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ORGANOBORANES—THE MODERN MIRACLE

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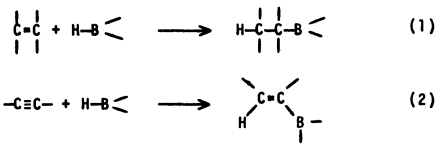
Abstract—Organoboranes, readily available via the hydroboration of unsaturated organic compounds, exhibit a remarkable versatility in their reactions. They offer unusual promise as intermediates for application in organic synthesis.

INTRODUCTION

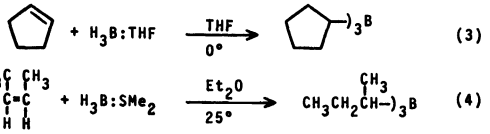
The hydroboration reaction involves the addition of the hydrogen–boron bond to the carbon–carbon double or triple bond, producing the corresponding organoborane (1, 2).[1-3]



(1)

(2)

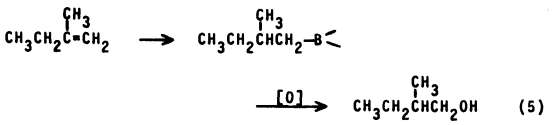
The reaction is essentially quantitative and instantaneous (3, 4).[1-3]



(3)

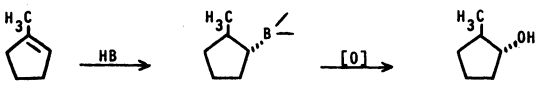
(4)

It proceeds in an anti-Markovnikov manner (5).[1-3]



(5)

The reaction involves a *cis* addition of the H–B bond (6).[1-3]

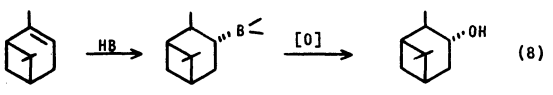


(6)

The addition takes place from the less hindered side of the double bond (7)

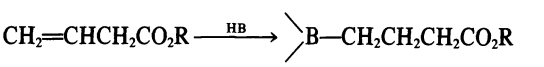
(7)

No rearrangements of the carbon skeleton have been observed, even in the hydroboration of labile olefins, such as α-pinene (8).[1-3]



(8)

Finally, unsaturated compounds containing a wide variety of functional groups can be hydroborated (9).[1-3]



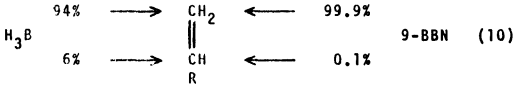
(9)

Consequently, for the first time we are in position to synthesize reactive organometallic intermediates containing such functional groups and to transfer the organic moiety from boron to carbon or other desired element in synthesizing more complex structures.

HYDROBORATING AGENTS

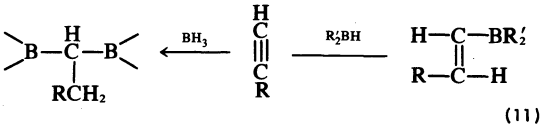
For many purposes it is adequate to carry out the conversion of the unsaturated organic compound to the desired organoborane with the borane-tetrahydrofuran complex (3) or the borane-methyl sulfide complex (4). In other cases, there are advantages in utilizing selected borane derivatives for the hydroboration.[3]

For example, some borane derivatives, such as 9-borabicyclo[3.3.1]nonane (9-BBN), achieve a more favorable distribution in the hydroboration stage (10).[3]



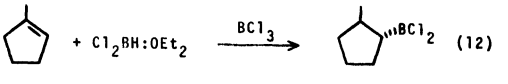
(10)

Others, such as disiamylborane, dicyclohexylborane, and catecholborane, make possible a more selective reaction (11).[3]



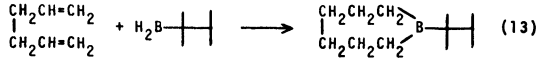
(11)

In still other cases, as in the dichloroborane derivative, the product is a more sterically available, more reactive intermediate (12).[3]



(12)

Monosubstituted boranes, such as thexylborane and monochloroborane-etherate, are valuable in achieving the cyclic hydroboration of dienes (13).[3]



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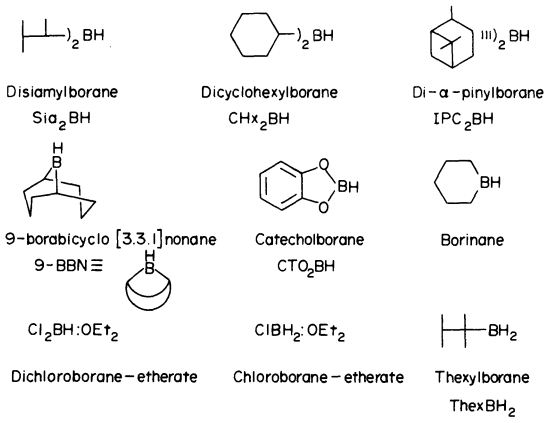


Fig. 1.

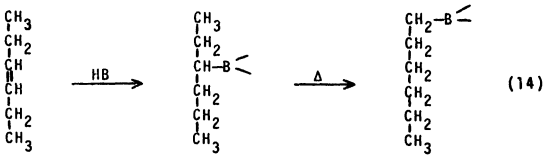
Typical derivatives which have found useful application in organoborane chemistry are summarized in Fig. 1.

THE ORGANOBORANES—FROM A TO Z

In view of the explosion of developments in the organoborane area, it is no longer possible in such a lecture to attempt to present a reasonably complete survey of the field with individual discussion of the various points of special interest. One is faced with the choice of limiting the discussion essentially to a single topic, which can be discussed in depth,[4-6] or to present the broad picture, with little discussion.[7] We have elected this alternative for the present survey.

A. *Isomerization*

At 160° organoboranes readily undergo isomerization involving the movement of the boron atom from an internal position predominantly to a terminal position (14),[8,9] or from a ring position to the side chain (15).[10]



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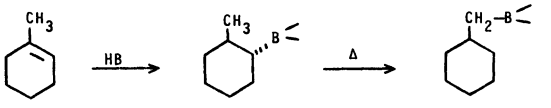


(15)

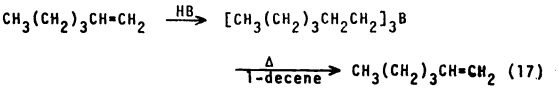
This facile isomerization makes possible some simple syntheses, such as that shown in 16.

The B-alkyl-9-BBN derivatives undergo much slower isomerization. On the other hand, the corresponding monoalkyldicyclohexylboranes exhibit greatly enhanced rates.[11] This suggests that the rates of isomerization of trialkylboranes may be greatly influenced by steric factors, providing a guide to the development of an improved process for such isomerizations.

B. *Displacement*

The mechanism proposed for the isomerization involves a series of eliminations and readditions of H–B⟨, so that the thermodynamic equilibrium is readily established between all of the possible organoboranes. The predominant product is that derivative which places the boron atom at the least hindered position.[1]

Introduction of a second alkene into the reaction mixture results in the capture of the H–B⟨ moiety. By utilizing a less volatile alkene, it becomes possible to distill out the original alkene (17, 18).[8,12]



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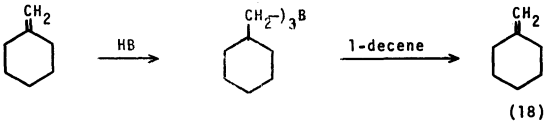
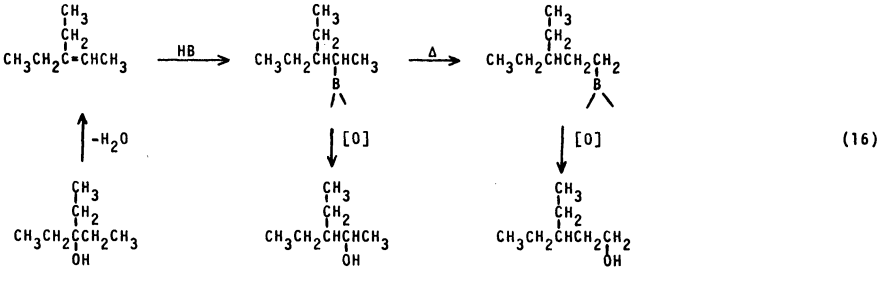


(18)

C. *Contrathermodynamic isomerization of alkenes*

By a combination of hydroboration, isomerization and displacement, it is possible to achieve the contrathermodynamic isomerization of alkenes (19).[13,14]



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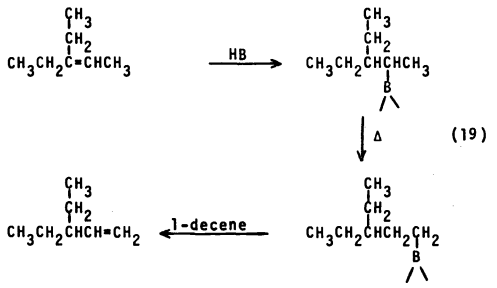
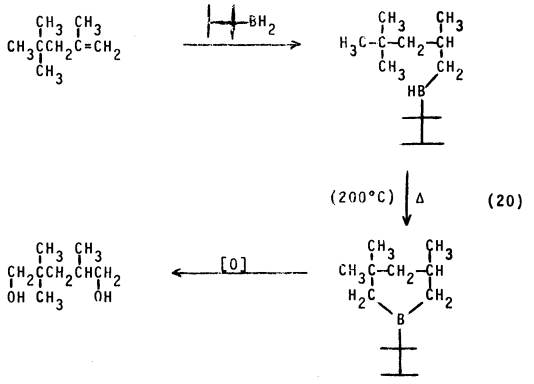


(19)

D. *Cyclization*

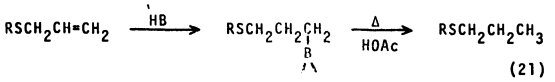
The boron–hydrogen bond of a dialkylborane exhibits a marked tendency to substitute carbon–hydrogen bonds in the 1,5-position, forming cyclic derivatives which can be oxidized to glycols (20).[15]



(20)

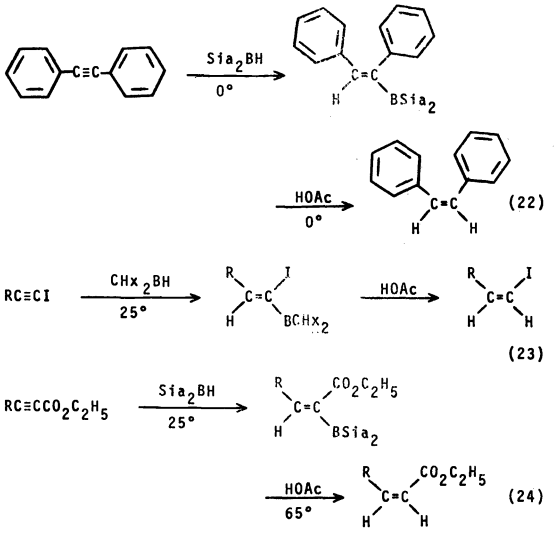
E. *Protonolysis*

Alkylboranes are stable to water, aqueous mineral acids, and aqueous alkalies, but they are readily cleaved by carboxylic acids.[16] This provides a convenient non-catalytic means of hydrogenating double-bonds in compounds where the usual catalytic hydrogenation is difficult (21).[16]



(21)

Vinylboranes undergo protonolysis with particular ease, providing a simple route from acetylenes to the *cis* derivatives (22–24).[17–19]



(22)

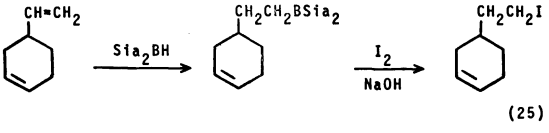
(23)

(24)

As will be discussed later, protonation of certain alkynyl- and alkenyldialkylboranes can proceed with concurrent migration of one or more alkyl groups from boron to carbon (Z).

F. *Halogenolysis*

Organoboranes exhibit a remarkable sluggishness toward rupture of the carbon–carbon bond by direct reaction with halogen. However, in the presence of alkali, reactions such as 25 and 26 proceed readily at 0°.[20,21]



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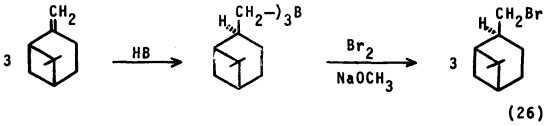
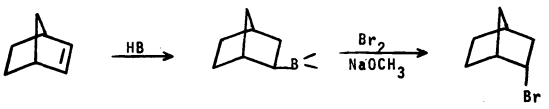


(26)

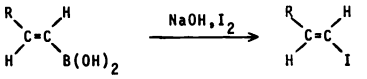
Hydroboration of norbornene gives the *exo* isomer predominantly (7). However, treatment of this organoborane with bromine and sodium methoxide in methanol yields *endo*-norbornyl bromide preferentially (27).[22]



(27)

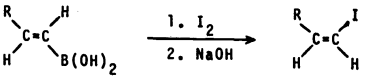
Not only does this procedure provide a convenient route to such bicyclic *endo* bromides (and iodides[23]), which are relatively inaccessible by other methods, but it also raises interesting questions about the mechanism of these base-induced halogenations.

Treatment of the *trans*-alkenylboronic acid with iodine in the presence of sodium hydroxide yields the *trans*-alkenyl iodide (28).[24]



(28)

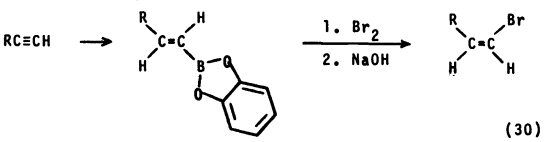
On the other hand, if the boronic acid is first treated with excess iodine (to form the diiodide addition product) and then treated with alkali, the *cis* iodide is formed (29).[25]



(29)

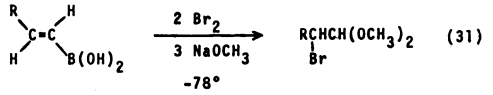
(This reaction is clean for R = straight-chain. Branching of the alkyl group results in the concurrent formation of the trans isomer.)

The *cis* bromides are readily synthesized from the boronic acids or the catecholborane intermediates by treatment with bromine, followed by sodium hydroxide (30).[26]



(30)

Addition of bromine to the alkenylboronic acid in sodium methoxide-methanol at −78° causes the reaction to take a new course, producing the α-bromoacetals in excellent yield (31).[27]



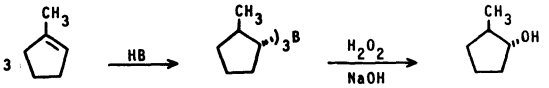
(31)

G. *Oxidation*

a. *Hydrogen peroxide.* Oxidation of organoboranes with hydrogen peroxide in the presence of alkali is essentially quantitative and possesses remarkable specificity for the boron–carbon bond (32).[28]

$$R_3B + 3HO_2H + NaOH \rightarrow 3ROH + NaB(OH)_4 \quad (32)$$

The reaction proceeds with retention of configuration. Consequently, hydroboration followed by *in situ* oxidation by alkaline hydrogen peroxide provides a remarkably simple and convenient procedure for the anti-Markovnikov hydration of double and triple bonds (33, 34).[28].



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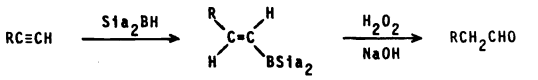
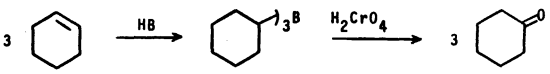


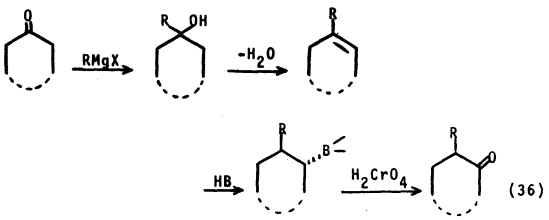
(34)

b. *Chromic acid.* Alicyclic organoboranes are readily oxidized *in situ* by aqueous chromic acid to the corresponding ketones (35).[29]



(35)

The reaction provides the basis for a general synthesis of certain types of ring ketones (36).



(36)

c. *Oxygen.* Oxygen is rapidly absorbed by solutions of organoboranes in tetrahydrofuran. The reaction is readily controlled to yield the diperoxy derivative (37).[30]

$$R_3B + 2O_2 \xrightarrow[-78° \text{ to } 0°]{THF} (RO_2)_2BR \quad (37)$$

To obtain the hydroperoxide, the intermediate is oxidized at 0° with hydrogen peroxide and the hydroperoxide is separated from the alcohol by extraction with base from the tetrahydrofuran solution (38).[30]

$$(RO_2)_2BR + H_2O_2 \xrightarrow[0°]{THF} 2RO_2H + ROH \quad (38)$$

The synthesis of peroxides from organoboranes can also be accomplished from the alkyldichloroborane-etherates (39).[31]

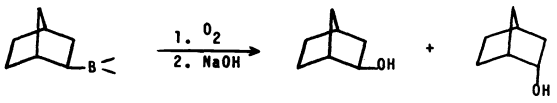
$$RBCl_2:OEt_2 + O_2 \xrightarrow{-18°} RO_2BCl_2 \xrightarrow{H_2O} RO_2H \quad (39)$$

84 to 94%

By limiting the amount of oxygen absorbed by the trialkylborane to the theoretical quantity (1·5 mol of O_2/mol of R_3B), it is possible to achieve an essentially quantitative conversion to the corresponding alcohol (40).[32]

$$R_3B + 1{\cdot}5O_2 \xrightarrow[0°]{THF} (RO_2)_{1.5}BR_{1.5} \xrightarrow[H_2O]{NaOH} 3ROH \quad (40)$$

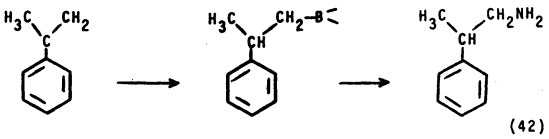
Since the oxidation involves a free radical mechanism,[6] there is some loss of the stereospecificity of the hydroboration stage in cases such as norbornene and 1-methylcyclopentene (41).



(41)

H. *Amination*

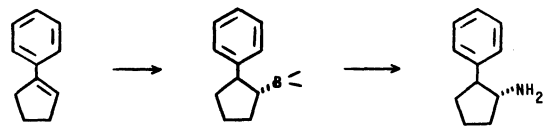
Organoboranes are converted by chloramine, or, preferentially, O-hydroxylaminesulfonic acid, to primary amines (42).[33]



(42)

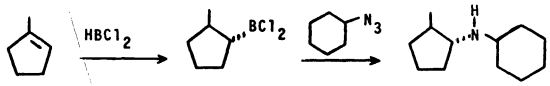
The reaction proceeds with retention of configuration, making it possible to retain the remarkable stereospecificity of the hydroboration reaction (43, 44).

(43)



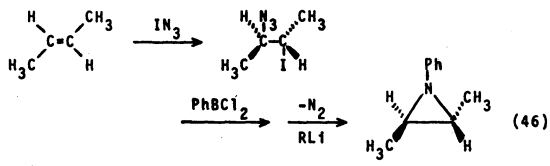
(44)

The reaction of organoazides with organoboranes, preferably the monoorganodichloroboranes, provides a convenient route to secondary amines (45).[34]



(45)

The reaction makes possible a stereospecific synthesis of *N*-alkyl- and *N*-arylaziridines (46).[35]



(46)

Dimethylchloroamine can apparently provide a related route to tertiary amines (47).[36]

$$n\text{-}Bu_3B + (CH_3)_2NCl \rightarrow n\text{-}BuN(CH_3)_2 + n\text{-}Bu_2BCl \quad (47)$$

Unfortunately, the scope of this synthesis has not yet been explored.

I. *Metallation*

In tetrahydrofuran solution, organoboranes from terminal alkenes react with mercuric acetate with remarkable ease at 0° to give the corresponding mercuriacetate (48).[37]

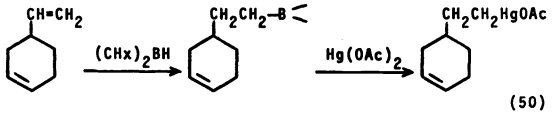
$$CH_2{=}CH(CH_2)_8CO_2R \xrightarrow{HB} CH_2CH_2(CH_2)_8CO_2R \xrightarrow{Hg(OAc)_2} CH_2CH_2(CH_2)_8CO_2R \quad (48)$$

(B and HgOAc substituents)

The reaction can be directed to achieve the synthesis of the corresponding dialkylmercurials (49).[38]

$$2RCH_2CH_2HgOAc \xrightarrow[B(OAc)_3]{Zn} (RCH_2CH_2)_2Hg \quad (49)$$

The selectivity of borane derivatives can be utilized to achieve selective and stereospecific conversions (50, 51).[37,39]



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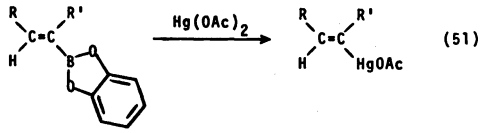
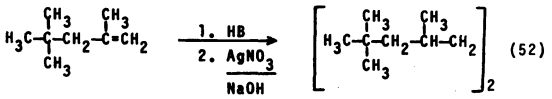


(51)

J. *Coupling*

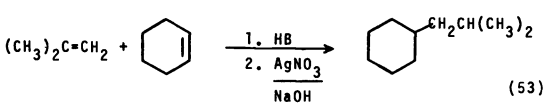
Treatment of organoboranes with alkali and silver nitrate at 0° leads to coupling of the alkyl groups (52).[40]



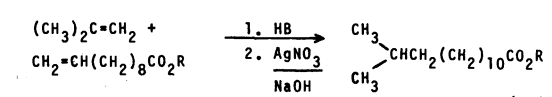
(52)

Presumably, the reaction involves a metallation to give the silver alkyl which then undergoes the usual transformation into silver metal and the coupled product.

With two different alkyl groups, R and R', the coupling is essentially statistical,[41] with 25% R–R, 50% R–R', and 25% R'–R. Even though the maximum yield is only 50% for an equimolar mixture of the two alkenes, the reaction does provide a simple, essentially one-flask synthesis of a variety of structures (53, 54).



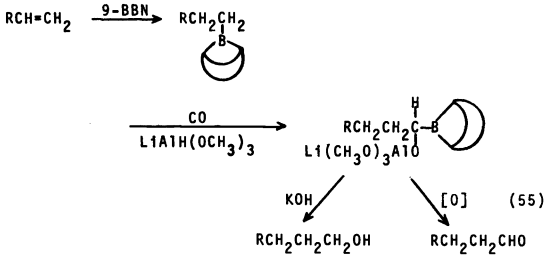
(53)



(54)

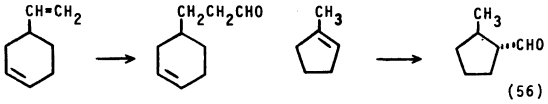
K. *Carbonylation to aldehydes*

Treatment of organoboranes with carbon monoxide in the presence of certain hydride reagents provides an intermediate which is oxidized to the aldehyde or hydrolyzed to the methylol derivative.[4] The use of 9-BBN is especially effective in permitting complete utilization of the alkyl groups (55).[42]



(55)

All of the selectivity and stereospecificity of the hydroboration reaction can be utilized (56, 57).[43,44]



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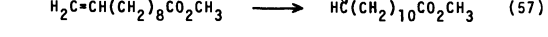


(57)

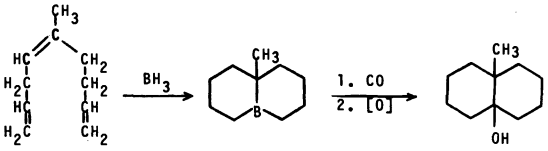
L. *Carbonylation to ketones and tertiary alcohols*

The reaction of organoboranes with carbon monoxide results in the transfer of the three groups from boron to carbon and the concurrent transfer of the oxygen from carbon to boron. Oxidation of the intermediate produces the tertiary alcohol (58).[4]

$$R_3B + CO \rightarrow R_3CBO \xrightarrow{[O]} R_3COH \quad (58)$$

The reaction can accommodate even highly bulky groups, such as 2-butyl, cyclohexyl, and *exo*-norbornyl.[45]

The ready replacement of boron by carbon makes possible a valuable new synthesis of complex structures. The boron is used to "stitch" together the unit and the boron is replaced by carbon to "rivet" the new structure into the desired form (59, 60).[46,47]



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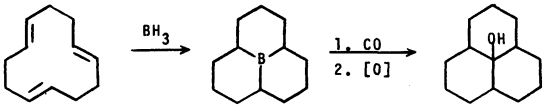
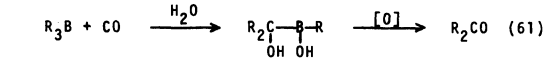


(60)

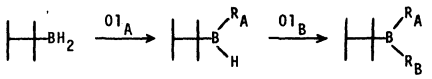
In the presence of water, the carbonylation reaction can be halted with the transfer of two groups from boron (61).[48]

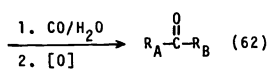


(61)

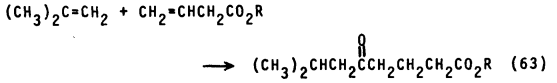
Thexylborane provides the basis for an elegant general

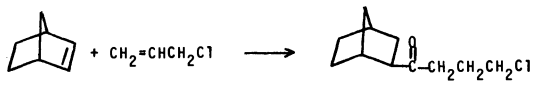
route to ketones which avoids the loss of one of the three groups (62).[49]



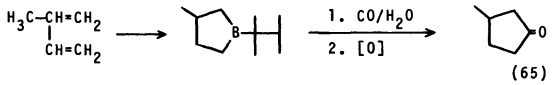


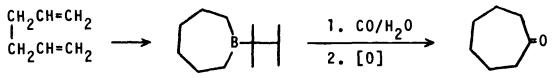
Many functional groups can be tolerated in this ketone synthesis (63, 64).[48]



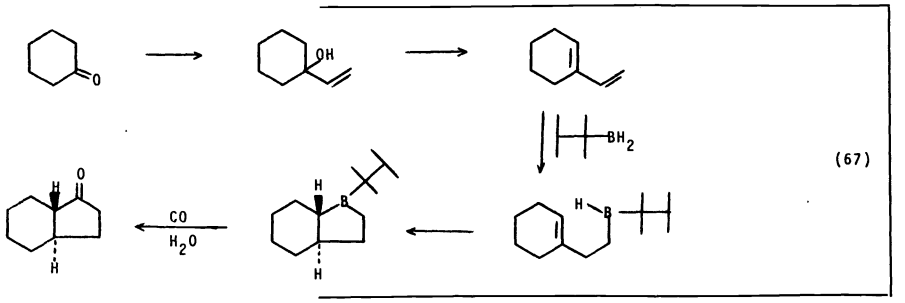


It makes possible a simple conversion of dienes into ring ketones (65, 66).[50]



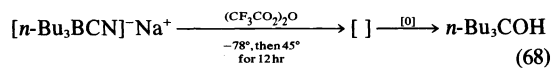


The reaction also provides the basis for versatile new annelation reaction of apparently wide applicability (67).[51]

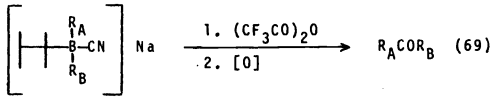


M. *Cyanidation to ketones and tertiary alcohols*

Cyanide ion is isoelectronic with carbon monoxide. Organoboranes do react with alkali metal cyanides, but the products are the simple coordination compounds. Treatment of these addition compounds with a suitable electrophilic reagent, such as trifluoroacetic anhydride, induces migration of the groups from boron to carbon (68).[52,53]

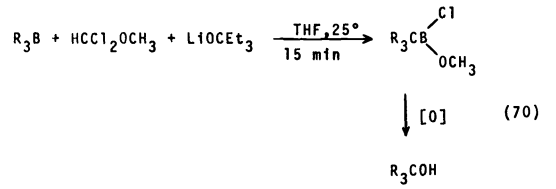


The reaction appears to be especially effective for the transfer of two groups, to provide the corresponding ketones. Indeed, the thexyldialkylboranes react readily, providing a highly convenient route to such ketones (69).[52]

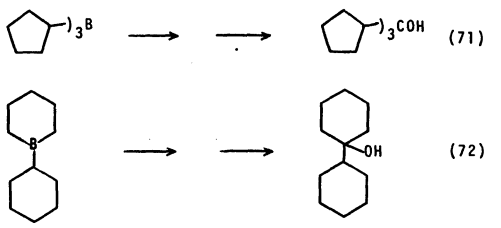


N. *Carbenoidation to ketones and tertiary alcohols*

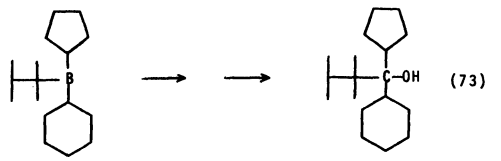
Organoboranes undergo a facile reaction with α,α-dichloromethyl methyl ether in the presence of a sterically demanding base. The product is readily oxidized to the corresponding tertiary alcohol (70).[54]



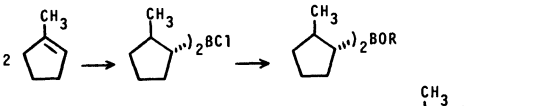
The reaction is widely applicable (71, 72).[54]

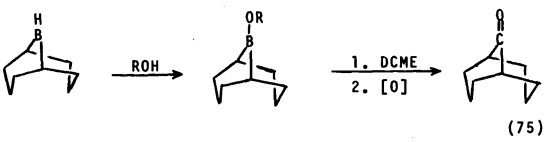


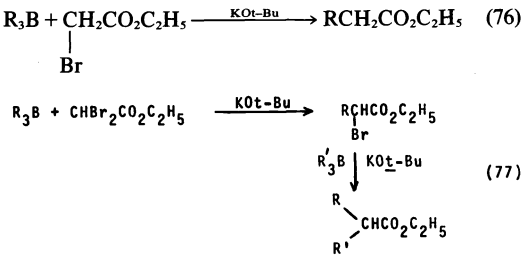
Indeed, it has proven capable of handling exceptionally hindered systems (73).[55]



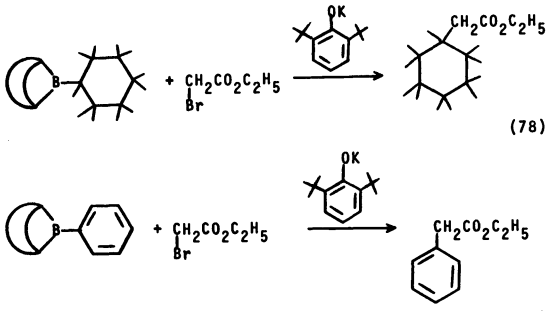
Dialkylborinic acid esters, now readily available via hydroboration with chloroborane-ethyl etherate, react readily with the reagent (74, 75).[56,57]



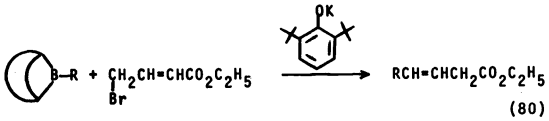




The products are generally unstable to the action of potassium *t*-butoxide, so that this reagent must be added last, carefully avoiding any excess. On the other hand, the products are usually stable to the potassium salt of 2,6-di-*tert*-butylphenol, so this base can be used in excess and can be present initially in the reaction mixture.[60] If B-alkyl-9-BBN or B-aryl-9-BBN derivatives are used, a more economical utilization of the organic group introduced is achieved (78, 79).[60]

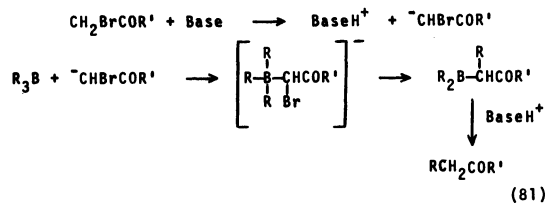


The reaction is broadly applicable.[5] Among the species which have been shown to undergo this reaction are $CH_2BrCO_2C_2H_5$, $CHBr_2CO_2C_2H_5$, $RCHBrCO_2C_2H_5$, $CH_2BrCOCH_3$, $CH_2BrCOC_6H_5$, CH_2ClCN, $CHCl_2CN$, RCHClCN, $CHCl(CN)_2$, $CHBrCNCO_2C_2H_5$, $CH_2BrSO_2C_6H_5$[61] and $CH_2BrCH{=}CHCO_2C_2H_5$. It is of special interest that ethyl 4-bromocrotonate provides a 4-carbon atom homologation (80).[62]

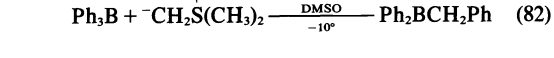


P. *Transfer reactions*

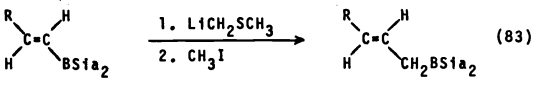
The α-alkylation and α-arylation reactions appear to involve the formation of the α-halocarbanion which coordinates with the boron species. This is followed by a B→C transfer (81).[63]



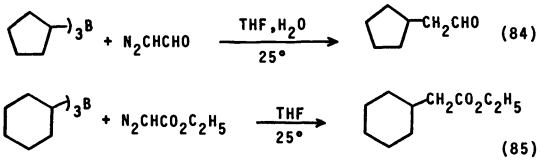
Tufariello and his coworkers established that various ylides can be utilized in related reactions (82).[64]



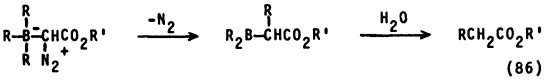
More recently Negishi and his coworkers have utilized an interesting related approach to synthesize allylic boranes (83).[65]



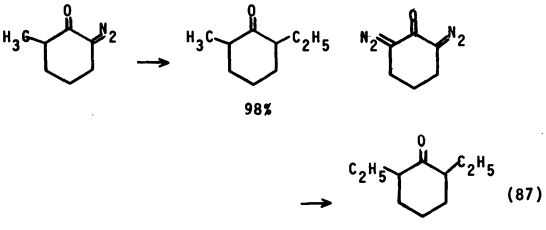
The reaction of organoboranes with diazo derivatives provides still another transfer reaction which permits forming carbon–carbon bonds under remarkably mild conditions (84, 85).[66–68]



The reaction evidently proceeds through an initial coordination, followed by loss of nitrogen and transfer of the group from boron to carbon (86).

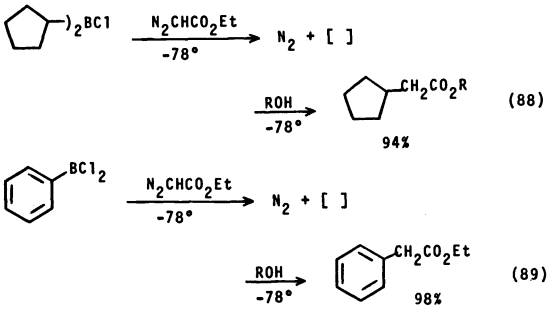


The promise of this approach is indicated by its application to achieve the mono- and dialkylation of cyclic ketones (87).[69]



The reaction suffers from certain disadvantages. First, it uses only one of the three alkyl groups of the R_3B reagent. Second, the reaction becomes quite sluggish with decreases in yield as the R groups become more bulky.

To some extent, these disadvantages can be overcome by use of the R_2BCl and $RBCl_2$ reagents (88, 89).[70,71]

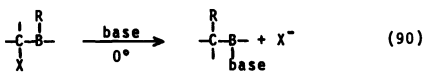


Earlier procedures for introducing organic substituents into the α-position of esters, ketones, nitriles, etc., largely relied on reaction of the carbanion with organic halides or similar derivatives. Only those structures capable of participating easily in SN2-type displacements were satisfactory. Aryl, vinyl, and certain aliphatic and alicyclic groups which are resistant to SN2 displacements

could not be utilized. On the other hand, the present approach makes it possible to introduce aryl, vinyl, and such resistant alicyclic groups as cyclohexyl and 2-norbornyl without difficulty and with retention of configuration in the group being transferred.

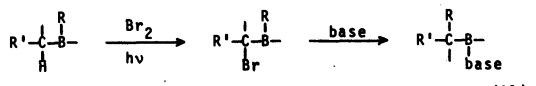
R. *α-Bromination*

It is evident from the above results that the migration of groups from boron to carbon is a facile reaction which occurs under very mild conditions in α-haloorganoboranes (90).



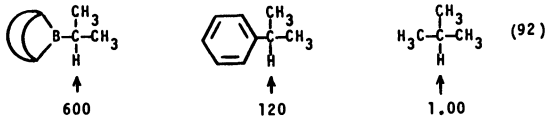
(90)

One approach to the α-bromo intermediate is the reaction of organoboranes with α-halocarbanions. A second approach is the hydroboration of appropriate vinyl halides. A third approach which has proved unexpectedly versatile is the photochemical bromination of organoboranes (91).



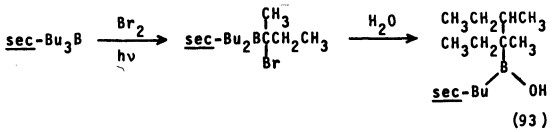
(91)

Fortunately, the carbon–boron bond of trialkylboranes is remarkably stable to the action of bromine, while the α-position is remarkably active toward attach by bromine atoms (92).[72]



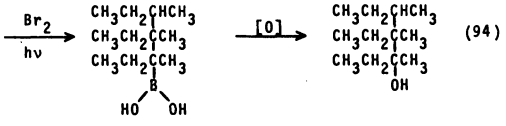
(92)

Bromination of the organoborane in the presence of water results in an immediate migration of the initially formed derivative (93).[73]



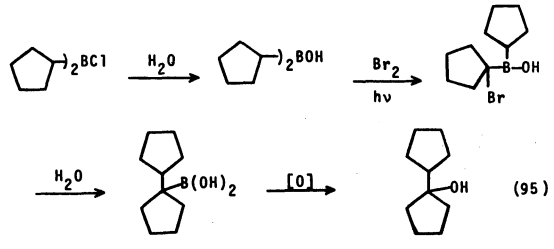
(93)

Further bromination results in the migration of the third *sec*-butyl group (94).



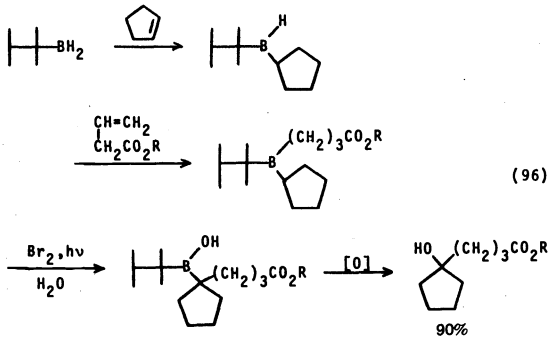
(94)

It is now possible to hydroborate with monochloroborane. These derivatives are useful intermediates in the α-bromination procedure (95).[74]



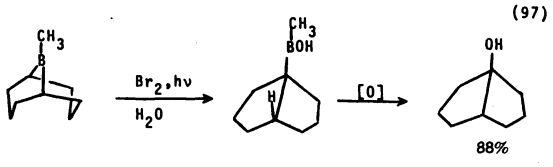
(95)

The thexyl derivatives can also be utilized (96).[75]



(96)

Finally, it is possible to apply this synthesis to polycyclic organoboranes (97).[76]



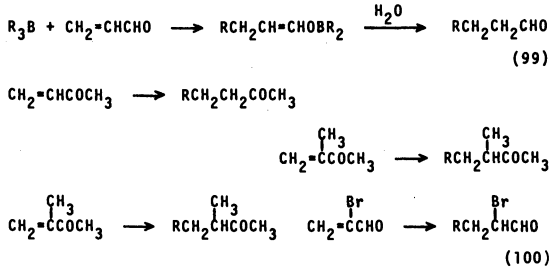
(97)

S. *Conjugate addition*

Organoboranes do not exhibit the facile addition to the carbonyl group characteristic of the Grignard reagent (98).

$$(C_2H_5)_3B + CH_3CHO \xrightarrow{25°} \text{no reaction} \qquad (98)$$

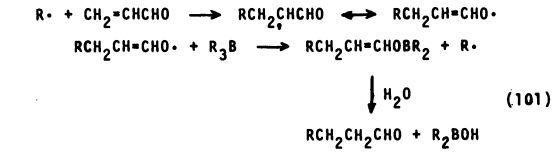
However, rapid reaction occurs with acrolein (99),[77] methylvinyl ketone[78] and similar derivatives (100).[79,80]



(99)

(100)

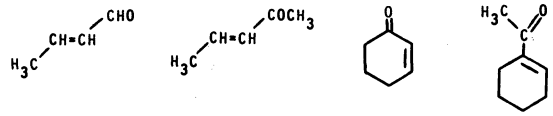
The reaction with acrolein, which provides a valuable means of lengthening the chain by three carbon atoms, involves a free radical chain mechanism (101).[81]



(101)

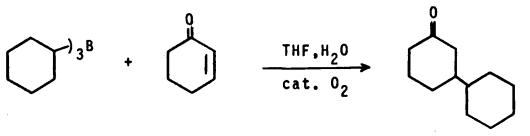
The reaction can be stopped by free-radical inhibitors such as galvanoxyl.[81]

Many α,β-unsaturated carbonyl derivatives undergo this conjugate addition spontaneously, i.e. without added catalysts (95, 96).[77–80] Others (102) fail to undergo a spontaneous reaction.



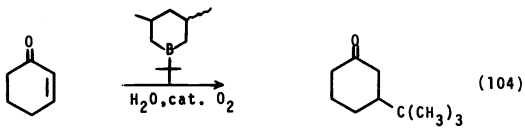
(102)

However, the introduction of free-radical initiators, such as diacetyl peroxide, or merely the introduction of small quantities of oxygen, brings about satisfactory addition (103).[82,83]



(103)

In these reactions, only one of the three groups on R_3B is utilized. Fortunately, there are means of circumventing this difficulty (104).[84]



(104)

T. *Free radical reactions*

The reaction of oxygen with organoboranes involves free radicals (105).[6]

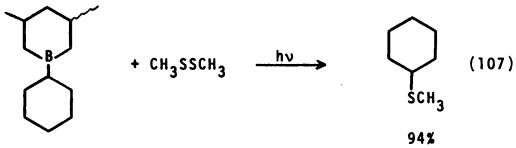
$$\begin{aligned} R_3B + O_2 &\rightarrow R^{\cdot} \\ R^{\cdot} + O_2 &\rightarrow RO_2^{\cdot} \\ RO_2^{\cdot} + R_3B &\rightarrow RO_2BR_2 + R^{\cdot}, \text{ etc.} \end{aligned} \quad (105)$$

Free radicals containing the odd electron on oxygen, nitrogen, or sulfur undergo this remarkable displacement of a free alkyl radical from boron.[85] Evidently this is the feature which accounts for the facile conjugate addition of R_3B to α,β-unsaturated aldehydes and ketones (101).

Similarly, trialkylboranes participate in facile free radical chain reactions with organic disulfides, producing the corresponding thioethers (106).[86]

$$R_3B + C_6H_5SSC_6H_5 \xrightarrow{h\nu} RSC_6H_5 + R_2BSC_6H_5 \quad (106)$$

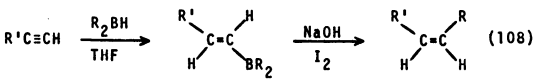
The reaction appears to be broadly applicable, readily accommodating groups such as 2-norbornyl, which resist SN2 substitution processes, such as are customarily used for thioether synthesis. The utilization of only one alkyl group (as in the phenyldisulfide reaction) or only two alkyl groups (as in the corresponding methyl disulfide reaction) can be circumvented by utilizing the 3,5-dimethylborinane derivatives (107).[86]



(107)

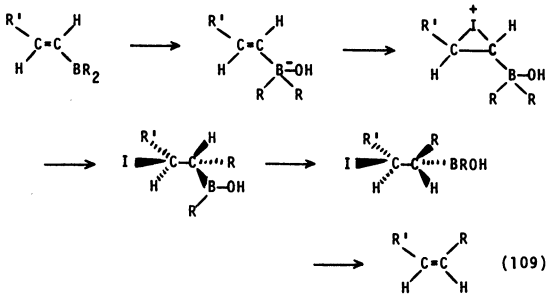
U. cis-*Olefin synthesis*

Treatment of the adduct of a dialkylborane and an acetylene with sodium hydroxide and iodine reaults in the transfer of an alkyl group and the formation of the *cis*-olefin (108).[87]



(108)

The reaction is believed to involve (1) coordination of the base with the boron atom, (2) formation of an iodonium ion, (3) transfer of one of the R groups, and (4) trans-elimination (109).

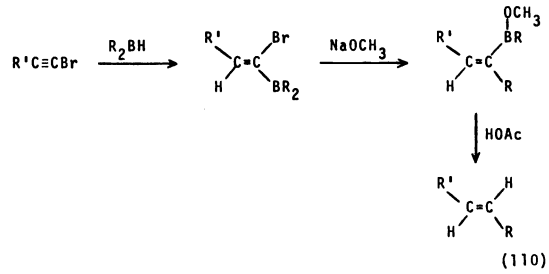


(109)

The Zweifel *cis*-olefin synthesis is a major development. It requires a simple route to dialkylboranes, now under development, and a means of avoiding the loss of 50% of the R groups in R_2BH for cases where R represents a valuable intermediate. Unfortunately, the thexylmonoalkylboranes do not solve the problem, both thexyl and R migrate competitively.

V. trans-*Olefin synthesis*

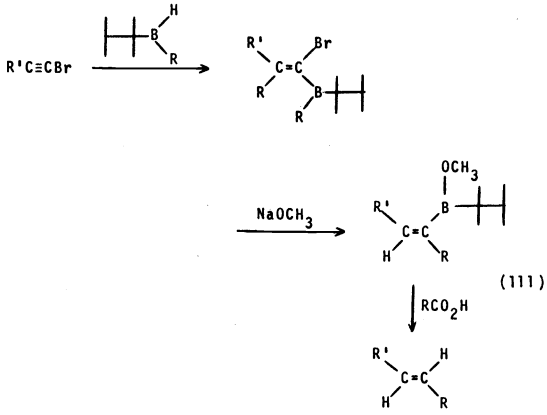
The Zweifel *trans*-olefin synthesis involves an ingenious modification (110).[88]



(110)

It is of interest that the base produces a transfer with inversion even though the halogen atom is vinylic. The R group transfers with retention of configuration both in this reaction and in the *cis*-olefin synthesis.[89]

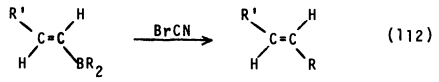
In the present case the thexylmonoalkylboranes can be utilized (111).[90]



(111)

A wide variety of R groups gives yields of *trans*-olefins in the 90% range.

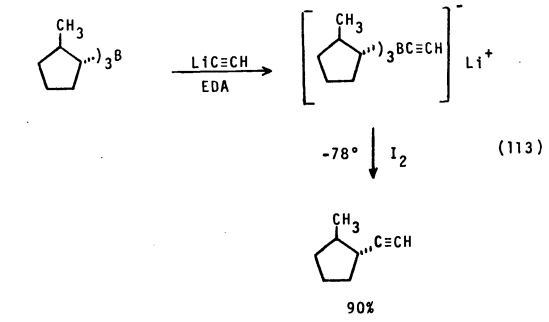
An alternative route to the *trans*-olefins is the treatment of the initial vinyldialkylborane with cyanogen bromide (112).[91]



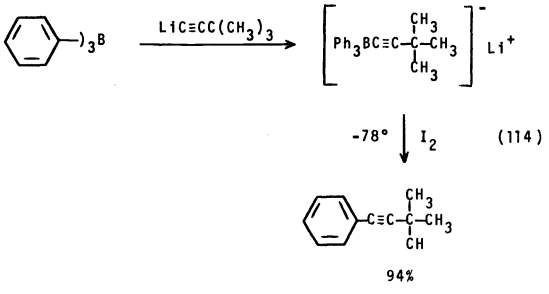
(112)

W. *Acethylene synthesis*

Treatment of the "ate" complexes of acetylenes with iodine provide a remarkably simple versatile route to both mono-[92] (113) and disubstituted[93] (114) acetylenes.



(113)

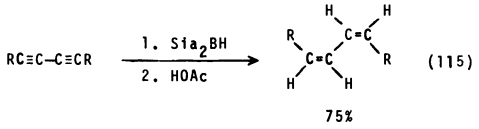


(114)

Here also the synthesis is not limited to the type of groups that can participate in the usual synthesis from RX and MC≡CR. Thus aryl groups are readily introduced (114), and groups can be transferred with complete retention of configuration (113).

X. *Diene synthesis*

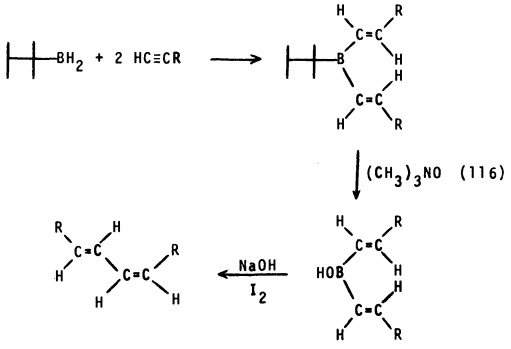
a. cis,cis-*Dienes. cis,cis*-Dienes are readily synthesized from diacetylenes via hydroboration-protonolysis (115).[94]



(115)

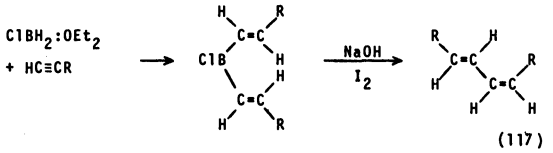
The reaction can also be directed to the synthesis of the corresponding *cis*-enynes to the α,β-acetylenic ketones.[94]

b. cis,trans-*Dienes.* The transfer induced by iodine can be utilized to provide the *cis,trans*-dienes (116).[95]



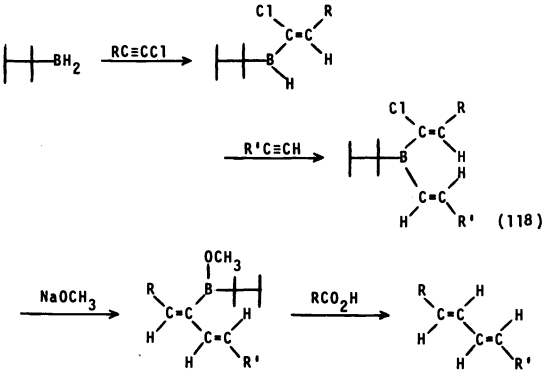
(116)

The procedure can be shortened considerably by utilizing chloro-borane-etherate for the hydroboration (117).[96]



(117)

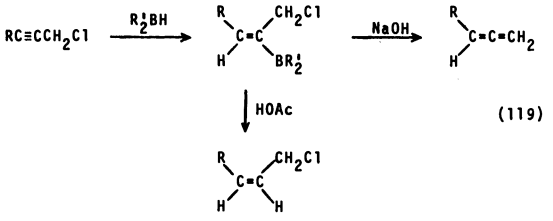
c. trans,trans-*Dienes.* Negishi and Yoshida have developed a route to *trans,trans*-dienes, both symmetrical and unsymmetrical (118).[97]



(118)

Y. *Allenes and trienes*

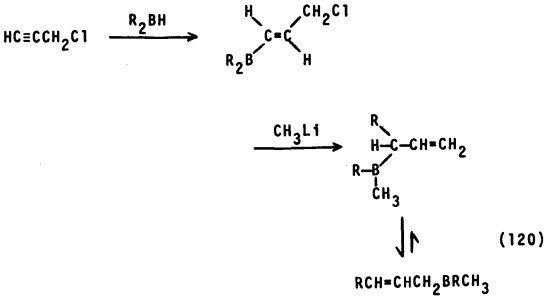
Hydroboration of the higher derivatives of propargyl alcohol with dialkylboranes proceeds to place the boron in the 2-position. Treatment of the intermediate with base results in an elimination to yield the corresponding allene (119).[98].



(119)

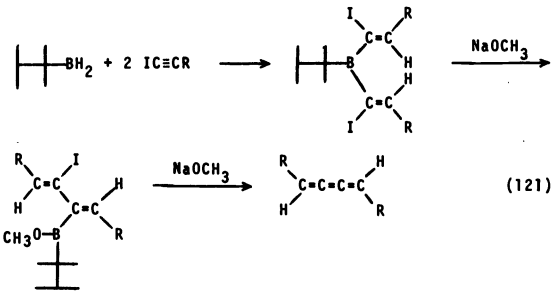
On the other hand, protonolysis with acetic acid gives the *cis* allylic chloride (119).

The corresponding hydroboration of propargyl chloride itself proceeds to place the boron in the 3-position. Treatment with methyl-lithium gives the corresponding allylic borane (120).[99]



(120)

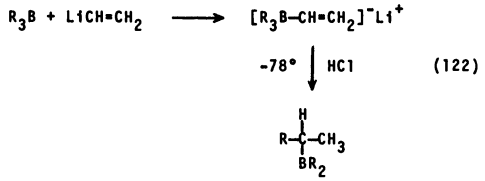
Recently, the first stereoselective synthesis of *trans*-1,4-disubstituted-1,2,3-butatrienes was described (121).[100]



(121)

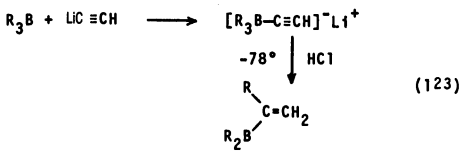
Z. *Markovnikov boranes*

The ate complex from vinyllithium and organoboranes undergo protonolysis to give the Markovnikov organoborane (122).[101]



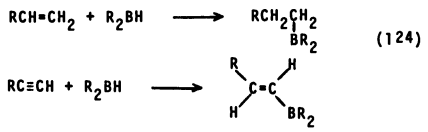
(122)

Similarly, the ate complex from lithium acetylide and organoboranes can be protonated to give the corresponding Markovnikov vinylborane (123).[101]



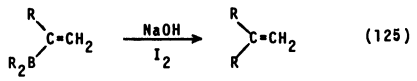
(123)

These contrast with the hydroboration products (124).



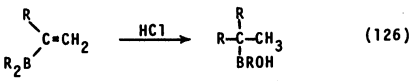
(124)

The product from 123 readily undergoes oxidation to the corresponding ketone, $RCOCH_3$. Treatment with iodine and base yields the 1,1-disubstituted olefin (125).



(125)

Finally, the intermediate can be protonated to yield the doubly-transferred product (126).



(126)

CONCLUSION

In attempting this summary of the remarkable developments in the organoborane field, it was clear that a detailed review of all of the contributions of interest and importance was no longer practical in a lecture of this kind. For example, merely in the reactions of alkynyltrialkylborate ate complexes some thirty publications have appeared in the past three years. Only three are included in this discussion. For omitting many such developments of major interest, the speaker can only apologize and refer to his more recent books[2,3] for more inclusive reviews.

Finally, in this lecture I have restricted myself largely to reactions of interest in synthetic organic chemistry. I have not attempted to discuss numerous other developments of both theoretical and practical interest. I should like to close by quoting from the Preface to my recent book[3] to indicate some of the possibilities of this new chemistry.

"The remarkably facile addition of diborane in ether solvents to alkenes and alkynes was discovered in 1956. For the next decade a major portion of the research effort of my students and associates was devoted to the study of this fascinating new reaction, hydroboration.

This reaction made the organoboranes readily available. However, organoboranes had not been of special interest in the past, and they had received relatively little research attention. It appeared desirable, therefore, to undertake a program to explore these derivatives in more detail. Consequently, the emphasis of our programs was shifted from the study of hydroboration to a study of the chemistry of organoboranes.

This proved to be an extraordinarily rich new area. There resulted a veritable explosion of new chemistry whose full potentiality we can only dimly visualize.

The problem is how to transmit the knowledge in the area to the chemists who must use the chemistry if its full potential is to be achieved.

Before us lies the utilization of these methods for the synthesis of complex molecules, such as natural products and pharmaceuticals. Before us lies the exploration of the applicability of this chemistry for the synthesis of fine chemicals. Before us lies the exploration of the utility of this chemistry in the petrochemical area.

But this is only the beginning. Still to be explored are also the reaction mechanisms involved in the remarkably clean reaction of the organoboranes. The spectroscopy of organoboranes is in its infancy. Structural effects have yet to be examined systematically.

Clearly, it will require another generation of chemists to fully explore this new continent. However, before the new generation of students can be taught the new chemistry, their teachers must learn it. It is clear that many chemists have hesitated to utilize these methods, and many instructors have hesitated to introduce them in their courses because of their inexperience in handling and working with hydroboration and organoboranes.

It is my hope that this book will serve to acquaint working chemists, teachers, and students with the chemistry and techniques or organoborane chemistry. A second effort to overcome this hurdle has been to persuade Dr. Alfred R. Bader of the Aldrich Chemical Company to set up a subsidiary, Aldrich-Boranes, Inc., to make readily available the basic chemicals and intermediates and certain specialized pieces of apparatus to facilitate application of these new methods by chemists. It is expected that both developments will contribute to surmounting the barrier.

A new continent has been discovered—it requires settlers to develop its riches to contribute to mankind."

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