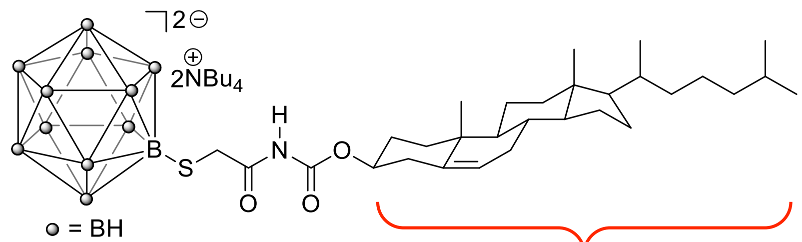


100 **102**

amyloid synthesis inhibitor

application in pharma (2)

BNCT = Boron Neutron Capture Therapy



active for BNCT

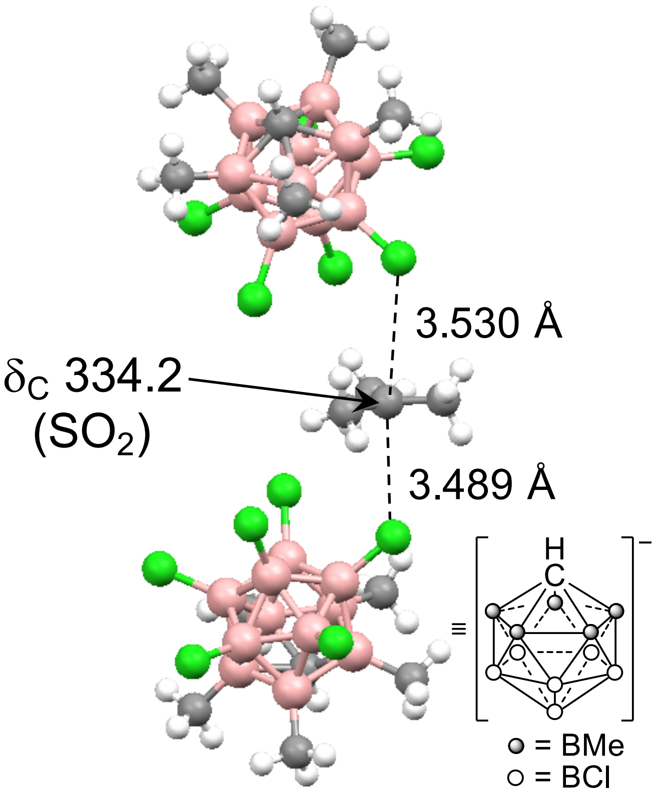
important to concentrate in cancer cells

Boron Clusters (3)

Application of carborane:

$[CB_{11}H_{12}]^-$ can be used as non-coordinating anion to stabilize unstable cation species

(1) X-ray crystallographic analysis of *tert*-Bu cation

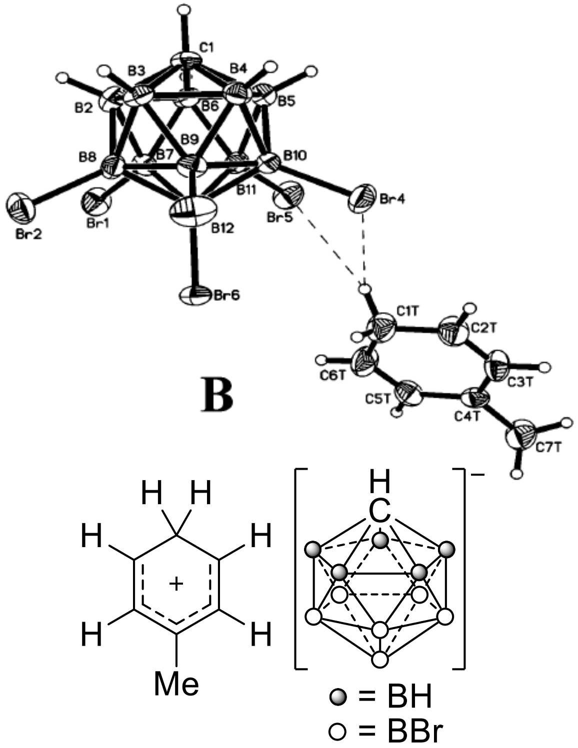


C–CH_3 = 1.429(4)–1.459(4) Å
=
=

ACIE **2004,** *43,* 2908.

Cl interacted with the vacant p-orbital of carbocation
= similar to the transition state of S_N2 reaction

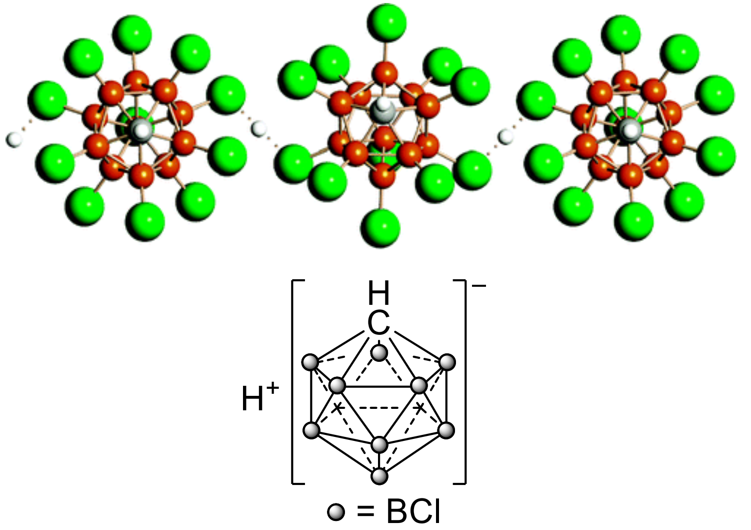
(2) model for Wheland intermediate (S_EAr reaction)



JACS **1972,** *94,* 2034.
JACS **2003,** *125,* 1796.

positions of delocalized cationic charge were identical to the old report for NMR observation

(3) carborane acid: the strongest acid



JACS **2005,** *127,* 7664.
JACS **2006,** *128,* 3160.

(4) application of carborane acid: protonation of C_{60}

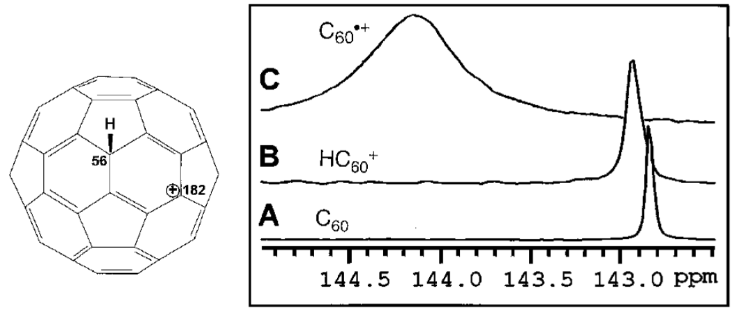
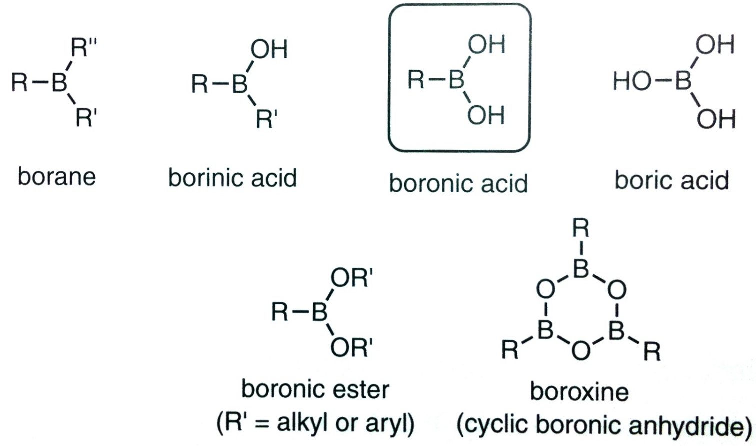


Fig. 4. Solution ^{13}C NMR spectra of (**A**) C_{60} in ODCB, (**B**) HC_{60}^+ in ODCB, and (**C**) $C_{60}^{\bullet+}$ in TCE.

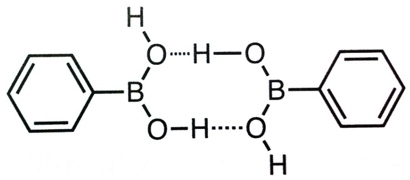
Science **2000,** *289,* 101.

Chemistry of Boronic Acid

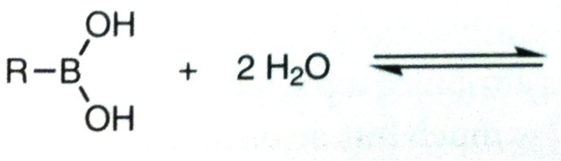
Boronic acid: carbon-substituted boric acid [$B(OH)_3$] derivatives



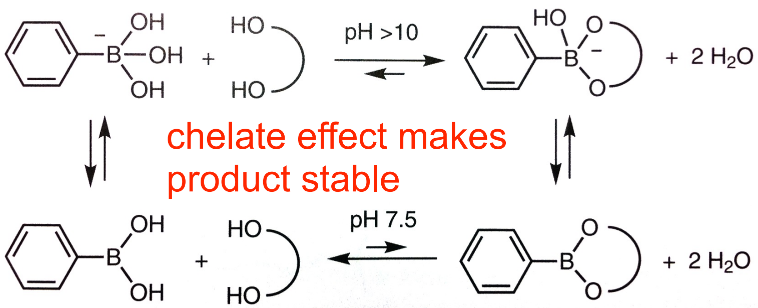
H-bonding dimer



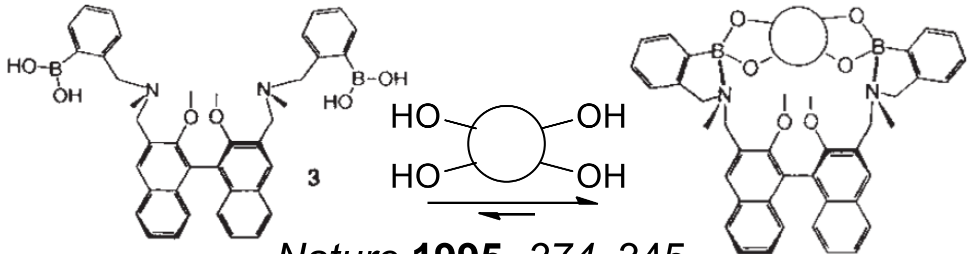
Reaction with H_2O to liberate H^+ (acid)



Fast formation of cyclic ester with diol



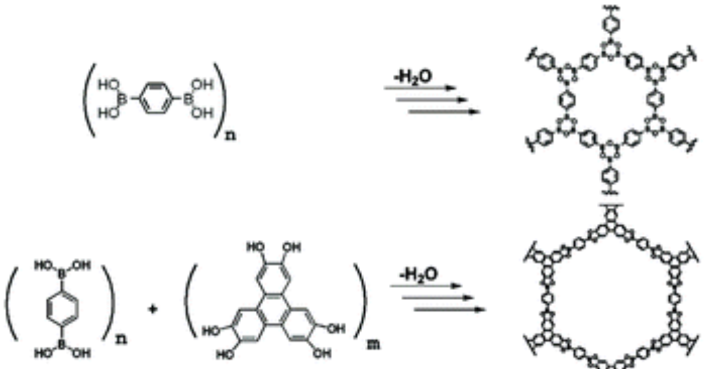
Application of cyclic ester (1): molecular recognition of sugar

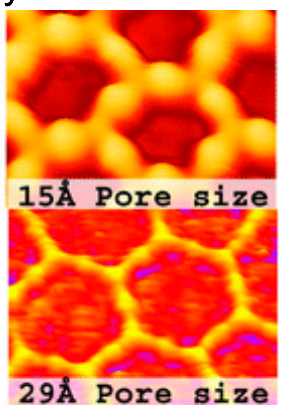


Nature **1995,** *374*, 345.

Formation of a complex with sugar leads fluorescence

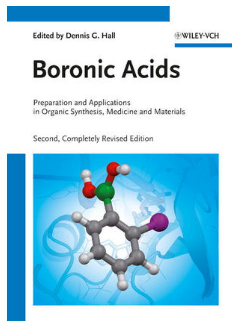
Application of cyclic ester (2): porous polymer





JACS **2008,** *130,* 11872.

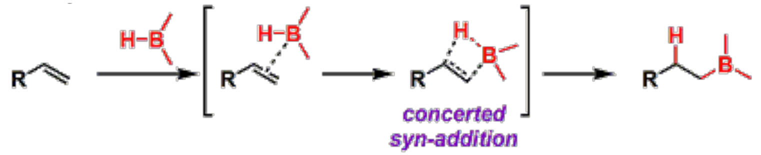
Spontaneous shift of equilibrium
through reversible reactions
Porous material consisting of covalent bonds



Boronic Acids
edited by Deniss G. Hall
Wiley-VCH, 2011

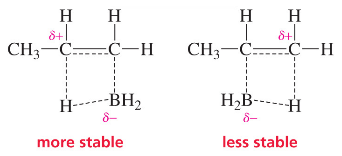
Hydrometallation with Group 13 Element

Hydroboration



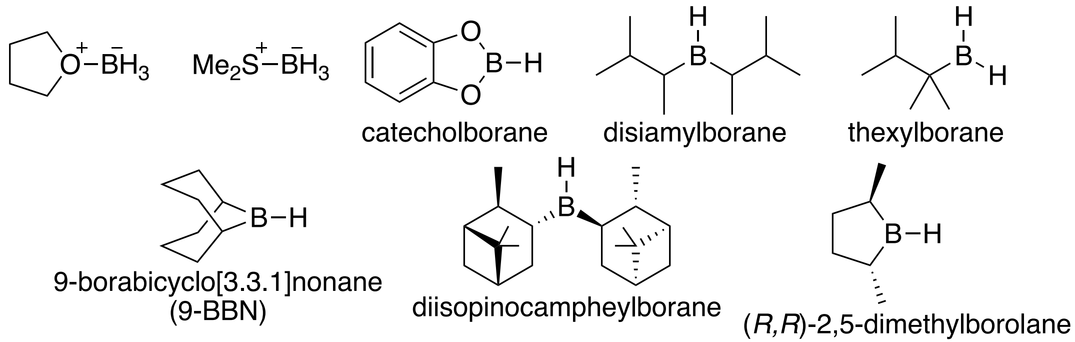
http://www.chem-station.com/odos/2009/06/brown-brown-hydroboration.html

4-centered TS

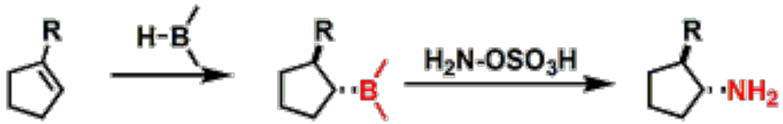


Herbert Brown
Nobel Prize 1979

Representative hydroboration reagents

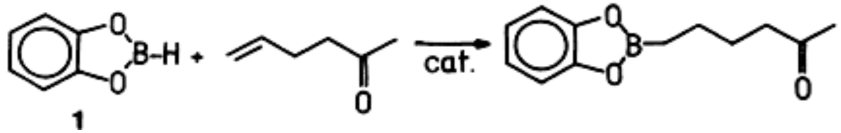


Oxidation of alkylborane



JACS, **1964,** *86,* 3565.

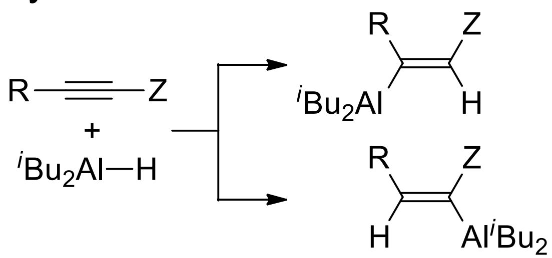
Metal-catalyzed hydroboration



cat = $Rh(PPh_3)_3Cl$
0.05 mol%, 20 min, 83%

ACIE **1985,** *24*, 878.

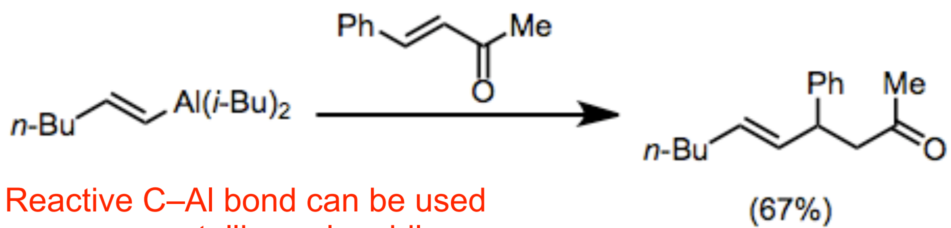
Hydroalumination of alkene



electron-donating groups
= *syn* addition
Z = NR'_2, OR'

electron-withdrawing groups
= *anti* addition
Z = AlR'_2, SiR'_3, GeR'_3, SO_2R'

Reaction of alkenylaluminum



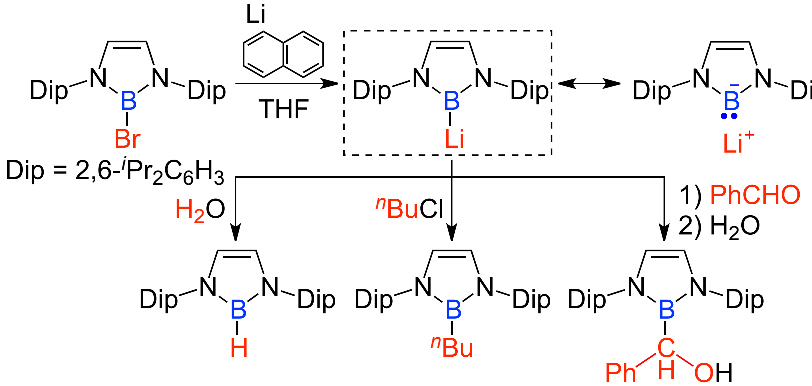
Reactive C–Al bond can be used
as organometallic nucleophile

Can. J. Chem. **1973**, *51*, 2098.

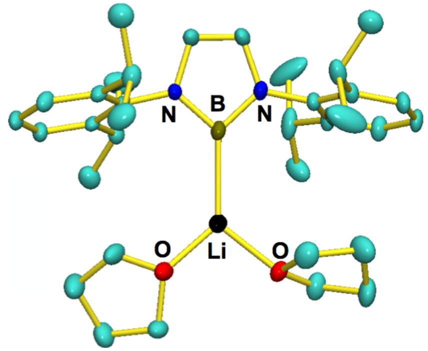
homework (5):
Explain the reason why *anti*-additon product was obtained with electron-withdrawing groups together with the structures of key intermediate (hint: after *syn*-addition, isomerization takes place)

“Lewis Basic” Boron Compounds

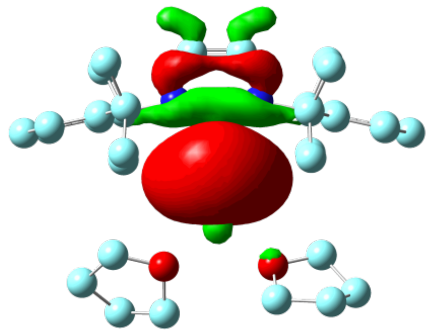
Boron derivative of alkyllithium, “boryllithium”

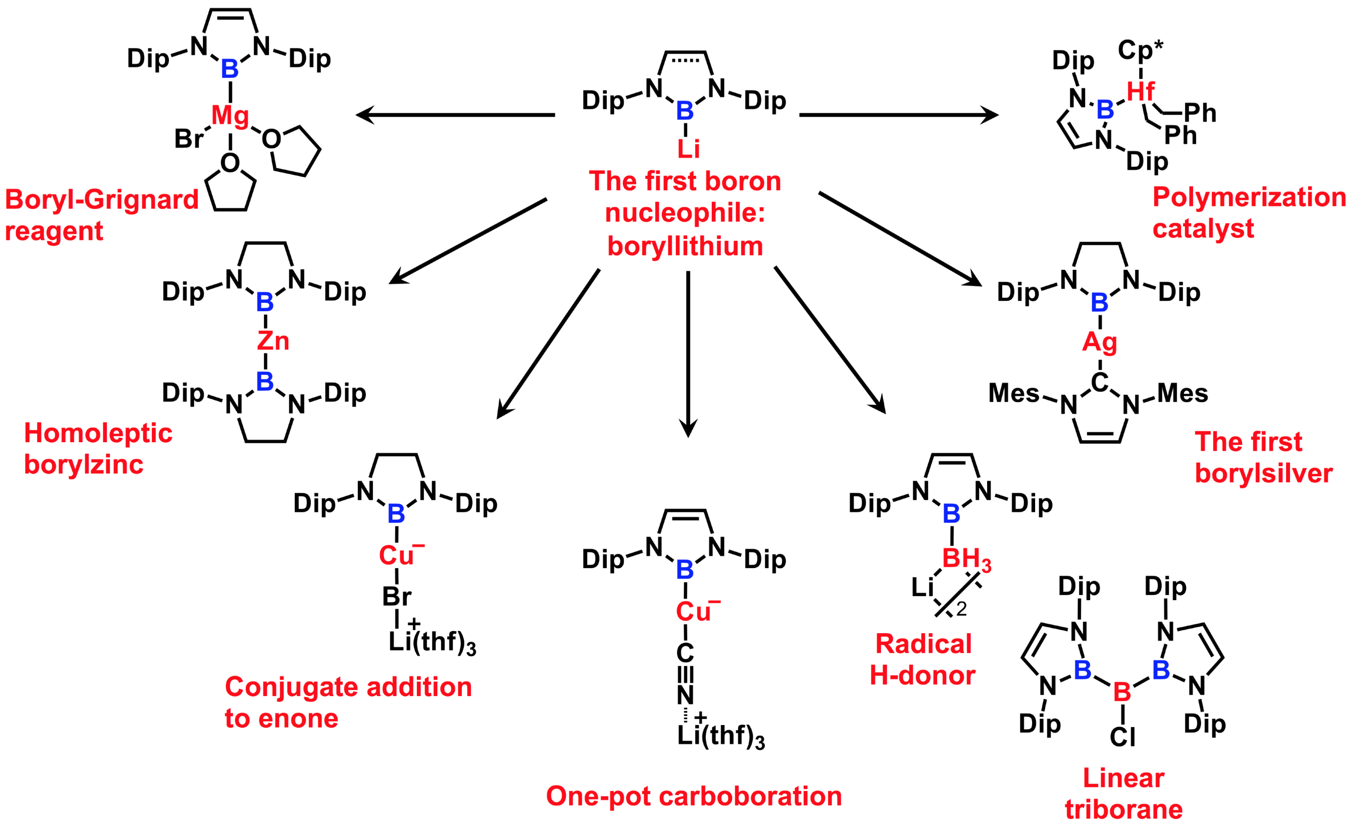


crystal structure



HOMO represents lone pair character





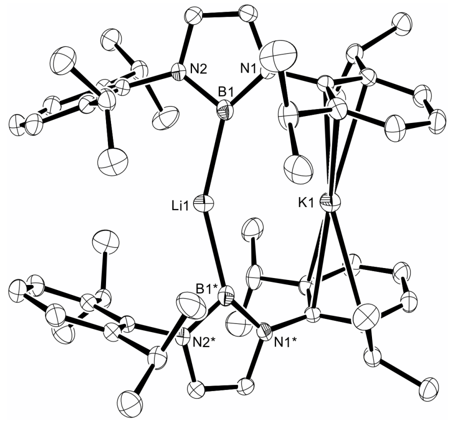
Boryllithium can undergo transmetallation as a “boryl anion”

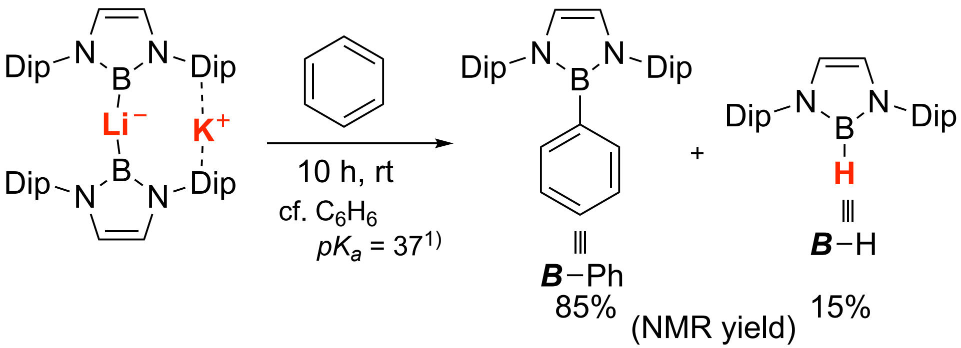
Science **2006,** *314,* 113. *ACIE* **2007,** *46,* 6710. *JACS* **2007,** *129,* 9570. *ACIE* **2008,** *47,* 6606.
JACS **2008,** *130,* 16069. *Chem. Lett.* **2008,** *37,* 802. *JACS* **2009,** *131,* 14162. *JACS* **2010,** *132,* 11449.
Chem. Commun. **2011,** *47,* 5888. *ACIE* **2011,** *50,* 920. *Eur. J. Org. Chem.* **2011,** 3951. *ACIE* **2014,** *53,* 6259.
JACS **2016,** *138,* 3548. *ACIE* **2016,** *55,* 11426. *ACIE* **2016,** *55,* 12827. *ACIE* **2017,** *56,* 1658.

"Lewis Basic" Boron Compounds

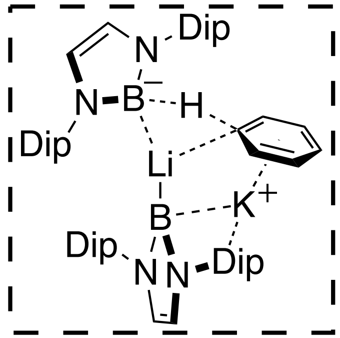
Highly basic boryl anion to deprotonate benzene

crystal structure





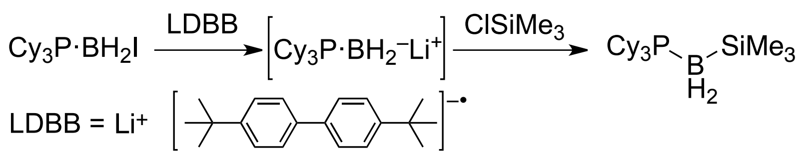
TS for deprotonation (DFT)



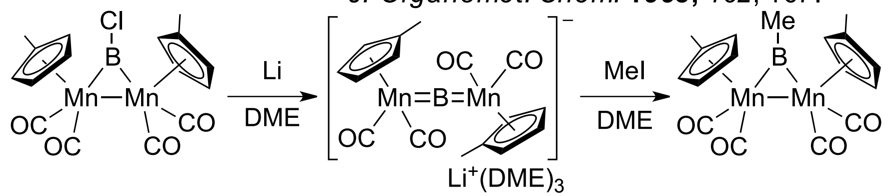
C_6H_6 coordinated to K^+ to enhance acidity of C-H

Ohsato, T.; Okuno, Y.; Ishida, S.; Iwamoto, T.; Lee, K.-H.; Lin, Z.; Yamashita, M.; Nozaki, K., *Angew. Chem. Int. Ed.* **2016,** *55*, 11426-11430.

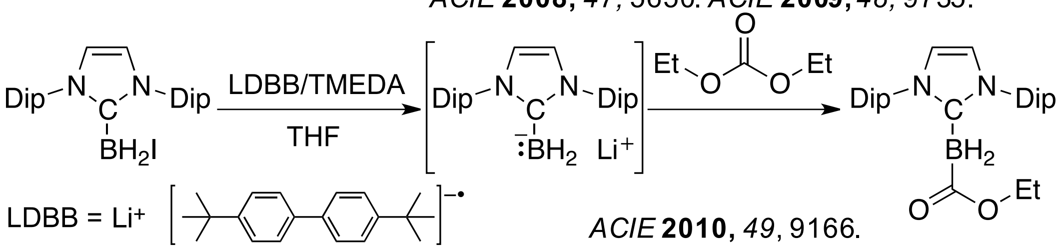
Related "boron nucleophiles"



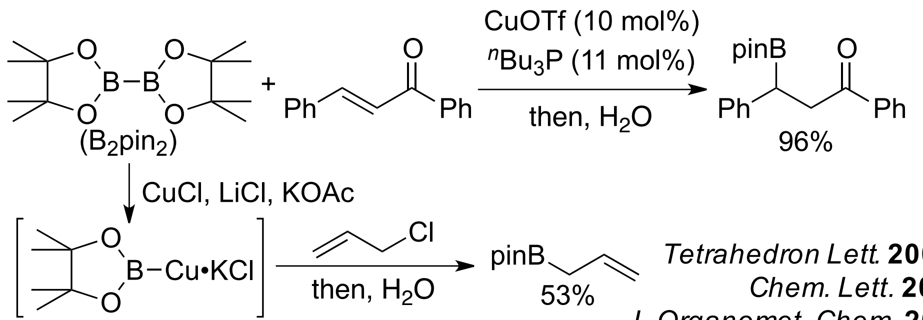
J. Org. Chem. **1994,** *59*, 6753.
J. Organomet. Chem. **1993,** *462*, 107.



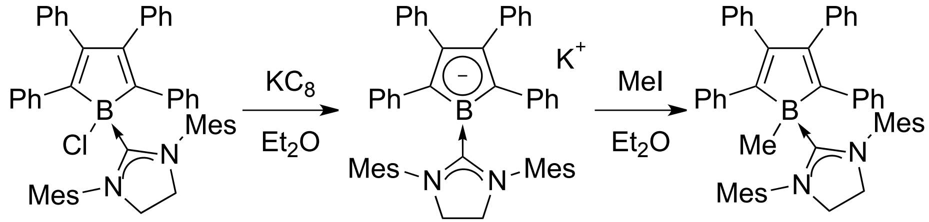
ACIE **2008,** *47,* 5650. *ACIE* **2009,** *48,* 9735.



ACIE **2010,** *49*, 9166.



Tetrahedron Lett. **2000,** *41*, 6821.
Chem. Lett. **2000,** *29*, 982.
J. Organomet. Chem. **2001,** *625*, 47.



ACIE **2010,** *49*, 2041.

About Homework

Solve all the problems [homework (1)-(5)] in this lecture and write down it to an A4 paper
(you can use PC instead of hand-writing)

Do not forget writing your name and student ID number on the report paper

Make a PDF file of the report paper or take a picture of the report paper,
then send it as an attachment file of email to makoto@oec.chembio.nagoya-u.ac.jp

Deadline of homework: June 9 (Fri) 2017, 17:00