C. (E)-Methyl α -(Trifluoromethyl)urocanate (14, 0.22 g, 4.0%): oil; IR (neat) 1730 (C=O), 1635 (C=C) cm⁻¹; ¹H NMR (10% in acetone- d_6) δ 3.87 (s, 3, OCH₃), 7.57 (qd, 1, J = 1.4, 0.4 Hz, β-CH=), 7.92 and 7.94 (2 s, 2, H-2, H-4); ¹⁹F NMR (10% in acetone- d_6) δ 15.3 (s, α -CF₃).

Further elution of the original column with methanol-ethyl acetate (1:19) afforded a small amount of material whose GC-MS and ¹⁹F NMR spectra suggested a mixture of diastereoisomers of structure 16. This material was followed by elution of 1.79 g of 11b and 2.09 g of 11a. In a second run with equimolar quantities of 11a and trifluoromethyl iodide, the yields of 12-14 were reduced somewhat, while those of 15 and 16 were somewhat higher.

Registry No. 1a, 673-49-4; 1b, 50580-77-3; L-1c, 36097-48-0; L-1d, 1604-44-0; 2a, 88181-33-3; 2b, 88181-34-4; L-2c, 88181-35-5; L-2d, 88181-36-6; 3a, 88181-37-7; 3b, 88181-38-8; L-3c, 88181-39-9; L-3d, 88181-40-2; 4a, 88181-41-3; 4b, 88181-42-4; L-4c, 88181-43-5; L-4d, 88181-44-6; 5e·HCl, 88181-45-7; L-5f·HCl, 88181-46-8; 6e· 2HCl, 88181-47-9; L-6f-2HCl, 88181-48-0; 7, 52091-37-9; 8, 33469-37-3; 9, 21202-42-6; 10, 33468-83-6; (E)-11a, 70346-51-9; (E)-11a·HCl, 54260-89-8; (Z)-11b, 88181-49-1; (Z)-12, 88181-50-4; (E)-13, 88181-51-5; (E)-14, 88181-52-6; (E)-15, 88181-53-7; 16 (isomer 1), 88181-54-8; 16 (isomer 2), 88181-55-9; trifluoromethyl iodide, 2314-97-8; trans-urocanoic acid, 3465-72-3; isonicotinaldehyde, 872-85-5; glyoxal, 107-22-2.

Hydroboration. 66. Addition of Lithium Triethylborohydride to Substituted Styrenes. A Simple, Convenient Procedure for the Markovnikov Hydroboration of Aromatically Conjugated Olefins and the Synthesis of Unusual Mixed Trialkylboranes

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The addition of lithium trialkylborohydride to substituted styrenes and the synthetic applications of the products are described. Styrene, α - and β -methyl-, p-chloro-, and p-methoxystyrene readily undergo the addition reaction in refluxing tetrahydrofuran or in diglyme at 100 °C. 1,1-Diphenylethylene reacts readily, even at 0 °C. The double bond in cinnamaldehyde also adds the reagent following initial reduction to the cinnamyl derivative. Substituents that decrease the electron density at the double bond increase the rate of the addition. For the system, $p-XC_{e}H_{4}CH=CH_{2}$, the rate is in the order of X = Cl > H > OMe. trans- β -Methylstyrene and α -methylstyrene react slower than styrene itself. Lithium tri-n-butylborohydride also undergoes these reactions. However, hindered trialkylborohydrides, such as lithium triisobutylborohydride and lithium tri-sec-butylborohydride, exhibit a slower reaction, which fails to go to completion, even with styrene. The resulting addition products, lithium tetraalkylborates, are transformed into the corresponding aromatic hydrocarbons by hydrolysis. More significantly, the protonolysis of these borates with strong acids yields mixed trialkylboranes by selective protonation of the ethyl group. Oxidation of these boranes gives only α -ols, indicating that the boron atom is attached exclusively to the α -carbon. The observed regiochemistry and electronic effects suggest that the reaction involves a nucleophilic attack of R₃BH⁻ on the styrene double bond to form the carbanion ArCHMe⁻, which is trapped by R₃B to form the tetraalkylborate product. Consequently, the present method provides a Markovnikov hydroboration of substituted styrenes with exceptional regioselectivity.

Addition of complex metal hydrides to aromatically conjugated olefins has been reported with a variety of reagents. Lithium aluminum hydride reacts with dibenzofulvenes,² 9-methylenexanthenes,^{3,4} methylenebenz-anthrene,⁴ and 1,1-diphenylethylenes⁴⁻⁶ but not with styrene.⁵ Cinnamaldehyde and cinnamyl alcohols are reduced to dihydrocinnamyl alcohol^{2,7,8} or to phenylcyclopropanes⁹ with lithium aluminum hydride and to dihydrocinnamyl alcohol with lithium trimethoxyaluminohydride.¹⁰ Similarly, sodium bis(2-methoxyethoxy)aluminum hydride¹¹ reduces some aromatically conjugated olefins such as

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1,1-diphenylethylene. Reductive alkylations of aromatic olefins have also been reported with lithium aluminum hydride⁵ and with sodium bis(2-methoxyethoxy)aluminum hydride.¹¹

Reduction of carbon-carbon double bonds conjugated with strong anion-stabilizing groups (e.g., COR, CO₂R, CN, SO_2R , NO_2) has been observed with sodium borohydride,¹² with potassium tri-sec-butylborohydride,¹³ and with the "ate" complex of copper(I) hydride.¹⁴ However, these reactions were shown to involve the 1,4-addition of the hydride molecule.

Sodium triethylborohydride has been reported to react with ethylene at high pressure and temperature to form sodium tetraethylborate (eq 1).¹⁵ However, no study was reported with aromatically conjugated olefins.

$$NaEt_{3}BH + CH_{2} = CH_{2} \xrightarrow[80]{140-150 \circ C} NaEt_{4}B \qquad (1)$$

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 (9) (a) Uyeda, R. T.; Cram, D. J. J. Org. Chem. 1965, 30, 2083. (b) Jorgenson, M. J.; Friend, A. W. J. Am. Chem. Soc. 1965, 87, 1815. (c)



Figure 1. Relative rates of the reaction of styrenes with lithium triethylborohydride in THF at 65 °C.

Recently, lithium triethylborohydride, LiEt₃BH, has received much attention for its remarkable applicability as a powerful reducing agent in organic synthesis.¹⁶ In the course of our exploratory study of the reducing properties of this reagent,¹⁷ we observed that styrene is slowly reduced in tetrahydrofuran at 0 °C. This discovery led us to examine in detail the addition reaction of this reagent with substituted styrenes and the properties of the lithium tetraalkylborates formed.¹⁸

Results and Discussion

Rate and Stoichiometry Study. The following compounds were selected for study: styrene, *p*-chlorostyrene, *p*-methoxystyrene, *trans*- β -methylstyrene, α -methylstyrene, 1,1-diphenylethylene, and cinnamaldehyde. Lithium triethylborohydride was prepared in tetrahydrofuran.¹⁷

For the approximate rate and stoichiometry studies, the olefin solution in tetrahydrofuran was added to the hydride solution in the same solvent at room temperature and the reaction mixture was brought to reflux. In the case of 1,1-diphenylethylene, the reaction was fast and hence was carried out at room temperature. The olefin concentration was adjusted to 0.67 M and 10% excess over the theoretical amount (1.1 mol per mol of compound) of the hydride used. At desired time intervals, the reaction mixture was brought to room temperature and a 3-mL aliquot was removed and analyzed for residual hydride by hydrolysis. For the reactions where 2 mol of the hydride per mol of

 Table I. Stoichiometry of the Reaction of Styrenes with Lithium Triethylborohydride^a

			reac-		
			tion	. •	1. 1.1.1
		1	temp,	time,	nyariae
	compound	solvent			uptake-
	styrene	THF	65	3	0.96
				6	0.99
	trans-β-	\mathbf{THF}	65	6	0.44
	methylstyrene			24	0.73
		DG	100	5	0.94
				12	1.05
	α-methylstyrene	\mathbf{THF}	65	6	0.39
				24	0.56
		DG	100	3	0.70
				6	0.71
		\mathbf{DG}^{c}	100	0.5	0.87
				1	0.97
	<i>p</i> -metho x y-	\mathbf{THF}	65	12	0.91
	styrene			15	1.00
		DG	100	1	0.95
				3	1.02
	<i>p</i> -chloro-	THF	65	1.5	0.85
	styrene	m r n n d		3	0.87
		THF	65	0.5	1.01
	1,1-diphenyl-	THF	25°	0.25	0.81
	ethylene			1	0.81
				2	0.75
		an i i i i	De	3	0.72
		IHF	0-	0.20	0.52
				0.0	0.63
				2 1	0.00
				о r	0.00
				0	1.00
	cinnamaldehyde	тнг	95	7 0.25	1.00
		THE	20 65	1	1 70
		1111.	00	<u>д</u>	1 0 9
				5	1 97
				0	1.01

^a Unless otherwise stated, 1.1 mol of the reagent per mol of compound was used in THF and 1.2 mol in diglyme. ^b Mol of hydride consumed per mol of compound. ^c 100% excess of the hydride. ^d The olefin solution was added to the refluxing solution of the hydride. ^e Immediate red color. ^f 2.2 mol of hydride per mol of compound.

olefins were necessary, the olefin concentration was adjusted to 0.5 M and 4-mL aliquots were used for hydrolysis.

The results are represented graphically in Figure 1 and summarized in Table I in comparison with those for the reactions in diglyme, discussed later.

Although styrene consumes a theoretical amount of the hydride in 6 h (0.99 mol per mol of compound), it is sometimes necessary to reflux overnight (about 15 h) to get a quantitative yield of the products (see the following section).

For *p*-chlorostyrene, it is essential to add the olefin solution slowly to the refluxing hydride solution to achieve complete hydride uptake. The reaction appears to be instantaneous. If the addition is carried out at room temperature and then immediately brought to reflux, only 0.85 equiv of the hydride is consumed initially without further significant change with time. It is probable that a base-catalyzed polymerization is competing with the addition. The uptake of hydride is further reduced to about 0.35 equiv by maintaining the reaction mixture at room temperature.

1,1-Diphenylethylene immediately takes up 0.8 mol of hydride per mol of compound at room temperature, developing a deep red color. A puzzling decrease in the hydride uptake with time was observed at this temperature. Although this is not yet fully understood, a full

⁽¹⁶⁾ For a review, see: Krishnamurthy, S. Aldrichimica Acta 1974, 7, 55.

⁽¹⁷⁾ Brown, H. C.; Kim, S. C.; Krishnamurthy, S. J. Org. Chem. 1980, 45, 1.

⁽¹⁸⁾ For a preliminary communication, see: Brown, H. C.; Kim, S. C. J. Org. Chem. 1977, 42, 1482.

equivalent of hydride uptake was achieved in 9 h by running the reaction at 0 $^{\rm o}C.^{\rm 19}$

These results indicate that the addition is faster with less electron-rich olefins and vice versa. This is the anticipated trend based on consideration of the nucleophilic character of the reagent. In fact, the relative rate study using the Ingold-Shaw method²⁰ shows the exact opposite trend to that realized in the electrophilic reaction with 9-BBN,²¹ as indicated by the relative rates (eq 2).



In the case of *trans*- β - and α -methylstyrene, steric as well as electronic effects may be involved (eq 3).



Since reaction with *p*-methoxy-, α -methyl-, and *trans*- β -methylstyrenes was rather sluggish, it was desirable to raise the reaction temperature by replacing tetrahydro-furan with a higher boiling solvent. This was successfully carried out by utilizing diglyme as the solvent, running the reactions at 100 °C on a steam bath. The results of these stoichiometry studies in tetrahydrofuran and in diglyme are summarized in Table I.

In the course of our studies directed toward optimization of the reactions, sodium triethylborohydride in tetrahydrofuran and in benzene were prepared and compared with the lithium reagent. The reactions of these reagents with *trans*- β -methylstyrene in refluxing solvents showed that the sodium reagent in both solvents was less reactive than the lithium reagent in tetrahydrofuran. The sodium reagent in benzene appeared to be the least reactive, with almost no reaction evident after 24 h, even though the reaction temperature was higher (80 °C) than that in tetrahydrofuran (65 °C). These results discouraged examination of the potassium reagent since the trend indicated that this should be even less reactive. At present, our main interest is not in the cation effect but on achieving optimum conditions for the reaction. The results are graphically represented in Figure 2.

Lithium tri-n-butylborohydride²³ in tetrahydrofuran also undergoes similar reactions, and the rates for the addition are comparable with those achieved with lithium triethylborohydride. However, in the case of more hindered trialkylborohydrides such as lithium triisobutylboro-



Figure 2. The rates of the reaction of $trans-\beta$ -methylstyrene with lithium and sodium triethylborohydride.

Table II. Reactions of Some Lithium Trialkylborohydrides with Styrenes in THF at 65° C

$LiR_{3}BH, R =$	olefin	time, h	hydride uptake ^a	
n-Bu	styrene	2	0.90	
		3	0.97	
	trans-β-	3	0.18	
	methylstyrene	6	0.31	
		24	0.65	
i-Bu	styrene ^{b,d,e}	1	0.87	
		6	0.86	
sec-Bu	styrene ^{c,d,e}	1	0.37	
		6	0.36	

^a Mol of hydride consumed per mol of compound. ^b Initial color change to light yellow in 5 min, which slowly changed to red in 1 h. ^c Color change to pale yellow in 1 h, then to pale orange, and finally to red within 4 h. ^d The color faded to pale yellow upon cooling to room temperature. ^e After a 24-h reaction, the reaction mixtures were treated with concentrated HCl and oxidized. Li-i-Bu₃BH (27%) and Li-sec-Bu₃BH (3%) of ethylbenzene were estimated by GC; however, no styrene remained in both reaction mixtures.

hydride²³ and lithium tri-*sec*-butylborohydride,²³ styrene exhibits decreased hydride uptake, presumably a result of a competing polymerization. The results are summarized in Table II.

Product Analysis. In order to understand the structures of the reaction products, the reaction with styrene was studied in detail. Two possible products,²⁴ 2a and 2b, from styrene and lithium triethylborohydride appeared reasonable (eq 4).

It has been observed that in the addition of lithium aluminum hydride^{2,4} and of sodium bis(2-methoxyethoxy)aluminum hydride¹¹ to aromatic olefins, the hydride

⁽¹⁹⁾ Fifty percent of the theoretical amount of hydride was consumed within 15 min and the rest was consumed slowly at this temperature (Table I). The same trend was observed even when 2 mmol of the reagent was used per mmol of compound.

⁽²⁰⁾ Ingold, C. K.; Shaw, F. R. J. Chem. Soc. 1927, 2818.

 ^{(21) (}a) Brown, H. C.; Liotta, R.; Scouten, C. G. J. Am. Chem. Soc.
 1976, 98, 5297. (b) Vishwakarma, L. C.; Fry, A. J. Org. Chem. 1980, 45, 5306.

⁽²²⁾ Since the hydroboration of internal olefins is much slower than terminal olefins, this value is rather a poor comparison.

⁽²³⁾ Brown, H. C.; Krishnamurthy, S. J. Am. Chem. Soc. 1972, 94, 7159.

⁽²⁴⁾ That this product does not exist as α -lithioethylbenzene and free triethylborane was confirmed by GC using low injection-port temperature (25 °C).



attack occurs on the β -position, forming benzylic carbanions (eq 5).



Although structure 2a seemed more favorable than 2b by analogy, it was essential to establish a proper procedure for the hydrolysis.

In the literature,²⁵ there is ambiguity concerning the stability of tetraalkylborates toward water. Schlesinger and Brown²⁶ reported that lithium trimethylethylborate dissolved in water and slowly evolved a gas. Hurd²⁷ described a vigorous decomposition of lithium tetramethylborate with a drop of water. Honeycutt and Riddle^{15a} stated that sodium tetraethylborate is hygroscopic and stable in water. Damico²⁸ showed that all of the lithium tetraalkylborates studied were fairly stable in water, decomposing from 0.5% to 13% at 35 °C in 16 h. He also observed that base had little effect on the rate, whereas acetic acid caused a rapid loss of one alkyl group with further protonation slow, even at 60 °C (eq 6).

$$MBR_{4} + HOAc \xrightarrow{fast} MOAc + R_{3}B + RH$$

$$R_{3}B + HOAc \xrightarrow{slow} RH + R_{2}BOAc$$
(6)

With the present reaction product 2, there are two possible pathways for the hydrolysis, leading to two different products. One is the protonation of the ethyl group to form mixed trialkylborane 3 (pathway A) and the other is protonation of the 1-phenylethyl group to form ethylbenzene (pathway B) (eq 7).

$$2a + H_2O \xrightarrow{A} PhCHBEt_2 + CH_3CH_3 + LiOH$$

$$3a \xrightarrow{B} PhCH_2CH_3 + Et_3B + LiOH$$

$$2b + H_2O \xrightarrow{A} PhCH_2CH_2BEt_2 + CH_3CH_3 + LiOH$$

$$3b$$

Whichever pathway is taken in the addition stage, the structure of the addition product is distinguishable since 2a will form α -deuterioethylbenzene by deuterolysis or 1-phenylethanol by the oxidation of 3a, whereas 2b will form β -deuterioethylbenzene or 2-phenylethanol.

Our observation with 2 is similar to Damico's, with the reaction product exhibiting considerable stability toward water at room temperature. When 2 in tetrahydrofuran was stirred with 10 equiv of water at room temperature, only 34% hydrolysis of the phenylethyl group (via pathway B) was observed by GC analysis. Aqueous sodium hydroxide had little effect on the rate. However, by raising the temperature to 65 °C, hydrolysis was complete in 1-2 h and ethylbenzene was formed in essentially quantitative yield (92-99% based on styrene used) (eq 8)

GC analysis of this reaction mixture after oxidation with H_2O_2 showed that the yield of ethanol was quantitative and there was no formation of 1- or 2-phenylethanol. This result shows that hydrolysis takes place exclusively via pathway B.

By deuterolysis of 2 with D_2O , pure α -deuterioethylbenzene (4) was isolated. This clarified that 2a is the correct structure of the complex (eq 9).

$$PhCH = CH_{2} + LiEt_{3}BH - \left[PhCHCH_{3}\right]Li^{+} D_{2}O PhCHCH_{3} (9)$$
$$- \left[- \\ -BEt_{3}\right]^{+} D$$
$$2a \qquad 4$$

With strong acids such as methanesulfonic acid and hydrochloric acid 2 behaves in a completely different manner. Treatment of 2 with an equimolar amount of methanesulfonic acid at room temperature causes a fast reaction to take place in which one of the ethyl groups is selectively protonated to ethane with the formation of mixed trialkylborane 3 via pathway A. 1-Phenylethanol (free of 2-isomer) is obtained by oxidation of the reaction mixture in the same flask without isolation (eq 10). The

$$\begin{bmatrix} PhCHCH_{3} \\ -BEt_{3} \end{bmatrix} L^{\dagger} + CH_{3}SO_{3}H \xrightarrow{THF}_{RT, 10 \text{ min}} PhCHCH_{3} + CH_{3}CH_{3}t + \\ BEt_{2} \\ 2 \\ 3 \\ CH_{3}SO_{3}Lil \\ 3 \\ \frac{NaOH}{H_{2}O_{2}} PhCHCH_{3} + PhCH_{2}CH_{3} \\ OH \\ 4-5\% \\ OH \\ 90-96\% \\ (100\% 1-ol) \\ \end{bmatrix}$$
(10)

absence of 2-phenylethanol confirms the result of the deuterolysis, which showed that the boron atom is attached exclusively to the α -position. The formation of a minor amount of the hydrolyzed product, ethylbenzene, during the oxidation stage is a well-known phenomenon for benzylic-type boranes.²⁹

Hydrochloric acid works as well and the presence of water has little effect on the protonolysis (eq 11).

When mixed trialkylborane 3 is the desired product, it can be isolated by simple distillation. Although no attempt was made to optimize the yield, 3 was isolated in a yield of 64%.

⁽²⁵⁾ For a review on tetraalkylborates, see: Negishi, E. J. Organomet. Chem. 1976, 108, 281.

⁽²⁶⁾ Schlesinger, H. I.; Brown, H. C. J. Am. Chem. Soc. 1940, 62, 3429.
(27) Hurd, D. T. J. Org. Chem. 1948, 13, 711.
(28) Damico, R. J. Org. Chem. 1964, 29, 1971.

^{(29) (}a) Brown, H. C.; Sharp, R. L. J. Am. Chem. Soc. 1966, 88, 5851.
(b) Weinheimer, A. J.; Marsico, W. E. J. Org. Chem. 1962, 27, 1926.



These hydrolyses and protonolyses are applicable to all but one of the reaction products (eq 12 and 13).

PhCH=CHCH₃ + LiEt₃BH
$$\frac{\text{THF}}{\text{reflux, 48 h}}$$
 $\stackrel{\text{H}^{\bullet}}{\stackrel{\text{PhCHCH}_2CH_3}{|}$ (12)
BEt₂
5 (64% isolated)

DCME reaction²⁹ of 5 gave excellent yield of the tertiary carbinol 6.

5 + CH₃OCHCl₂
$$\xrightarrow{\text{LiOCE}_{13}}$$
 $\xrightarrow{\text{COJ}}$ PhCHCH₂CH₃ (13)
HO $\xrightarrow{-\text{CCH}_2\text{CH}_3}$
CH₂CH₃
6 (81.3% isolated)

Cinnamaldehyde can be converted into cinnamyl alcohol (7), hydrocinnamyl alcohol (9), or 1-phenyl-1.3-propanediol (10), whichever is the desired product (eq 14).

10 (79.5% isolated (100% isomeric purity))

In the case of 1,1-diphenylethylene, a deep red color of the reaction mixture-a feature lacking in the other cases—supports the conclusion⁴⁻⁶ that the product is 1lithio-1,1-diphenylethane (11) rather than its triethylborane complex 12 (eq 15).





^b References 29a and 32. ^a Reference 33.

The color immediately disappears on either hydrolysis or protonolysis, producing a single product, 1,1-diphenylethane.

These results are summarized in Table III.

The mechanisms of the hydrolysis and protonolysis are not yet clear. At present, the mechanism proposed by Damico for hydrolysis of tetraalkylborates appears to be reasonable for the protonolysis with acids (eq 16) with a dissociation mechanism²⁵ (eq 17) for the hydrolysis.³¹





 $PhCH_2CH_3$ (17)

The remarkable regiospecificity and the position of the boron are noteworthy. It has been observed that in the hydroboration of substituted styrenes with diborane^{29a,32} distribution of boron in the products are markedly altered by the nature of the substituents. The electron-withdrawing substituents increase the amount of boron dis-

1.1

and is readily attacked by water to form ethylbenzene. On the other hand, the acids being highly reactive toward 2, they attack less hindered ethyl groups more readily than 1-phenylethyl groups before any signifi-(32) Brown, H. C.; Zweifel, G. J. Am. Chem. Soc. 1960, 82, 4708.

(33) Liotta, R. Ph.D. Thesis, Purdue University, 1976.

(34) Brown, H. C.; Gallivan, R. M., Jr. J. Am. Chem. Soc. 1968, 90, 2906.

⁽³⁰⁾ Brown, H. C.; Carlson, B. A. J. Org. Chem. 1973, 38, 2422. Brown, H. C.; Katz, J.-J.; Carlson, B. A. Ibid. 1973, 38, 3968.

⁽³¹⁾ These proposed mechanisms are also based on some other results not appearing in this paper. The general trend shows that for hydrolysis the groups that have lower pKa values tend to be hydrolyzed more readily than those of higher pKa values. In the protonolysis, the less the α carbon atoms are substituted, the more they are likely to be protonolyzed. Therefore, in the hydrolysis of 2, a small equilibrium concentration of $PhCH(CH_3)Li$ is formed by the equilibrium

Table III. Product Analysis of the Reaction of Lithium Triethylborohydride with Substituted Styrenes^a

					products				unreac-
		temp,	time,	proce-		yield, ^{g,h}		yield, ^g	ted ole-
compound	solvent	°C	h	dure ^b	oxidized	%	hydrolyzed	%	fin, %
styrene	THF	65	5-15	Α	1-phenylethanol	90-96	ethylbenzene	4-5	0
				в		0		92-99	0
<i>trans-β-</i> methyl-	\mathbf{THF}	65	24	A	1-phenylpropanol	64	<i>n</i> -propylbenzene	1	27
styrene				в		0		63	26
	DG	100	12	Α		82		10	2
				В		0		91	2
α -methylstyrene	\mathbf{THF}	65	24	Α	1-phenyl-2-propanol	14	isopropylbenzene	31	4
				В		0		44	4
	DG	100	1	Α .		10		44	4
	DG^{c}	100	1	Α		25		61	2
				В		0		88	2
<i>p</i> -methoxystyrene	$\mathbf{T}\mathbf{H}\mathbf{F}$	65	24	В	1-(<i>p</i> -methoxyphenyl)-	0	<i>p</i> -methoxyethyl-	54	0
	DG	100	3	Α	ethanol	87	benzene	2	1
				В		0		88	1
<i>p</i> -chlorostyrene	THF^{d}	65	0.5	А	1-(<i>p</i> -chlorophenyl)-	74	<i>p</i> -chloroethyl-	18	trace
				В	ethanol	0	benzene	94	trace
1,1-diphenylethylene	THF^{e}	0	9	A, C			1,1-diphenylethane	94	4
cinnamaldehyde	THF^{f}	65	6	A	1-phenyl-1,3-	79.5	3-phenylpropanol	1	0
-				В	propanediol ⁱ	0	•	98	0
<i>p</i> -methoxystyrene <i>p</i> -chlorostyrene 1,1-diphenylethylene cinnamaldehyde	DG DG ^c THF DG THF ^d THF ^e THF ^f	100 100 65 100 65 0 65	1 1 24 3 0.5 9 6	B A A B B A B A B A C A B	 1-(p-methoxyphenyl)- ethanol 1-(p-chlorophenyl)- ethanol 1-phenyl-1,3- propanediolⁱ 	0 10 25 0 0 87 0 74 0 79.5 0	<i>p</i> -methoxyethyl- benzene <i>p</i> -chloroethyl- benzene 1,1-diphenylethane 3-phenylpropanol	44 44 61 88 54 2 88 18 94 94 94 1 98	4 2 2 0 1 1 trace trace 4 0

^{a,c-f} See corresponding footnotes in Table I. ^b Procedure A: protonolysis with acid, followed by oxidation. Procedure B: hydrolysis with water at 65-100 °C for 1 h. Procedure C: hydrolysis with water at room temperature for 15 min. ^g GC yield, unless otherwise stated. ^h All alcohols were 100% in their isomeric purity. ⁱ Isolated yield.

tribution on the α -position and vice versa. Reaction with lithium triethylborohydride, however, is not affected by these substituents, the only products being α -isomers. The positions of the boron atom are indicated by the arrows in Chart I.

Consequently, our present methods provide not only a simple hydrogenolysis of substituted styrenes but also an indirect Markovnikov hydroboration with exceptional regioselectivity. Thus it is now possible to effect both Markovnikov and anti-Markovnikov hydration of aromatically conjugated olefins (eq 18 and 19).



Mechanism. To summarize our results, the reaction of LiEt₃BH with styrene is favored by electron-withdrawing substituents and disfavored by electron-releasing ones.

The products in all cases studied have boron attached to the α -position. These two facts strongly suggest that the reaction involves a nucleophilic attack of R₃BH⁻ on the β -position of styrene to form ArCHCH₃⁻ as the intermediate, followed by trapping of the intermediate by R₃B (eq 20). The deep red color obtained in the reaction of 1,1-

ArCH=CH₂ +
$$R_3BH^-$$
 = [ArCHCH₃ + R_3B] - ArCH-CH₃

diphenylethylene with LiEt₃BH also supports our proposal of the intermediacy of benzylic anions in these reactions.

Experimental Section

All hydride solutions and organoboranes were always handled under an atmosphere of nitrogen. Hypodermic syringes and the double-ended needle technique³⁵ were used for transferring all air-sensitive materials. All glassware, syringes, and needles were oven-dried at 150 °C before use. The glassware was assembled while hot and cooled under a flow of nitrogen. ¹H NMR, IR, and mass spectra were obtained with a Varian T-60, a Perkin-Elmer 137, and a Hitachi RMU-6A, respectively. ¹¹B NMR spectra were obtained with a Varian XL-100-15 spectrometer. GC analyses of the products were carried out by using a Varian Model 1200 FID chromatograph using the following columns: 5% Carbowax 20M on a Varaport 30; 6 ft and 4 ft × 0.125 in and 5% SE-30 on Varaport 30, 6 ft × 0.125 in. Microanalysis was carried out by the Purdue Microanalytical Laboratory.

Materials. Tetrahydrofuran was distilled over $LiAlH_4$.³⁵ Diglyme was dried over CaH_2 and distilled over $LiAlH_4$ under reduced pressure.³⁵ Analytical-grade benzene was used after being stored over type 4A molecular sieves under nitrogen without further purification. All of the olefins used were commercially available and purified by distillation before use. Their purities were checked to be satisfactory by their refractive indices and some by GC. Triethylborane, tri-*n*-butylborane, and triisobutylborane obtained from Callery Chemical Co. were used without further purification. The absence of any peroxide or dialkylboranes was confirmed by ¹H NMR and the hydrolysis of an aliquot. Lithium hydride (96.8% assay) and sodium hydride (57% dispersion in oil) were obtained from Ventron Corp. Alfa Products. Lithium tri-sec-butylborohydride was obtained from

⁽³⁵⁾ Brown, H. C.; Kramer, G. W.; Levy, A. B.; Midland, M. M. "Organic Synthesis via Boranes"; Wiley-Interscience: New York, 1975.

Table IV. Stability of LiEt₃BH in Diglyme^a

time, h	loss at 100 °C, ^b %	loss at 160 °C, ^c %	
1		31	
3		71	
6		92	
12	5		
24	10		

^a Determined by hydrolysis for residual hydride concentration. ^b On a steam bath. ^c In refluxing diglyme.

Aldrich Chemical Co. as a 1 M solution in THF. Lithium triethylborohydride in THF was prepared by the reported procedure. 17

Preparation of LiEt₃**BH in Diglyme.** The quantities and procedure are essentially the same as the reagent in THF. The initial exothermic reaction may take place after about 10 min of addition, but sometimes it is necessary to warm to about 50 °C on a water bath. In either case, the temperature of the solution should be maintained below 100 °C (60–70 °C recommended) by cooling with ice because of the poor stability of the reagent in this solvent at high temperature (see Table IV). After the initial exothermic reaction, the solution was heated to 50–60 °C overnight and filtered. The concentration was in the range of 1.45-1.50 M. The solution is indefinitely stable for months at room temperature under dry nitrogen atmosphere.

Preparation of NaEt₃**BH**, Li-*n*-**Bu**₃**BH**, and Li-*i*-**Bu**₃**BH** in **THF** and **NaEt**₃**BH** in **Benzene**. These reagents were prepared by essentially the same procedure as that of LiEt₃**BH** in THF from the corresponding trialkylboranes and metal hydrides.

General Procedure for Rate and Stoichiometry Study. In all of the reactions, a one-necked, 50-mL, round-bottomed flask with a side arm fitted with a silicon rubber stopper was used. This was equipped with a magnetic stirring bar and a reflux condenser connected to a mercury bubbler, and a positive pressure of nitrogen was kept above the solution at all times. The reaction of LiEt₃BH with styrene in THF is representative. Thus, 17.2 mL(26.4 mmol, 10% excess) of a 1.54 M solution of LiEt₃BH in THF was introduced into the reaction flask, followed by 2.9 mL of THF and 8 mL (24 mmol) of a 3 M solution of isopropylbenzene (as internal standard for product analysis) in THF. Finally, 8 mL (24 mmol) of a 3 M solution of styrene in THF was injected while vigorously stirring (final concentration, 0.67 M in styrene) and the mixture was brought to reflux with a preheated heating mantle. After 1 h, the reaction mixture was cooled to room temperature with a water bath and 3 mL (2 mmol in the starting styrene and 2.2 mmol in LiEt₃BH) of an aliquot was removed with a syringe and hydrolyzed with a THF-water-glycerine (1:1:1) mixture. The volume of the hydrogen was measured in a gas buret, which indicated that 0.77 mol of hydride had reacted per mol of styrene; 2-, 3-, and 6-h readings showed 0.91, 0.96, and 0.99, respectively. The results for other compounds with various reagents are summarized in Tables I and II and graphically represented in Figures 1 and 2.

General Procedure for Product Studies. Procedure A. The above reaction mixture was further refluxed overnight, and 7.5 mL (5 mmol in styrene and 5.5 mmol in LiEt₃BH) of an aliquot was transferred to another flask and placed in a water bath. While vigorously stirring, 0.35 mL (5.5 mmol) of methanesulfonic acid was added dropwise. An immediate gas evolution (112 mL) was observed with a formation of white precipitate. The mixture was stirred for 15 min at room temperature and oxidized with 1.8 mL of 3 N NaOH and 2 mL of 30% H₂O₂ and stirred for 1 h at 40–50 °C in order to complete the oxidation. The aqueous layer was saturated with potassium carbonate, and the clear THF layer was analyzed by GC using a 6 ft Carbowax 20M column. Formations of 1-phenylethanol and ethylbenzene were observed in yields of 91% and 4%, respectively.

The procedure using HCl is essentially the same as above. Dry HCl was prepared in THF by dissolving HCl gas in cold (0 °C) THF and standardizing with standard base. In all cases, 1 mol of HCl was added per mol of LiEt_3BH .

Procedure B. The remaining reaction mixture was hydrolyzed with 5 mL of water and refluxed for 2 h. After oxidation, GC analysis showed formation of ethylbenzene in a 96% yield. There was no detectable 1-phenylethanol formed.

The results are summarized in Table III.

Deuterolysis of 2 with D₂**O**. The procedure is essentially the same as above; 10 mmol of styrene was refluxed with 11 mmol of LiEt₃BH in THF overnight and 1 mL (55 mmol) of D₂O was added and further refluxed for 4 h. After the workup, the product was distilled and further purified by preparative GC. A ¹H NMR spectrum of the sample showed that the product was α -deuterioethylbenzene (4): NMR (CCl₄, Me₄Si) δ 1.2 (td, J = 7.4 Hz, 3 H), 2.55 (tq, J = 7.4 Hz, 1 H), 7.1 (s, 5 H).

General Procedure for the Relative Rate Study. A typical reaction setup was assembled and 1.4 mL of THF, 4 mL (4 mmol) each of 1 M solutions of styrene, trans- β -methylstyrene, and isopropylbenzene (as internal standard) were introduced into the reaction flask. The mixture was stirred well, and 2.6 mL (4 mmol) of a 1.51 M solution of LiEt₃BH in THF was added dropwise. The resulting solution (0.25 M each in olefin and LiEt₃BH) was brought to gentle reflux and stirred for 4 h. At that time, an aliquot showed no hydride activity. The reaction mixture was cooled to room temperature, and 8 mL (2 mmol in each starting olefin) of an aliquot was treated with 0.15 mL (2.2 mmol) of methanesulfonic acid, according to procedure A. The remaining solution was hydrolyzed with 5 mL of water and refluxed for 1 h (procedure B). After oxidation of both mixtures, GC analysis showed the results summarized in Table V.

The relative rate, $k_{\rm rel} = k_{trans-\beta-methylstyrene}/k_{\rm styrene}$, was calculated to be 0.0082 and 0.015 by procedures A and B, respectively, by employing the expression of Ingold and Shaw,¹⁹ $k_{\rm rel} = (\log A_{\rm o} - \log A)/(\log B_{\rm o} - \log B)$.

The relative rates for other olefins were similarly calculated and these values are summarized in eq 2 and 3.

Preparation of Diethyl(1-phenylethyl)borane (3). A 43.7-mL (66 mmol) sample of a 1.51 M solution of LiEt₃BH in THF was introduced into a 200-mL flask, and 15 mL (60 mmol) of a 4 M solution of styrene in THF was added while vigorously stirring. The mixture was then refluxed overnight (~ 15 h) and cooled to room temperature with a water bath. To this was added 4.7 mL (73 mmol) of methanesulfonic acid dropwise. Ice was added to the water bath occasionally to cool the reaction mixture; 1.5 l of gas evolution was measured. After addition was complete, it was allowed to stir for 1 h at room temperature and the precipitate (MeSO₃Li) was filtered by using a sintered-glass filtering funnel (medium) under the positive pressure of nitrogen. The resulting clear solution was concentrated in vacuum and distilled under nitrogen. A total of 6.6 g (64% yield) of the product was collected as a colorless liquid: bp 67 °C (2 mmHg); ¹H NMR (neat, Me₄Si) δ 0.7–1.5 (m, 13 H, -CH₂-, -CH₃), 2.95 (q, J = 7.3 Hz, 1 H, >CH), 7.1 (s, 5 H, aromatic); ¹¹B NMR (THF, BF₃·OEt₂) δ 80.2.

GC analysis after oxidation of 1 mL (0.855 g, 4.91 mmol) of the product showed the formation of 4.44 mmol of 1-phenylethanol, 0.25 mmol of ethylbenzene, and 9.67 mmol of ethanol [(1-phenylethanol + ethylbenzene):ethanol, 1:2.06].

Preparation of Diethyl(1-phenylpropyl)borane (5). The procedure is the same as above. To 71.9 mL (110 mmol) of a 1.53 M solution of LiEt_3BH in THF was added 13.1 mL (100 mmol) of *trans-\beta*-methylstyrene in 50 mL of THF, and the solution was

pre	ocedure	ethyl- benzene ^b	1-phenyl- ethanol ^b	styrene ^c	<i>n-</i> propyl- benzene ^b	1-phenyl-1- propanol ^b	<i>trans-β-</i> methylstyrene ^c	
	A B	0.04 2.96	2.8 0	0.68 0.68	0 0.08	0.04 0	3.92 3.88	

^a 0.25 M in each olefin and LiEt₃BH. ^b mmol formed per 4 mmol of compound. ^c mmol unreacted per 4 mmol of compound.

refluxed for 48 h. After the mixture was cooled to room temperature, 7.2 mL (110 mmol) of methanesulfonic acid was added and the precipitate was filtered. Distillation gave 12.0 g (64% yield) of the product as a colorless liquid: bp 55 °C (0.3 mmHg); ¹H NMR (CCl₄, Me₄Si) δ 0.7–1.3 (m, 13 H, -CH₂-, -CH₃), 1.8 (m, 2 H, -CH₂-), 2.8 (dd, J = 8, 6 Hz, 1 H, >CH), 7.05 (s, 5 H, aromatic); ¹¹B NMR (THF, BF₃·OEt₂) δ 81.7.

Oxidation of the product (1 mL, 0.85 g, 4.52 mmol) gave 4.36 mmol of 1-phenyl-1-propanol, 0.14 mmol of *n*-propylbenzene, and 9.07 mmol of 1-propanol [(1-phenyl-1-propanol + *n*-propylbenzene):1-propanol, 1:2.02].

Preparation of 3-Ethyl-4-phenyl-3-hexanol (6) by DCME **Reaction of 5.** The reported procedure by Brown and co-workers was followed.³⁰ In a 100-mL flask, 25 mL of THF and 5 mL (4.27 g, 22.7 mmol) of 5 were introduced and cooled to 0 °C. To this was added 2.5 mL (27.5 mmol) of freshly distilled dichloromethyl methyl ether, followed by the dropwise addition of 13.5 mL (23.2 mmol) of a 1.72 M solution of lithium triethylcarboxide in hexane. The mixture was then allowed to warm to room temperature for 30 min, during which time a heavy white precipitate of lithium salt formed. Then, 25 mL of 95% ethanol was added, followed by 6 g of sodium hydroxide pellets. Oxidation was carried out by the slow, careful addition of 20 mL of 30% hydrogen peroxide at 0 °C, followed by warming to 50-60 °C for 1 h. The aqueous layer was saturated with potassium carbonate and the layers were separated. The organic layer was washed with saturated potassium carbonate solution $(2 \times 25 \text{ mL})$ and dried over potassium carbonate. Solvents were evaporated on a rotary evaporator, and vacuum distillation gave 3.81 g (81.3% yield) of the product as a colorless oil: bp 112–113 °C (3 mmHg); n²⁰_D 1.5108; ¹H NMR $(CCl_4, Me_4Si) \delta 0.8-2.0 (m, 15 H, -CH_2, -CH_3), 1.3 (s, 1 H, -OH),$ 2.5 (dd, J = 10, 6 Hz, 1 H, \geq CH), 7.2 (s, 5 H, aromatic); mass spectrum 75 eV), m/e (relative intensity), 206 (0.5, M⁺), 188 (2, $M^+ - H_2O$), 177 (30, $M^+ - C_2H_5$), 91 (53, $C_7H_7^+$), 87 (100, $C_5H_{11}O^+$); IR (neat) 3490, 1160, 1140 cm⁻¹.

Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.75. Found: C, 81.57; H, 10.87.

Reaction of LiEt₃BH with Cinnamaldehyde (1:1) in THF at 25 °C. In a 50-mL flask, 2.2 mL of THF, 5.8 mL (8.8 mmol, 10% excess) of a 1.52 M solution of LiEt₃BH in THF, and 2 mL (4 mmol) of a 2 M solution of ethylbenzene (internal standard) were placed, and 2 mL (8 mmol) of a 4 M solution of cinnamaldehyde in THF was added while stirring at room temperature. After 15 min, hydrolysis of 3 mL of an aliquot evolved 4.5 mL of hydrogen, which corresponded to the hydride uptake of 1.01. The mixture was allowed to stir for another 15 min and hydrolyzed with 2 mL of water. After oxidation, GC analysis showed the formation of cinnamyl alcohol (8) in 97% yield and a trace of hydrocinnamyl alcohol.

Reaction of LiEt₃BH with Cinnamaldehyde (2:1) in THF at 65 °C. Synthesis of 1-Phenyl-1,3-propanediol (10) by Procedure A. In a 500-mL flask, 145 mL (220 mmol) of a 1.52 M solution of LiEt₃BH in THF was placed and 12.6 mL (100 mmol) of cinnamaldehyde in 50 mL of THF was added at room temperature while stirring, and the mixture was refluxed for 6 h. The flask was cooled to 0 °C with an ice bath, and 14.5 mL (226 mmol) of methanesulfonic acid was added over 10 min (gas evolution!). The mixture was allowed to warm to room temperature for 30 min and oxidized with 74 mL of 3 N NaOH and 74 mL of 30% H_2O_2 . The mixture was allowed to stir for 1 h at 40-50 °C, and then the aqueous layer was saturated with potassium carbonate. The organic layer was separated and washed with saturated aqueous potassium carbonate solution $(2 \times 20 \text{ mL})$ and dried over potassium carbonate. Upon evaporating the solvent with a rotary evaporator, 15.1 g of a slightly yellowish oil was obtained. Vacuum distillation of this oil produced 12.1 g (79.5% yield) of the product as a colorless oil: bp 117-118 °C (0.25 mmHg); n^{20}_{D} 1.5447 [lit.¹⁷ bp 100 °C (0.2 mmHg), n^{20}_{D} 1.5451]; ¹H NMR (CDCl₃, Me₄Si) δ 1.8 (m, 2 H, -CH₂-), 3.61 (m, 2 H, -CH₂-), 4.1 (t, 1 H, -OH), 4.55 (d, 1 H, -OH), 4.75 (m, 1 H, \geq CH), 7.23 (s, 5 H, aromatic).

The isomeric purity of this diol was determined by silation³⁶ with trimethylchlorosilane in pyridine and analyzing by GC (6 ft SE-30). The product was found to be 100% 1,3-diol by comparison with the retention times of 1-phenyl-1,3-propanediol and 3-phenyl-1,2-propanediol.

Registry No. 2, 62483-56-1; 3, 62497-97-6; 4, 1861-02-5; 5, 62497-98-7; 6, 62497-99-8; 7, 104-54-1; 8, 62483-57-2; 9, 122-97-4; 10, 4850-49-1; 11, 67997-44-8; PhCH=CH2, 100-42-5; trans-PhCH=CHCH3, 873-66-5; PhCH=CHCH0, 104-55-2; LiEt₃BH, 22560-16-3; PhCH₂CH₃, 100-41-4; Li(*n*-Bu)₃BH, 67335-72-2; Li-(*i*-Bu)₃BH, 63717-73-7; Li(*sec*-Bu)₃BH, 38721-52-7; CH₃SO₃H, 75-75-2; CH₃OCHCl₂, 4885-02-3; α -methylstyrene, 98-83-9; *p*-methoxystyrene, 637-69-4; *p*-chlorostyrene, 1073-67-2; 1,1-diphenylethylene, 530-48-3; 1-phenylethanol, 98-85-1; 1-phenyl-propanol, 93-54-9; 1-phenyl-2-propanol, 1123-85-9; 1-(*p*-methoxyethylbenzene, 103-65-1; isopropylbenzene, 98-82-8; *p*-methoxyethylbenzene, 105-95-3; *p*-chlorostyrlene, 622-98-0; 1,1-diphenylethane, 612-00-0.

(36) Pierce, A. E. "Silation of Organic Compounds"; Pierce Chemical Co.: Rockford, IL, 1968.