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From Little Acorns to Tall Oaks: From Boranes Through Organoboranes

Herbert C. Brown

This Nobel lecture provides me with an exceptional opportunity to trace my research program in boranes from its inception in 1936, as an investigation initiated for my Ph.D. thesis, to the present time, when this program has been recognized by the award of the Nobel Prize for 1979 (shared with my good friend, Georg Wittig).

In 1936 diborane, B_2H_6, was a rare substance, prepared in less than gram quantities in only two laboratories, that of Alfred Stock at Karlsruhe, Germany, and that of H. I. Schlesinger at the University of Chicago. The existence of the simplest hydrogen compound of boron, not as BH_3, but as B_2H_6, was considered to constitute a serious problem for the electronic theory of G. N. Lewis (*1*). The reactions of diborane were under study at the University of Chicago by Schlesinger and his research assistant, Anton B. Burg, in the hope that a knowledge of the chemistry would aid in resolving the structural problem.

I received the Associate of Science degree from Wright Junior College (Chicago) in 1935 and the B.S. degree from the University of Chicago in 1936. Why did I decide to undertake my doctorate research in the exotic field of boron hydrides? As it happened, my girl friend, Sarah Baylen, soon to become my wife, presented me with a graduation gift, Alfred Stock's book, *The Hydrides of Boron and Silicon* (*1*). I read this book and became interested in the subject. How did it happen that she selected this particular book? This was the time of the Depression. None of us had much money. It appears that she selected as her gift the most economical chemistry book ($2.06) available in the University of Chicago bookstore. Such are the developments that can shape a career.

Shortly before I undertook research on my doctorate, Schlesinger and Burg had discovered that carbon monoxide reacts with diborane to produce a new substance, borane-carbonyl, H_3BCO (*2*). There was considerable discussion as to whether the product was a simple addition compound, or whether the reaction had involved a migration of a hydride unit from boron to carbon.

It was thought that an understanding of the reaction of diborane with aldehydes and ketones might contribute to a resolution of this problem. Accordingly, I was encouraged to undertake such a study.

Once I mastered the high-vacuum techniques developed by Stock for work with diborane, it did not take me long to explore the reactions of diborane with aldehydes, ketones, esters, and acid chlorides. It was established that simple aldehydes and ketones react rapidly with diborane at 0°C (even at −78°C) to produce dialkoxyboranes

$$2\ R_2CO + 1/2(BH_3)_2 \rightarrow (R_2CHO)_2BH \qquad (1)$$

These dialkoxyboranes are rapidly hydrolyzed by water to give the corresponding alcohols

$$(R_2CHO)_2BH + 3\ H_2O \rightarrow 2\ R_2CHOH + H_2 + B(OH)_3 \qquad (2)$$

The reactions with methyl formate and ethyl acetate were slower, but quantitative reductions were achieved. No appreciable reaction was observed with chloral, acetyl chloride, and carbonyl chloride (*3*).

My Ph.D. thesis was completed in 1938 and the contents were published in 1939 (*3*). At the time the organic chemist had available no really satisfactory method for reducing the carbonyl group of aldehydes and ketones under such mild conditions. Yet little interest in this development was evinced. Why?

In 1939 diborane was a very rare substance, prepared in only minor amounts in two laboratories in the world, handled only by very specialized techniques. How could the synthetic organic chemist consider using such a rare substance as a reagent in his work?

It would be nice to report that one of the three authors had the foresight to recognize that the development of practical methods of preparing and handling diborane would make this reductive procedure of major interest to organic chemists throughout the world. But that was not the case. The problem was later solved, but primarily because of the requirements of research supporting the war effort, and not because of intelligent foresight.

The Alkali Metal Hydride Route to Diborane and Borohydrides

In 1939 Burg transferred to the University of Southern California and I became research assistant to Schlesinger. In the fall of 1940 he was requested to undertake for the National Defense Research Committee a search for new volatile compounds of uranium of low molecular weight. As his research assistant, I

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became his lieutenant in this war research program.

Just prior to this development, aluminum borohydride (*4*), $Al(BH_4)_3$, beryllium borohydride (*5*), $Be(BH_4)_2$, and lithium borohydride (*6*), $LiBH_4$, had been synthesized in our laboratories. The lithium derivative was a typical nonvolatile, saltlike compound, but the aluminum and beryllium derivatives were volatile, the most volatile compounds known for these elements. Accordingly, we undertook to synthesize the unknown uranium(IV) borohydride

$$UF_4 + 2\ Al(BH_4)_3 \rightarrow U(BH_4)_4 \uparrow + 2\ AlF_2(BH_4) \downarrow \quad (3)$$

The synthesis was successful (*7*). Moreover, the product, $U(BH_4)_4$, had a low molecular weight (298) and adequate volatility. We were requested to supply relatively large amounts of the material for testing.

The bottleneck was diborane. We had six diborane generators operated by six young men. Each generator could produce 0.5 gram of diborane per 8-hour working day—a total production, when all went well, of 3 g per day, or 1 kilogram per year. Clearly, we had to find a more practical route to diborane.

We soon discovered that the reaction of lithium hydride with boron trifluoride in ethyl ether solution provided such a route (*8*)

$$6\ LiH + 8\ BF_3{:}OEt_2 \xrightarrow{Et_2O} (BH_3)_2 \uparrow + 6\ LiBF_4 \downarrow \quad (4)$$

We could now prepare diborane in quantity and transform it into uranium(IV) borohydride by the simple reactions 5 (*9*) and 6 (*10*)

$$LiH + 1/2(BH_3)_2 \xrightarrow{Et_2O} LiBH_4 \quad (5)$$

$$AlCl_3 + 3\ LiBH_4 \xrightarrow{\Delta} Al(BH_4)_3 \uparrow + 3\ LiCl \downarrow \quad (6)$$

$$UF_4 + 2\ Al(BH_4)_3 \rightarrow U(BH_4)_4 \uparrow + 2\ AlF_2(BH_4) \downarrow \quad (3)$$

Unfortunately, we were informed that lithium hydride was in very short supply and could not be spared for this synthesis. We would have to use sodium hydride instead. But with the solvents then available, the direct use of sodium hydride was not successful. However, a new compound, sodium trimethoxyborohydride (*11*), readily synthesized from sodium hydride and methyl borate, solved the problem

$$NaH + B(OCH_3)_3 \rightarrow NaBH(OCH_3)_3 \quad (7)$$

	$NaBH_4$									$LiAlH_4$
Aldehyde	+									+
Ketone	+									+
Acid chloride	R									+
Lactone	−									+
Epoxide	−									+
Ester	−									+
Acid	−									+
Acid salt	−									+
tert-Amide	−									+
Nitrile	−									+
Nitro	−									+
Olefin	−									−

Fig. 1. Sodium borohydride and lithium aluminum hydride as extremes in a possible spectrum of hydridic reducing agents.

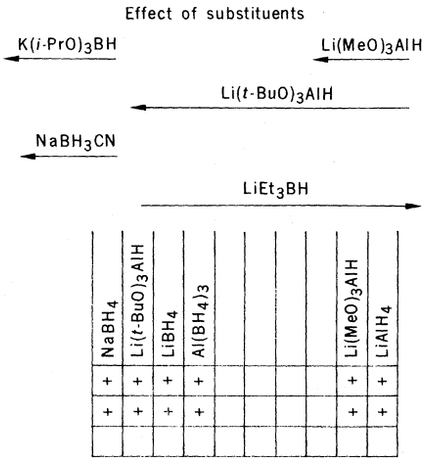


Fig. 2. Alteration of the reducing power of the two extreme reagents, sodium borohydride and lithium aluminum hydride.

	$NaBH_4$ in ethanol	$Li(t\text{-}BuO)_3AlH$ in THF	$LiBH_4$ in THF	$Al(BH_4)_3$ in DG	B_2H_6 in THF	Sia_2BH in THF	9-BBN in THF	AlH_3 in THF	$Li(MeO)_3AlH$ in THF	$LiAlH_4$ in THF
Aldehyde	+	+	+	+	+	+	+	+	+	+
Ketone	+	+	+	+	+	+	+	+	+	+
Acid chloride	(+)	+	+	+	−	−	+	+	+	+
Lactone	−	±	+	+	+	+	+	+	+	+
Epoxide	−	±	+	+	+	±	±	+	+	+
Ester	−	±	+	+	±	−	±	+	+	+
Acid	−	−	−	+	+	−	±	+	+	+
Acid salt	−	−	−	−	−	−	−	+	+	+
tert-Amide	−	−	−	−	+	+	+	+	+	+
Nitrile	−	−	−	−	+	−	±	+	+	+
Nitro	−	−	−	−	−	−	−	−	+	+
Olefin	−	−	−	−	+	+	+	−	−	−

Fig. 3. Variation in reduction characteristics with electrophilic and nucleophilic reagents.

It proved to be very active and provided the desired transformations previously achieved with lithium hydride (reactions 4 to 6).

At this stage we were informed that the problems of handling uranium hexafluoride had been overcome and there was no longer any need for uranium borohydride. We were on the point of disbanding our group when the Army Signal Corps informed us that the new chemical, sodium borohydride, appeared promising for the field generation of hydrogen. However, a more economical means of manufacturing the chemical was required. Would we undertake a research program with this objective?

We soon discovered that the addition of methyl borate to sodium hydride maintained at 250°C provided a mixture of sodium borohydride and sodium methoxide (*12*)

$$4\ NaH + B(OCH_3)_3 \xrightarrow{250^\circ C} NaBH_4 + 3\ NaOCH_3 \quad (8)$$

This provides the basis for the present industrial process for the manufacture of sodium borohydride.

Reductions with Complex Hydrides

In the course of search for a solvent to separate the two reaction products, acetone was tested. Rapid reduction of the acetone was observed (*9*)

$$NaBH_4 + 4\ R_2C{=}O \rightarrow NaB(OCHR_2)_4 \quad (9)$$
$$\downarrow H_2O$$
$$NaB(OH)_4 + 4\ R_2CHOH$$

In this way it was discovered that sodium borohydride is a valuable reagent for the hydrogenation of organic molecules.

At this stage I departed the University of Chicago for Wayne University (Detroit). With the much smaller opportunities for research at this institution, I concentrated on my program dealing with steric strains (*13*, *14*).

At the University of Chicago the alkali metal hydride route was successfully extended for the synthesis of the corresponding aluminum derivatives. Thus lithium aluminum hydride was synthesized in 1945 by the reaction of lithium hydride and aluminum chloride in ether solution (*15*)

$$4\ LiH + AlCl_3 \xrightarrow{Et_2O} LiAlH_4 + 3\ LiCl \quad (10)$$

The discovery of sodium borohydride (*9*) in 1942 and of lithium aluminum hy-

dride (*15*) in 1945 brought about a revolutionary change in procedures for the reduction of functional groups in organic molecules (*16*). As first described by W. G. Brown and his co-workers, there is a major difference in the behavior of these two reducing agents (*16*). Lithium aluminum hydride is an exceedingly powerful reducing agent, capable of reducing practically all functional groups. On the other hand, sodium borohydride is a remarkably mild reducing agent, readily reducing only aldehydes, ketones, and acid chlorides (*16*). Consequently, we had available two reagents which exhibited extremes in their reducing capabilities (Fig. 1).

In 1947 I came to Purdue University with the opportunity for markedly expanding my research program. I decided to explore means of increasing the reducing properties of sodium borohydride and of decreasing the reducing properties of lithium aluminum hydride. In this way the organic chemist would have at his disposal a full spectrum of reducing agents—he could select that reagent which would be most favorable for the particular reduction required in a given situation.

We quickly established that changes in the metal ion from sodium to lithium, to magnesium, and to aluminum greatly increase the reducing power of the borohydride moiety (*17*)

$$\underset{\text{increasing reducing power}}{\xrightarrow{\quad}} \quad NaBH_4 < LiBH_4 < Mg(BH_4)_2 < Al(BH_4)_3 \qquad (11)$$

On the other hand, the reducing power of lithium aluminum hydride could be diminished by the introduction of alkoxy substituents (*18, 19*)

$$\underset{\text{decreasing reducing power}}{\xleftarrow{\quad}} \quad LiAlH(Ot\text{-}Bu)_3 < LiAlH(OMe)_3 < LiAlH_4 \qquad (12)$$

Indeed, it has proven possible to enhance the reducing power of a borohydride ($LiEt_3BH$) (*20*) until it exceeds that of lithium aluminum hydride and to diminish the reducing power [$K(i\text{-}PrO)_3BH$] (*21*) so that it is even less than that of the parent borohydride (Fig. 2).

Finally, we discovered major differences between reduction by electrophilic reagents, such as diborane (*22*) and aluminum hydride (*23*), and by nucleophilic reagents, such as sodium borohydride (*16*) and lithium aluminum hydride (*16*) (Fig. 3). It is often possible now to reduce group A in the presence of B, or group B in the presence of A, by a careful choice of reagents. This is nicely illustrated by the synthesis of both (*R*)- and (*S*)-mevalonolactone from a common precursor (*24, 25*) (Fig. 4).

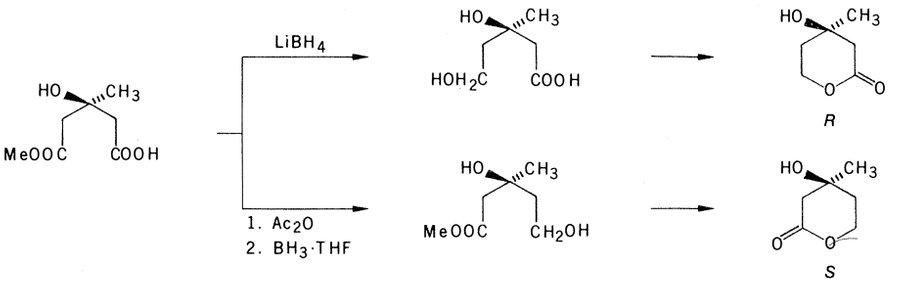


Fig. 4. Synthesis of both (*R*)- and (*S*)-mevalonolactone by selective reduction of a common precursor.

It should be pointed out that these studies were greatly facilitated by many exceptional co-workers, among whom I would like to mention especially Nung Min Yoon and S. Krishnamurthy.

Hydroboration

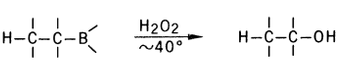
In the course of these studies of selective reductions, a minor anomaly resulted in the discovery of hydroboration. My co-worker, B. C. Subba Rao, was examining the reducing characteristics of sodium borohydride in diglyme catalyzed by aluminum chloride (*17*). He observed that the reduction of ethyl oleate under our standard conditions, 4 moles of hydride per mole of compound, 1 hour at 25°C, took up 2.37 equivalents of hydride per mole of ester. This contrasted with a value of 2.00 for ethyl stearate. Investigation soon established that the reagent was adding an H — B$\leq$ bond to the carbon-carbon double bond to form the corresponding organoborane (*26*).

Exploration of this reaction soon established improved procedures for carrying it out. Of special value was the discovery that the addition of diborane to alkenes was markedly catalyzed by ethers (*27*). In the presence of such ethers, the reaction is practically instantaneous and quantitative

(13)

(My parents were farseeing in giving me the initials H.C.B.)

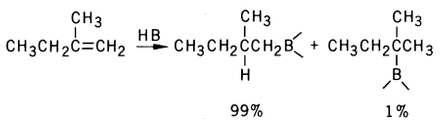
Subba Rao established that oxidation of such organoboranes, in situ, with alkaline hydrogen peroxide, proceeds quantitatively, producing alcohols with the precise structure of the organoborane (*26, 27*)



(14)

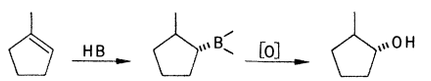
At this stage in the development, Subba Rao returned to India after spending 5 years with me. Fortunately, an equally competent and productive co-worker, George Zweifel, soon joined my group. Although he had been trained at the E.T.H. (Swiss Federal Institute of Technology) in Zurich as a carbohydrate chemist, he expressed a deep interest in the possibilities of the hydroboration reaction and progress was extraordinarily rapid (*28*).

It was soon established that the addition proceeds in an anti-Markovnikov manner



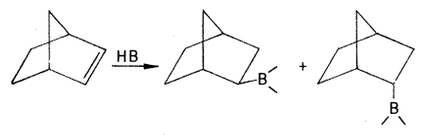
(15)

The reaction involves a *cis*-addition of the H — B$\leq$ bond



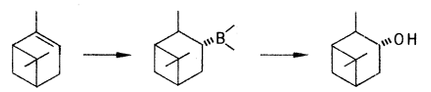
(16)

The addition takes place preferentially from the less hindered side of the double bond



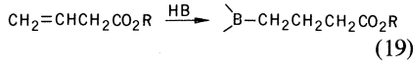
(17)

No rearrangements of the carbon skeleton have been observed, even in molecules as labile as α-pinene.



(18)

Most functional groups can tolerate hydroboration



(19)

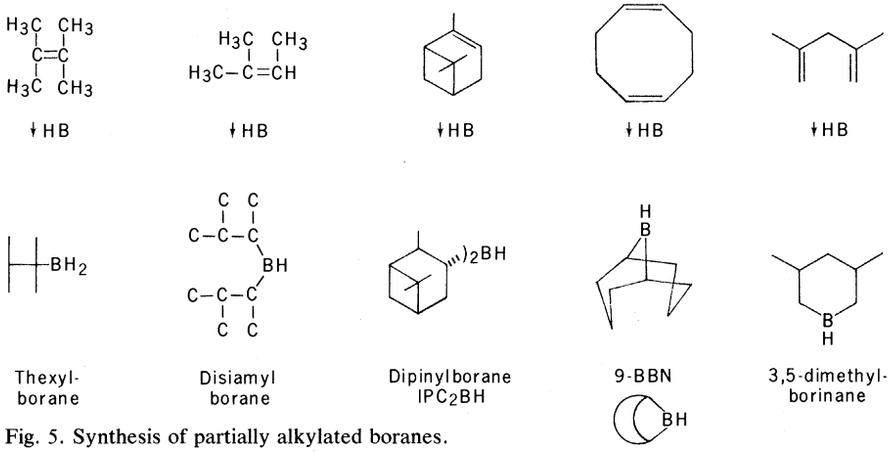


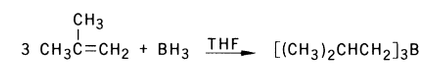
Fig. 5. Synthesis of partially alkylated boranes.

Now the organic chemist can conveniently synthesize reactive intermediates containing functional groups and utilize those intermediates to form products with new carbon-carbon bonds.

Standardized procedures for hydroboration have been developed and are fully described, as well as the utilization of the organoborane products for organic syntheses (*29*). (To conserve space, references will be given only to developments which have appeared since the publication of this book.)

New Hydroborating Agents

The hydroboration of simple olefins generally proceeds directly to the formation of the trialkylborane (*28, 29*)

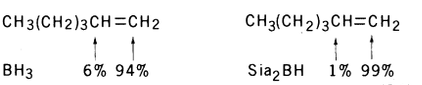


(20)

However, in a number of instances it has been possible to control the hydroboration to achieve the synthesis of monoalkylboranes, dialkylboranes, and cyclic and bicyclic boranes (Fig. 5). Many of these reagents, such as thexylborane (*30*), disiamylborane (*31*), dipinylborane (*32*), and 9-borabicyclo-[3.3.1]nonane (*33*), have proven to be valuable in overcoming problems encountered with the use of diborane itself.

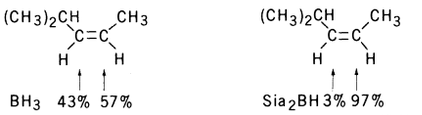
In a number of cases, hydroboration with heterosubstituted boranes has also proven valuable. Research in this area was greatly facilitated by exceptional contributions from S. K. Gupta, N. Ravindran, and S. U. Kulkarni. For example, catecholborane (*34*) and the chloroborane etherates (*35*) (Fig. 6) permit the synthesis of boronic and borinic acid esters, as well as the synthesis of the simple mono- and dialkylchloroboranes, $RBCl_2$ and R_2BCl. The corresponding haloborane–dimethyl sulfides are stabler and easier to work with (*36*) (Fig. 7).

These reagents often exhibit marked advantages in hydroboration over diborane itself. For example, disiamylborane yields far less of the minor isomer in the hydroboration of terminal olefins than does diborane



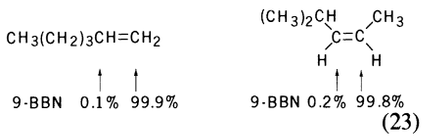
(21)

Disiamylborane also favors addition of the boron atom to the less substituted position of a 1,2-dialkylethylene



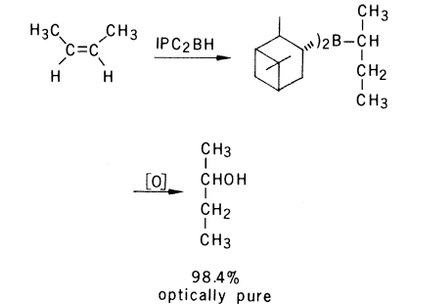
(22)

9-BBN exhibits an even greater selectivity



(23)

The use of optically active α-pinene yields dipinylborane, IPC_2BH, an asymmetric hydroborating agent. It achieves asymmetric syntheses with remarkable efficiency (*32*)



(24)

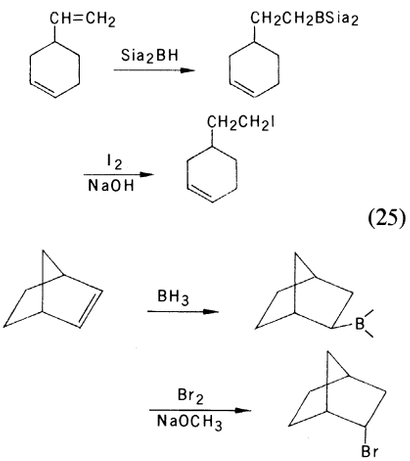
The Versatile Organoboranes

At the time we were exploring the hydroboration reaction, many individuals expressed skepticism to me about the wisdom of devoting so much research effort to this reaction. After all, hydroboration produced organoboranes. Relatively little new chemistry of organoboranes had appeared since the original classic publication by Frankland in 1862 (*37*). They took the position that the lack of published material in this area meant that there was little of value there.

In this case it is now clear that this position is not correct. After our exploration of the hydroboration reaction had proceeded to the place where we felt we understood the reaction and could apply it with confidence to new situations, we began a systematic exploration of the chemistry of organoboranes. This research, facilitated by a host of exceptionally capable co-workers, among whom may be mentioned M. M. Rogić, M. M. Midland, C. F. Lane, A. B. Levy, R. C. Larock, and Y. Yamamoto, made it clear that the organoboranes are among the most versatile chemical intermediates available to the chemist.

It is not possible here to give more than a taste of the rich chemistry. For a more complete treatment, the reader must go elsewhere (*29, 38*).

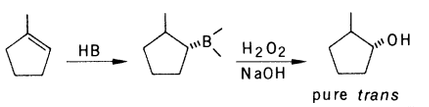
Simple treatment of the organoborane with halogen in the presence of a suitable base produces the desired organic halide (*39, 40*)



(25)

(26)

Oxidation with alkaline hydrogen peroxide produces the alcohol in essentially quantitative yield with complete retention of configuration (*41*)



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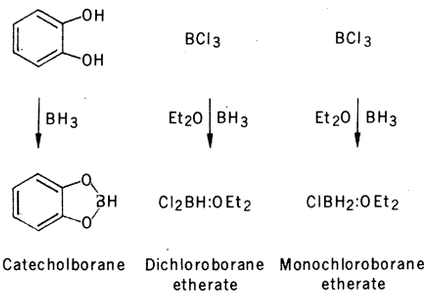
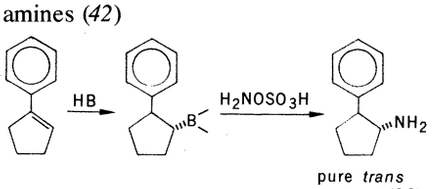


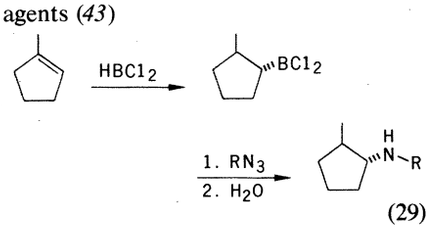
Fig. 6. Synthesis of heterosubstituted boranes.

Either chloroamine or *O*-hydroxylaminesulfonic acid can be used to convert organoboranes to the corresponding amines (*42*)



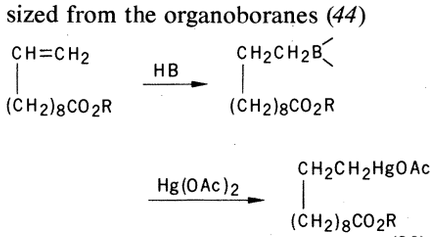
(28)

The reaction of organoboranes with organic azides proceeds sluggishly with the more hindered organoboranes. Fortunately, this difficulty can be circumvented with the new hydroborating agents (*43*)



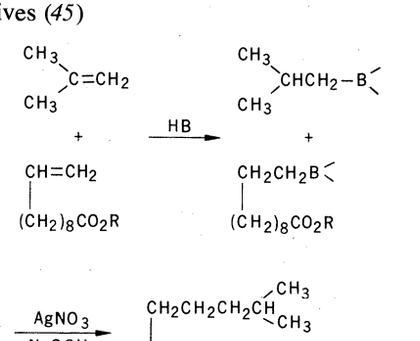
(29)

Other organometallics can be synthesized from the organoboranes (*44*)



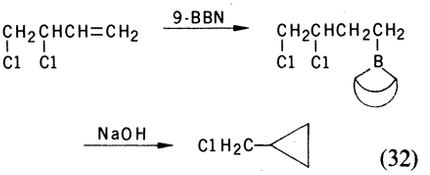
(30)

The organoboranes can also be utilized to form carbon-carbon bonds (*29*). One procedure utilizes transmetallation to the silver derivative, followed by the usual coupling reaction of such derivatives (*45*)



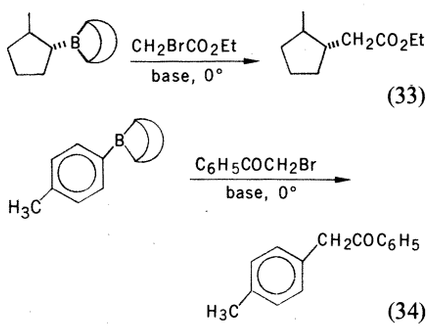
(31)

Cyclopropanes are readily synthesized (*46*)



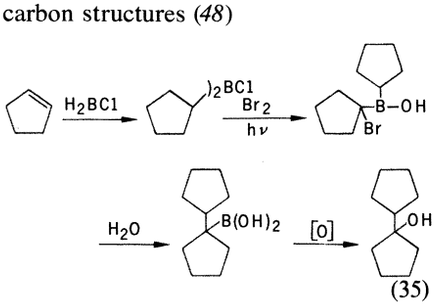
(32)

It is possible to achieve the α-alkylation and -arylation of esters, ketones, nitriles, and so on (*47*)



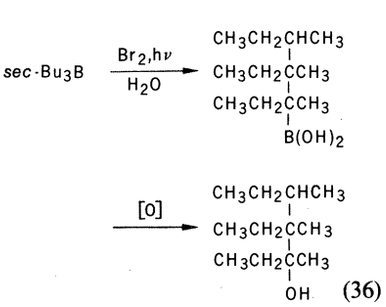
(33) (34)

α-Bromination provides still another route to achieve the synthesis of desired carbon structures (*48*)



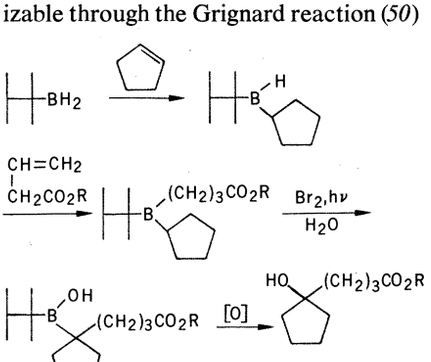
(35)

By means of this reaction, it is possible to combine three *sec*-butyl groups (*49*)



(36)

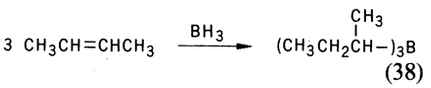
Finally, it is possible to utilize this reaction to synthesize derivatives not realizable through the Grignard reaction (*50*)



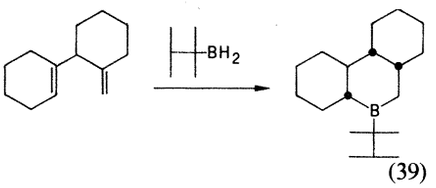
(37)

Stitching and Riveting

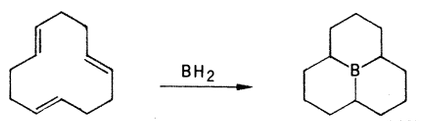
The hydroboration reaction allows the chemist to unite to boron under exceptionally mild conditions either three different olefins (reaction 38), or to cyclize dienes (reaction 39) or trienes (reaction 40)



(38)



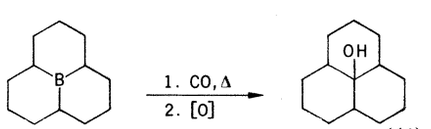
(39)



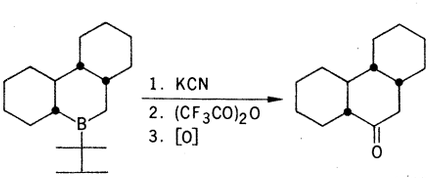
(40)

Thus, hydroboration allows us to use borane and its derivatives to "stitch" together with boron either the segments of individual molecules or the segments of a relatively open complex structure.

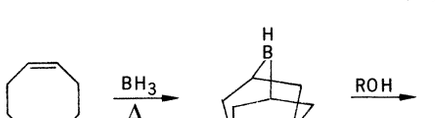
If we could replace boron by carbon, we would be in position to "rivet" these temporary structures into the desired carbon structure. In fact, there are now three different procedures which can be used in this way: carbonylation (*51*), cyanidation (*52*), and the DCME reaction (*53*), reactions 41, 42, and 43, respectively

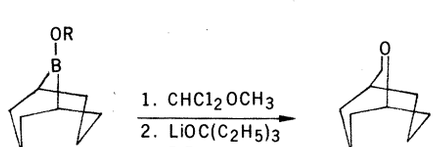


(41)



(42)

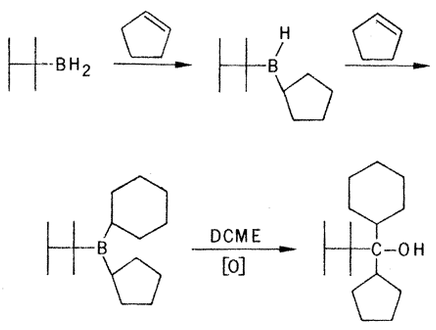




(43)

Consequently, stitching and riveting provides an elegant new procedure for

the synthesis of complex structures. Its versatility is indicated by the synthesis of an exceptionally hindered tertiary alcohol, reaction 44 (*54*), and by the annelation reaction (*55*) (Fig. 8).



(44)

Again, these studies were greatly facilitated by a number of exceptional coworkers, among whom may be mentioned M. W. Rathke, Ei-ichi Negishi, J.-J. Katz, and B. A. Carlson.

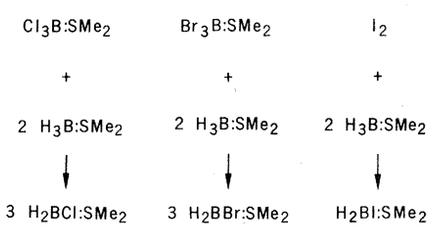


Fig. 7. Synthesis of heterosubstituted boranes.

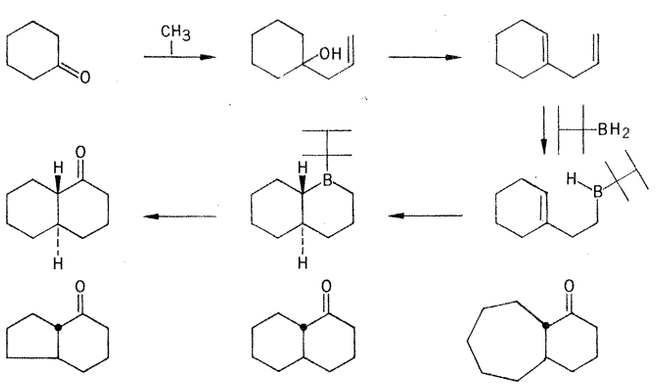


Fig. 8. General annelation reaction through hydroboration-carbonylation.

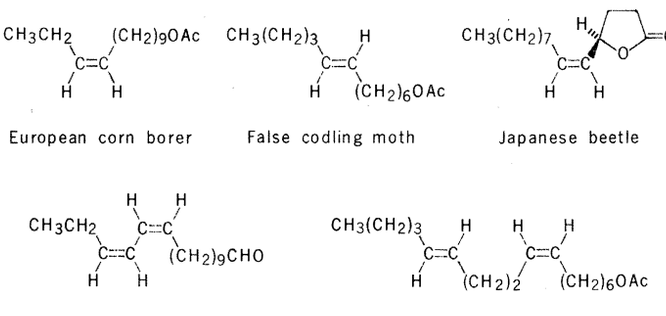
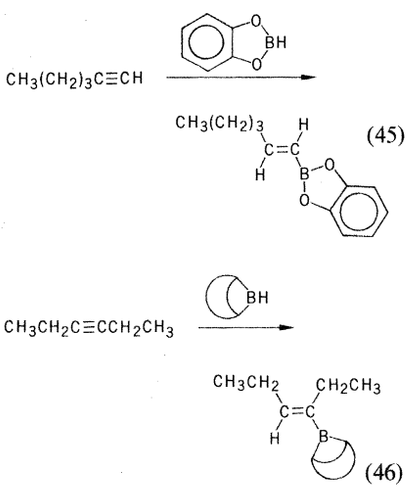


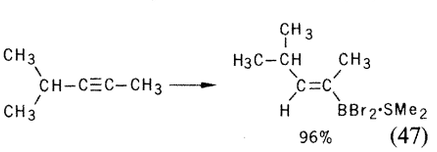
Fig. 9. Representative insect pheromones.

Hydroboration of Acetylenes

Early attempts to hydroborate acetylenes with diborane led to complex mixtures (*28*). Fortunately, the problem can be solved by use of borane derivatives (*32, 33*)

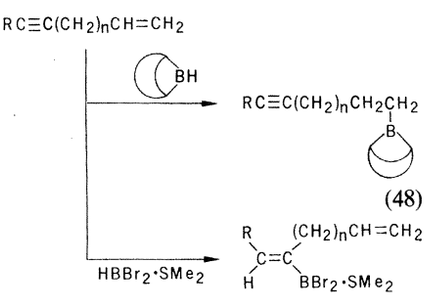


Dibromoborane-dimethyl sulfide (*56*) appears to be especially valuable for such hydroboration of acetylenes (*57*). The reaction readily stops at the monohydroboration step and it exhibits a valuable sensitivity to steric effects (*56*)



(47)

The different reagents exhibit very different selectivities toward double and triple bonds (*56, 57*). Thus it is now possible to achieve the preferential hydroboration in an appropriate enyne of the double bond in the presence of the triple bond (*58*), or to hydroborate the triple bond selectively in the presence of the double bond (*57*), reactions 48 and 49, respectively

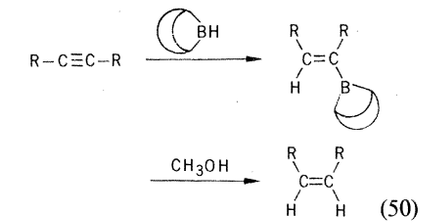


(48)

(49)

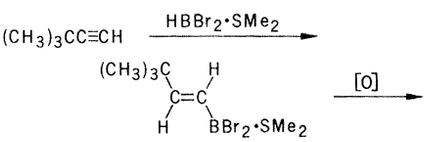
Vinyl Boranes

The monohydroboration of acetylenes makes the vinyl boranes readily available. These reveal an exceptionally rich chemistry. For example, protonolysis proceeds readily and provides an excellent synthesis of *cis*-alkenes of high purity (*59*)



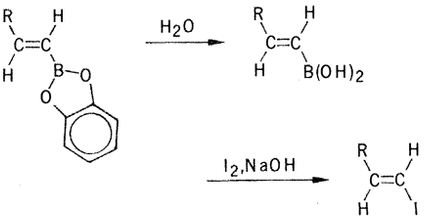
(50)

Oxidation produces the aldehyde or ketone (*57*)

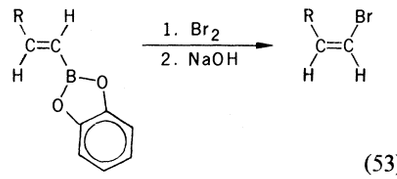


(51)

The halogenation can be controlled to yield the halide either with retention (*60*) or inversion (*61*)

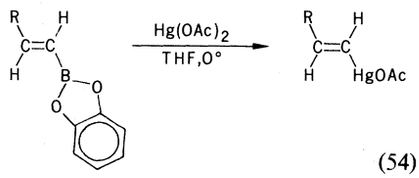


(52)



(53)

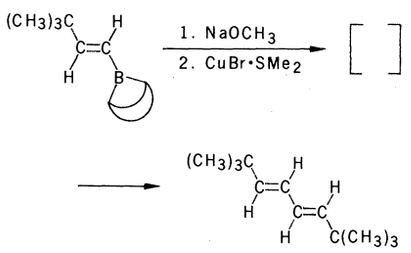
Mercuration readily yields the corresponding mercurial with complete retention of stereochemistry (*62*)



(54)

Pappo and Collins (*63*) adopted this approach in their synthesis of prostaglandins.

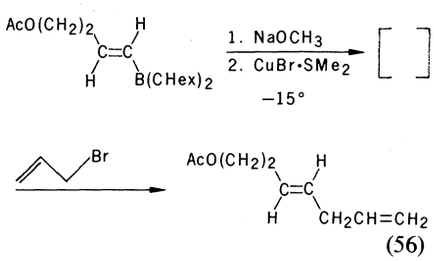
The ready conversion of these vinyl boranes into organomercurials suggested an exploration of their conversion into the organocopper intermediates. The research in this area was greatly facilitated by J. B. Campbell, Jr. Indeed, treatment of the 9-BBN adduct with sodium methoxide and the $CuBr{\cdot}SMe_2$ complex at 0°C gave the diene with complete retention of stereochemistry (*64*)



(55)

Presumably the diene arises from a thermal decomposition of the vinyl copper intermediate.

At −15°C the intermediate is sufficiently stable to be diverted along another reaction path by reaction with relatively reactive organic halides (*65*)



(56)

This gentle procedure for synthesizing vinyl copper intermediates can accommodate such functional groups as the acetoxy group utilized in the example shown.

Our research efforts in this area were greatly facilitated by exceptional contributions by a number of co-workers, including James B. Campbell, Jr., and Gary Molander.

Although time does not permit a detailed review here, attention is called to the elegant procedures developed by my former co-workers, George Zweifel and Ei-ichi Negishi, and their associates, for the synthesis of *cis*- and *trans*-olefins, and the synthesis of *cis,cis*-, *cis,trans*-, and *trans,trans*-dienes (*66*).

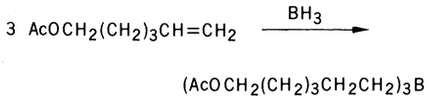
Pheromones

Pheromones offer a promising new means for controlling insect populations without the problems of some of the earlier methods (*67*). The pheromones are chemicals of relatively simple structure emitted by insects as a means of communicating with other members of the same species. Typical examples are shown in Fig. 9.

Even though the structures are relatively simple, they must be very pure so that procedures utilized for their synthesis possess unusually severe requirements for high regio- and stereospecificity. It appeared that synthetic procedures based on organoborane chemistry should be especially favorable for this objective. Accordingly, we have undertaken a new program directed toward developing simple syntheses of such pheromones based upon organoborane chemistry. This research program has been greatly facilitated by G. A. Molander and K. K. Wang.

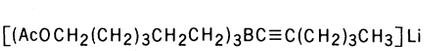
One example, the synthesis of the looper moth sex pheromone, will be presented (*68*).

Hydroboration of 6-acetoxy-1-hexene yields the corresponding organoborane



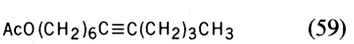
(57)

Reaction with the lithium acetylide from 1-hexyne gives the ate complex



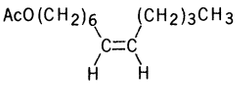
(58)

Treatment of the ate complex with iodine at −78°C provides the acetylene (*69*)



(59)

Hydroboration with 9-BBN, followed by protonolysis with methanol, gives the desired product in an isolated yield of 75 percent, exhibiting a purity of > 98 percent



(60)

It should be noted that the entire synthetic procedure can be carried out in a single flask without isolation of any material until the final product.

Conclusion

In this Nobel lecture I elected to discuss the results of a research program over the past 43 years on the chemistry of borane and its derivatives. This was a deliberate choice. I felt that in this way I could transmit a valuable message to my younger colleagues.

In 1938, when I received my Ph.D. degree, I felt that organic chemistry was a relatively mature science, with essentially all of the important reactions and structures known. There appeared to be little new to be done except the working out of reaction mechanisms and the improvement of reaction products. I now recognize that I was wrong. I have seen major new reactions discovered. Numerous new reagents are available to us. Many new structures are known to us. We have at hand many valuable new techniques.

I know that many of the students of today feel the same way that I did in 1938. But I see no reason for believing that the next 40 years will not be as fruitful as in the past.

In my book, *Hydroboration* (*28*), I quoted the poet: "Tall oaks from little acorns grow" (*70*). But in this lecture I have started further back, to a time when the acorn was a mere grain of pollen. I have shown how that grain of pollen developed first into an acorn. Then the acorn became an oak. The oak tree became a forest. Now we are beginning to see the outlines of a continent.

We have been moving rapidly over that continent, scouting out the major mountain ranges, river valleys, lakes, and coasts. But it is evident that we have only scratched the surface. It will require another generation of chemists to settle that continent and to utilize it for the good of mankind.

But is there any reason to believe that this is the last continent of its kind? Surely not. It is entirely possible that all around us lie similar continents awaiting discovery by enthusiastic, optimistic explorers. I hope that one result of this lecture will be to inspire young chemists to search for such new continents. Good luck.

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Neural Basis of Rhythmic Behavior in Animals

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General principles are important in biological science because they help unify observations made in widely different groups of organisms. The field of neurobiology has a number of such principles but few, if any, that apply broadly across the animal kingdom also address levels of organization beyond that of the single cell. This may be due partly to the greater apparent complexity of events at the multicellular level. For example, while it seems reasonable to believe that an action potential has a single physiological basis in all animals, it may not seem quite so obvious that the neural basis of a behavior like locomotion might be similar in animals as different as a cockroach and a cat. Yet there is no intrinsic reason why general principles of integration underlying simple behaviors should not exist.

Evidence presented over the last two decades overwhelmingly supports one such general principle: that the central nervous system does not require feedback from sense organs in order to generate properly sequenced, rhythmic movement during repetitive behaviors such as locomotion. Recognition of this principle will mean the resolution of a controversy nearly three-quarters of a century old, a resolution brought about in part by the recognition that the competing hypotheses underlying the controversy are not mutually exclusive.

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The Concept of Central Control

Rhythmic behaviors are those in which all or part of an animal's body moves in a cyclic, repetitive way; examples are walking, swimming, scratching, and breathing. Historically, there have been two main hypotheses about the neural mechanisms underlying such simple behaviors. These hypotheses were intended to explain the observation that contractions of the muscles that produce the behavior always occur in a rhythmic and predictable pattern, such as the alternation of extensor and flexor muscles in a limb during walking or the serial activation of body wall muscles during undulatory swimming.

The first hypothesis, peripheral control, holds that these rhythmic patterns are achieved through the use of sensory feedback from the moving parts of the body. One phase of the cycle of movement is thought to provide the sensory cues necessary for the proper timing of the next phase, so that loss of the normal sensory feedback disrupts the behavior.

The second hypothesis, central con-

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