of several aromatics. These observations are summarized in Table IV.

The logarithms of the partial rate factors are plotted against the standard electrophilic substituent constants,[13] σ^+, in Fig. 1. With but one exception, *p*-fluoro, the data are correlated with excellent precision. Omission of the *p*-fluoro point yields the reaction constant for the ethylation reaction as -2.44.

Experimental Part

Materials.—Gallium bromide,[5] ethyl bromide[5] and ethylene dichloride[14] were prepared and purified following procedures previously described. The halobenzenes were samples purified by Goldman.[15] Authentic *o*-chloroethylbenzene was prepared by the Sandmeyer reaction from *o*-ethylaniline. *m*-Bromoethylbenzene was available from an earlier study.[16] The chlorination and bromination of ethylbenzene providing the *ortho* and *para* isomers were carried out by procedures previously utilized to establish the isomer distribution in toluene.[7,17]

Relative Rates.—A solution of gallium tribromide in ethyl bromide was prepared with careful exclusion of moisture. An appropriate small quantity of this standard solution, usually about 1 ml., was taken up in a hypodermic syringe and introduced into 50 ml. of a solution of the halobenzene and benzene in ethylene dichloride at 25°. After an appropriate reaction period, 2 to 10 hours in different experiments, the reaction mixture was quenched in ice-water. The ethylene dichloride layer was separated, washed, and dried.

The solution was analyzed on a Perkin-Elmer Fractometer (model 154C) equipped with an integrator utilizing a 2-m. column with tricresyl phosphate as the liquid phase on Celite. The concentration of each aromatic was evaluated; *i.e.*, benzene in the ethylated mixture was determined relative to benzene in the original solution and each halobenzene similarly determined. In view of excellent reproducibility in sampling techniques, 1%, an internal standard was not employed. The temperatures utilized for the analyses were: benzene, 58°; fluorobenzene, 58°; chlorobenzene, 104°; bromobenzene, 130°. The results are summarized in Table I.

Isomer Distribution.—In a typical experiment an ethylene dichloride solution of bromobenzene, 0.7 *M*, was treated with gallium tribromide, 0.04 *M*, and ethyl bromide, 0.5 *M*. After 8 hours, the reaction mixture was quenched and analyzed on a 4-m. column of tricresyl phosphate on Celite.

For fluorobenzene and chlorobenzene, ethylene dichloride was eliminated and excess aromatic was employed as the solvent. Thus fluorobenzene was treated with ethyl bromide, 0.5 *M*, and gallium bromide, 0.04 *M*. After 2 hours, the reaction mixture was quenched, dried, and analyzed on a Perkin-Elmer Fractometer (model No. 154D) equipped with a 50-m. polypropylene glycol column and a flame ionization detector.

The isomer distributions obtained are summarized in Table II.

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[13] H. C. Brown and Y. Okamoto, *J. Am. Chem. Soc.*, **80**, 4929 (1958).

[14] F. R. Jensen, G. Marino and H. C. Brown, *ibid.*, **81**, 3303 (1959).

[15] H. C. Brown and G. Goldman, *ibid.*, **84**, 1650 (1962).

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[17] H. C. Brown and L. M. Stock, *ibid.*, **79**, 5175 (1957).

[CONTRIBUTION FROM THE RICHARD B. WETHERILL LABORATORY OF PURDUE UNIVERSITY, LAFAYETTE, IND.]

Relative Rates and Isomer Distributions in the Aluminum Chloride-Catalyzed Acetylation of the Halobenzenes in Ethylene Dichloride. Partial Rate Factors for the Acetylation Reaction[1]

BY HERBERT C. BROWN AND GIANLORENZO MARINO[2]

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The rate of aluminum chloride-catalyzed acetylation of chlorobenzene relative to benzene in ethylene dichloride at 25° is 0.0209. Under these conditions the reaction yields 0.5% *m*- and 99.5% *p*-chloroacetophenone. These results lead to the partial rate factors m_f^{Cl} 0.0003 and p_f^{Cl} 0.125. Comparison of the rate of acetylation of fluorobenzene and bromobenzene relative to chlorobenzene leads to the relative rates, $k_{FC_6H_5}/k_{C_6H_6}$ 0.252 and $k_{BrC_6H_5}/k_{C_6H_6}$ 0.0140. In both cases essentially 100% substitution in the *para* position is observed. These results provide the partial rate factors, p_f^F 1.51 and p_f^{Br} 0.084. The negligible substitution in the *ortho* position is in accord with the very large steric requirements of the acetylation reaction, noted previously in the acetylation of toluene The order $p_f^F > p_f^{Cl} > p_f^{Br}$ agrees with the relative conjugative abilities of these halogens and with their relative effectiveness in facilitating reaction in mercuration, ethylation and *t*-cumyl solvolysis. The observation that p_f^F is greater than unity is in agreement with the results for mercuration and *t*-cumyl chloride solvolysis, but not with the behavior of *p*-fluoro in the ethylation reaction. The available data on the acetylation of monosubstituted benzenes provide an excellent linear free energy correlation with the electrophilic substituent constants, σ^+, derived from the solvolysis of the *t*-cumyl chlorides.

Introduction

The acetylation reaction has previously proved to be a convenient tool for the investigation of directive effects in toluene,[3] *t*-butylbenzene,[4] anisole,[5] biphenyl[6] and fluorene.[6] In previous papers of this group, electrophilic substitution data for the halobenzenes in the mercuration[7a] and ethylation[7b] reactions have been reported. These reactions exhibit a relatively low selectivity, with S_f 1.014 and 0.587, respectively. In the present paper, data for the acetylation reaction, one of higher selectivity, S_f 2.192, are presented. In the following paper the more selective halogenation reactions are examined[7c] and in the final paper[7d] the applicability of the Selectivity Relationship[8,9] for the correlation of the available data on the electrophilic substitution of the halobenzenes is considered.

Several studies of the acetylation of the halobenzenes have been reported. Thus, the acetylation of chlorobenzene, either in carbon disulfide[10-12] or

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[1] Directive Effects in Aromatic Substitution. LII.

[2] Post-doctorate research associate, 1957–1959, on project no. AT(11-1)-170 supported by the Atomic Energy Commission.

[3] H. C. Brown, G. Marino and L. M. Stock, *J. Am. Chem. Soc.*, **81**, 3310 (1959).

[4] H. C. Brown and G. Marino, *ibid.*, **81**, 5611 (1959).

[5] H. C. Brown and G. Marino, unpublished research.

[6] H. C. Brown and G. Marino, *J. Am. Chem. Soc.*, **84**, 1236 (1962).

[7] (a) H. C. Brown and G. Goldman, *ibid.*, **84**, 1650 (1962); (b) H. C. Brown and A. H. Neyens, *ibid.*, **84**, 1655 (1962); (c) L. M. Stock and F. W. Baker, *ibid.*, **84**, 1661 (1962); (d) L. M. Stock and H. C. Brown, *ibid.*, **84**, 1668 (1962).

[8] H. C. Brown and K. L. Nelson, *ibid.*, **75**, 6292 (1953).

[9] H. C. Brown and C. W. McGary, Jr., *ibid.*, **77**, 2300 (1955).

TABLE I

HALOBENZENE TO BENZENE REACTIVITY RATIOS FOR THE ALUMINUM CHLORIDE-CATALYZED ACETYLATION IN ETHYLENE DICHLORIDE AT 25.0°

Concentrations, *M*								
Starting materials					Products			
[$CH_3COCl \cdot AlCl_3$]	[C_6H_6]	[FC_6H_5]	[ClC_6H_5]	[BrC_6H_5]	[$XC_6H_4COCH_3$]	[$ClC_6H_4COCH_3$]	Exptl. relative rates[a]	Reactivity ratio, $k_{C_6H_5X}/k_{C_6H_6}$
0.200	0.300		0.900		0.1840	0.0159	0.0191	0.0191
.150	.225		.675		.1375	.0125	.0198	.0198
.100	.150		.900		.0652	.0121	.0238	.0238
							Mean value	.0209[b]
0.0600		0.0524	0.225		0.0239	0.0116	11.5	0.239
0.0600		0.0800	0.324		0.0135	0.00464	12.7	0.266
							Mean value	0.252[c]
0.0800			0.133	0.134	0.0162	0.0247	0.628	0.0131
0.0600			0.136	0.117	0.00432	0.00696	0.710	0.0148
							Mean value	0.0140[d]

[a] Comparisons of chlorobenzene to benzene, fluorobenzene to chlorobenzene and bromobenzene to chlorobenzene, respectively. [b] X = Cl. [c] X = F. [d] X = Br.

chlorobenzene[13] as solvent, has been reported to give *p*-chloroacetophenone exclusively. Similarly, *p*-bromoacetophenone is reported to be the sole product from the acetylation of bromobenzene.[11,14–16]

McDuffie and Dougherty determined the rates of acetylation of chlorobenzene and bromobenzene relative to benzene by a competitive procedure.[17] The values obtained are chlorobenzene, 0.031, and bromobenzene, 0.024, relative to benzene, 1.00. Unfortunately, the conditions employed by McDuffie and Dougherty could result in a heterogeneous reaction. Moreover, the observed toluene to benzene rate ratio,[17] 13.3, was in serious error with the value, 128, obtained for the relative rate under homogeneous conditions in ethylene dichloride.[3] More recently Smeets and Verhulst examined the kinetics of the acylation of a number of aromatic compounds including chlorobenzene and bromobenzene.[18] They followed the reaction by titration of the hydrogen chloride liberated in the course of the reaction. Unfortunately, the reaction with benzene proved to be too fast for this technique.

A careful review of these studies suggested the possibility of rather large errors or uncertainties. Accordingly, it appeared desirable to re-examine the acetylation of the halobenzenes under standard conditions employing gas chromatography and infrared spectroscopy for the analysis of rates and isomer distributions.

Results

Relative Rate Determinations.—Mixtures of the halobenzenes and benzene in ethylene dichloride were treated with a freshly prepared solution of aluminum chloride–acetyl chloride in ethylene dichloride. After an appropriate time, the reaction mixture was quenched, washed, dried, and analyzed by gas chromatography for the products. The relative reactivities were calculated by means of the relationship 1

$$\frac{k_X}{k_B} = \frac{\log(B^0 - X_B)/B^0}{\log(A^0 - X_A)/A^0} \tag{1}$$

In this expression, A^0 and B^0 are the initial concentration of benzene and the halobenzene, respectively. The symbols X_A and X_B refer to the final concentration of product acetophenone and the isomeric haloacetophenone. The first experiments established the relative rate of acetylation of chlorobenzene compared to benzene. In subsequent work, it proved more convenient to compare fluorobenzene and bromobenzene with chlorobenzene rather than in direct competition with benzene.

The relative rate data are assembled in Table I.

Analysis of reaction mixtures which were maintained for periods of time sufficient to complete the reaction revealed the yields of acetophenones were not quantitative. Yields were only 50–65% of the theoretical. This is in contrast with the results for more active aromatics which provided essentially quantitative conversions to the acetophenones.[3–6]

It is known that the 1:1 complex of aluminum chloride and acetyl chloride, $CH_3COCl \cdot AlCl_3$, is somewhat unstable. Solutions of aluminum chloride in acetyl chloride are reported to undergo secondary reactions.[19–21] It was observed that freshly prepared solutions of the complex in ethylene dichloride evolved hydrogen chloride slowly at 25°. The decomposition is sufficiently slow as to be unimportant in the case of the more active aromatics.[3–6] The side-reaction, however, becomes significant with the less reactive halobenzenes. Fortunately, this side-reaction does not influence the relative rates. The latter results are based on a comparison of the two acetophenones produced in the competitive reactions. The data reveal reason-

TABLE II

PARTIAL RATE FACTORS FOR THE ACETYLATION OF THE HALOBENZENES IN ETHYLENE DICHLORIDE AT 25°

Halogen	Relative rate	Partial rate factors		
		o_f	m_f	p_f
Fluoro	0.252	Small	Small	1.51
Chloro	.0209	Small	0.0003	0.125
Bromo	.0140	Small	Small	0.084

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(16) W. J. Hale and L. Thorp, *J. Am. Chem. Soc.*, **35**, 262 (1913).

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(18) F. Smeets and J. Verhulst, *Bull. soc. chim. Belg.*, **63**, 439 (1954).

(19) A. Combes, *Compt. rend.*, **103**, 816 (1886).

(20) J. Boeseken, *Rec. trav. chim.*, **20**, 102 (1901).

(21) N. N. Greenwood and K. Wade, *J. Chem. Soc.*, 1527 (1956).

TABLE III

PARTIAL RATE DATA FOR THE ALUMINUM CHLORIDE-CATALYZED ACETYLATION OF SUBSTITUTED BENZENES IN ETHYLENE DICHLORIDE AT 25.0°

Substituent	Rel. rate, k_R/k_B	Isomer distribution %			Partial rate factors			Ref.
		ortho	*meta*	*para*	o_f	m_f	p_f	
Methoxy	2.93×10^5			(~100)			1.76×10^6	a
(Fluorene)[f]	12600			(~100)			3.8×10^4	b
Methyl	128	1.17	1.25	97.6	4.5	4.8	749	c
Ethyl	129	0.3	2.7	97.0	1.0	10.4	753	d
Isopropyl	128	0	3.0	97.0	0.0	11.5	745	d
t-Butyl	114	0	3.8	96.2	0	13.0	658	d
Phenyl	85			97.3			248	c
Hydrogen	1.00				1.00	1.00	1.00	
Fluoro	0.252			(~100)			1.51	e
Chloro	.0209		0.5	99.5		0.0003	0.125	e
Bromo	.0140			(~100)			0.084	e

[a] Ref. 5. [b] Ref. 6. [c] Ref. 3. [d] Ref. 4. [e] Present study. [f] Substitution of fluorene in the 2-position.

able agreement between different experiments in which the concentrations of the complex and the two aromatics were varied.

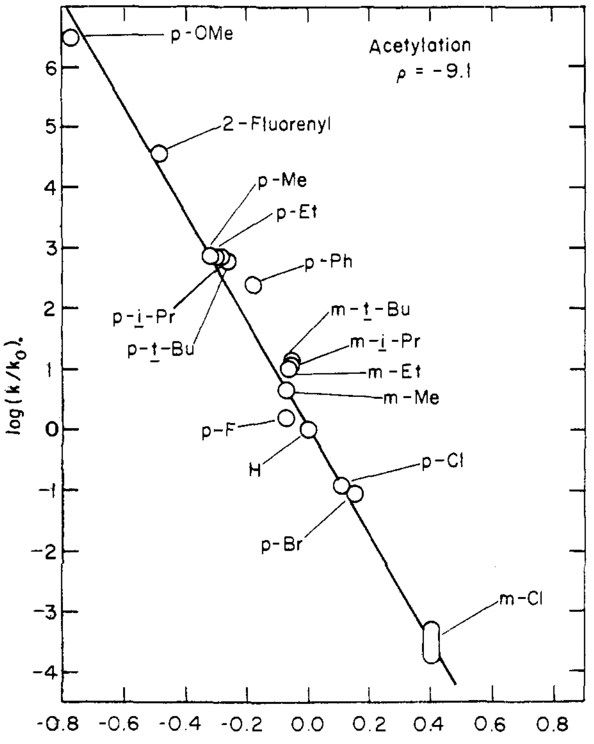

Fig. 1.—Relationship between log(k/k_0) for acetylation and the σ^+-constants.

Isomer Distributions.—Each of the three halobenzenes was acetylated under the conditions established for the relative rate studies to determine the isomer distributions. Examination of the products of acetylation of each halobenzene by gas chromatography revealed only a single sharp peak. Pure crystalline samples of *p*-chloro- and *p*-bromoacetophenone were prepared and utilized as standards for the infrared examination of the reaction products from the acetylation. The results confirmed the formation of *p*-chloro- and *p*-bromoacetophenone completely free of isomeric impurities.

A more detailed study was made of the reaction product from chlorobenzene in an attempt to establish the amount of *m*-chloroacetophenone formed in the acetylation reaction. Synthetic mixtures of carefully purified *m*- and *p*-chloroacetophenone containing 0.2, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0% of the *meta* isomer were prepared and analyzed by infrared spectroscopy with the pure *para* isomer in the reference cell. The product formed in the acetylation of chlorobenzene was examined under the same conditions. A comparison of the optical densities at 12.5 and 14.6 μ (characteristic bands for *m*-benzene derivatives),[22] indicated the *meta* isomer was present in 0.5% quantity. The intensities of the bands at such a low concentration are of the same order of magnitude as that of the background noises. Accordingly, the value must be considered only approximate.

Discussion

The relative rates of acetylation of fluoro-, chloro- and bromobenzene and the isomer distributions (100% *para*) permit calculation of the partial rate factors for *para* substitution. In the case of chlorobenzene, the rough estimate of 0.5% *m*-chloroacetophenone yields the approximate value, m_f^{Cl} 0.0003. These results are summarized in Table II.

The negligible substitution in the *ortho* position is in accord with the apparently large steric requirements of the acetylation reaction. Thus, acetylation of toluene was observed to give 1.17% *o*-, 1.25% *m*- and 97.6% *p*-methylacetophenone.[3]

The halogen substituents deactivate the rings toward substitution, but the effect is particularly important in the *meta* position. The value of m_f^{Cl} is only 0.2% of p_f^{Cl}. As a consequence of the large steric factor in the *ortho* position, and the strong deactivation of the *meta* position, the selective acetylation reaction produces the *para* isomer in an isomeric purity approaching 100%.

The *para* partial rate factors increase in the order: $p_f^F > p_f^{Cl} > p_f^{Br}$. This is the order to be anticipated on the basis of the conjugative properties of the three halogens. It is noteworthy that p_f^F is greater than unity. This behavior corresponds qualitatively with the observations for the mercuration reaction,[7a] and for the solvolysis of the *t*-cumyl chloride.[23] The result is contrary, however, to the

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[22] L. J. Bellamy, "The Infrared Spectra of Complex Molecules," 2nd ed., Methuen and Co., Ltd., London, 1958.

influence of the *p*-fluoro substituent in ethylation.[7b] A more detailed discussion is reserved for the final paper.[7d]

Correlation of the Acetylation Data.—Data have now been obtained for 11 *para* substituents and 5 additional *meta* groups covering a broad range of reactivity. It is of interest at this time to test a correlation of these data against the set of electrophilic substituent constants, σ^+, based upon the solvolysis of substituted *t*-cumyl chlorides.[23] The data are summarized in Table III.

The linear relationship between $\log(k/k_0)$ and σ^+ is illustrated in Fig. 1.

Experimental Part

Materials.—Aluminum chloride, acetyl chloride and ethylene dichloride were purified as described previously.[3,24,25] The halobenzenes were commercial products distilled through an efficient column: fluorobenzene, b.p. 83.9–84.2° at 751 mm., n^{20}_D 1.4666; chlorobenzene, b.p. 130.7–130.8° at 745 mm., n^{20}_D 1.5244; bromobenzene, b.p. 154° at 748 mm., n^{20}_D 1.5595.

p-Chloroacetophenone was synthesized in 85% yield,[26] converted to the semicarbazone, and the latter was recrystallized to constant m.p. 200–200.5°.[27] The ketone was regenerated by heating with hydrochloric acid,[28] The product exhibited the constants: b.p. 84–85,5° at 3 mm., n^{20}_D 1.5555, m.p. 19°.[27] *m*-Chloroacetophenone was a sample available from an earlier synthesis by Mr. T. Kawanami (methylcadmium chloride and *m*-chlorobenzoyl chloride): b. p. 102.5–103.5° at 10 mm. Similarly, *p*-bromo- and *p*-fluoroacetophenone were available from earlier studies.

Relative Rates.—The procedure utilized for the relative rate studies was essentially that developed earlier for determining the toluene to benzene reactivity ratio.[3] After the reaction mixture had been quenched, *p*-nitroanisole was added as an internal standard. Calibration curves were constructed for synthetic mixtures of *p*-nitroanisole and the acetophenones. The concentrations of the ketones were determined by comparison of the area of the product peaks with the area of the internal standard peak. The results are summarized in Table I.

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[CONTRIBUTION FROM THE GEORGE HERBERT JONES LABORATORY OF THE UNIVERSITY OF CHICAGO, CHICAGO 37, ILL.]

Rates and Isomer Distributions in the Non-catalytic Chlorination of the Halobenzenes and Certain Halotoluenes in Aqueous Acetic Acid. Partial Rate Factors for the Halogenation of the Halobenzenes[1]

BY LEON M. STOCK AND FRANK W. BAKER[2]

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The non-catalytic chlorination of the halobenzenes and certain halotoluenes has been examined in an acetic acid solvent containing 20.8 *M* H_2O and 1.2 *M* HCl at 25°. The relative rates of chlorination established are benzene, 1.00; fluorobenzene, 0.74; chlorobenzene, 0.10; bromobenzene, 0.072. The isomer distributions found for reaction under kinetic conditions were 10.9% *o*- and 89.1% *p*-chlorofluorobenzene; 32.4% *o*- and 67.6% *p*-dichlorobenzene; 38.6% *o*- and 61.4% *p*-chlorobromobenzene. These observations provide the partial rate factors: o_f^{F} 0.22, p_f^{F} 4.0; o_f^{Cl} 0.097, p_f^{Cl} 0.41; o_f^{Br} 0.084, p_f^{Br} 0.31. *meta* Partial rate factors were estimated by an examination of the relative rates and product distributions for the chlorination of *p*-fluoro-, *p*-chloro- and *p*-bromotoluene. The rates relative to benzene adopted as 1.00 were *p*-fluorotoluene, 1.94; *p*-chlorotoluene, 0.51; *p*-bromotoluene, 0.49. The product distributions were found to be 64.2% 2- and 35.8% 3-chloro-4-fluorotoluene; 76.8% 2,4- and 24.2% 3,4-dichlorotoluene; 86.3% 2- and 13.7% 3-chloro-4-bromotoluene. The m_f-values estimated from rate data were not fully consistent with those predicted from the product ratios. The average m_f-values are m_f^{F} $5.6 \pm 1.9 \times 10^{-3}$, m_f^{Cl} $2.3 \pm 0.6 \times 10^{-3}$, m_f^{Br} $3.2 \pm 1.6 \times 10^{-3}$. A study of the chlorination of *o*- and *m*-chlorotoluene revealed the rates exhibited a 30% deviation from calculated values. Apparently the additivity principle is not entirely satisfactory for these aromatics. The results for non-catalytic halogenation and bromination by hypobromous acid are summarized and examined for adherence to a first-order $\rho\sigma^+$ treatment. The correlations obtained are indicative of the utility of the σ^+-constants.

Introduction

The influences of the halogens on reactivity have presented a difficult test of theory. A most salient observation was made by Dippy and Lewis[3] who pointed out the combination of the electron-withdrawing inductive effect with the electron-donating resonance effect could lead to any order of reactivity of the four halogens. The information available in the literature suggested the inductive effect was dominant in aliphatic compounds.[4] On the other hand, reactions involving the development of an electron-deficient transition state revealed the resonance contributions of the halogens to be considerable.[5]

Few quantitative studies of the electrophilic substitution reactions of the halobenzenes have been reported. An examination of the data for the halogenation indicated several deficiencies. The most pertinent study, an investigation of the chlorination in 80% acetic acid, was carried out in 1948.[6] Unfortunately, the relative rates for the halobenzenes compared to benzene in the chlorination reaction were based on an estimated rate constant for benzene under the conditions adopted. Further, the product ratios for non-catalytic chlorination

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(1) Directive Effects in Aromatic Substitution. LIII. In view of the similar objectives of this study and the efforts of Professor Herbert C. Brown in this area, this report is presented together with the other studies of the substitution reactions of the halobenzenes.

(2) National Science Foundation Summer Fellow, 1961.

(3) J. F. J. Dippy and R. H. Lewis. *J. Chem. Soc.*, 644 (1936).

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