SOME MODERN METHODS OF ORGANIC SYNTHESIS

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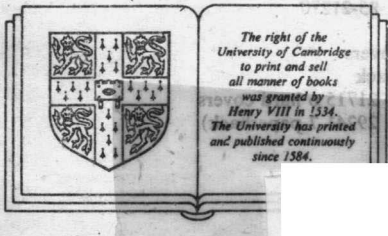
THIRD EDITION



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Preface to the first edition

This book is addressed principally to advanced undergraduates and to graduates at the beginning of their research careers, and aims to bring to their notice some of the reactions used in modern organic syntheses. Clearly, the whole field of synthesis could not be covered in a book of this size, even in a cursory manner, and a selection has had to be made. This has been governed largely by consideration of the usefulness of the reactions, their versatility and, in some cases, their selectivity.

A large part of the book is concerned with reactions which lead to the formation of carbon–carbon single and double bonds. Some of the reactions discussed, such as the alkylation of ketones and the Diels–Alder reaction, are well established reactions whose scope and usefulness has increased with advancing knowledge. Others, such as those involving phosphorus ylids, organoboranes and new organometallic reagents derived from copper, nickel, and aluminium, have only recently been introduced and add powerfully to the resources available to the synthetic chemist. Other reactions discussed provide methods for the functionalisation of unactivated methyl and methylene groups through intramolecular attack by free radicals at unactivated carbon–hydrogen bonds. The final chapters of the book are concerned with the modification of functional groups by oxidation and reduction, and emphasise the scope and limitations of modern methods, particularly with regard to their selectivity.

Discussion of the various topics is not exhaustive. My object has been to bring out the salient features of each reaction rather than to provide a comprehensive account. In general, reaction mechanisms are not discussed except in so far as is necessary for an understanding of the course or stereochemistry of a reaction. In line with the general policy in the series references have been kept to a minimum. Relevant reviews are noted but, for the most part, references to the original literature are given only for points of outstanding interest and for very recent work. Particular reference is made here to the excellent book by H. O. House, *Modern Synthetic Reactions* which has been my guide at several points and on which I have tried to build, I feel all too inadequately.

I am indebted to my friend and colleague, Dr K. Schofield, for much helpful comment and careful advice which has greatly assisted me in writing the book.

W. CARRUTHERS
26 October 1970

Preface to the third edition

The general plan of this third edition follows that of the earlier editions, but the opportunity has been taken to bring the book up to date as far as possible and to take account of advances in knowledge and of new synthetic methods which have come into use since publication of the second edition. Perhaps the most striking trend in synthesis since then has been the development of highly stereoselective reactions and their application in complex syntheses. These reactions include the stereoselective alkylation of carbonyl compounds, stereoselective aldol condensations and stereoselective oxidations, epoxidations and reductions, and these are among the topics discussed in this edition. New methods for the stereoselective formation of carbon–carbon double bonds, and modern applications of the Diels–Alder reaction, particularly its use in the control of stereochemistry in the synthesis of natural products, and the related class of 1,3-dipolar cyclo-addition reactions are also considered. Other sections of the book are concerned with the increasingly important application in synthesis of organo-metallic reagents, including organoboranes and organosilanes and reagents derived from copper, nickel and palladium, and with the continuing interest in selective reactions at unactivated carbon–hydrogen bonds.

The book is addressed principally to advanced undergraduates and to graduates at the beginning of their research careers, and my aim has been to bring out the salient features of the reactions and reagents rather than to provide a comprehensive account. Reaction mechanisms are not discussed except in so far as is necessary for an understanding of the course or stereochemistry of a reaction. To prevent the book from becoming too big some material of less immediate interest which appeared in earlier editions has been excised from this one. Discussion of new reactions is supported by references.

W. CARRUTHERS

May 1985

Contents

1 Formation of carbon–carbon single bonds

In spite of the fundamental importance in organic synthesis of the formation of carbon–carbon single bonds there are comparatively few general methods available for effecting this process, and fewer still which proceed in good yield under mild conditions. Many of the most useful procedures involve carbanions, themselves derived from organometallic compounds, or from compounds containing 'activated' methyl or methylene groups. They include reactions which proceed by attack of the carbanion on a carbonyl or conjugated carbonyl group, as in the Grignard reaction, the aldol and Claisen ester condensations and the Michael reaction, and reactions which involve nucleophilic displacement at a saturated carbon atom, as in the alkylation of ketones and the coupling reactions of some organometallic compounds. Other reactions employed in the formation of carbon–carbon bonds involve carbonium ions and pericyclic processes and recently free-radial reactions have been finding useful application. Examples of all of these procedures will be discussed in this chapter.

1.1. Alkylation: importance of enolate anions

It is well known that certain unsaturated groups attached to a saturated carbon atom render hydrogen atoms attached to that carbon relatively acidic, so that the compound can be converted into an anion on treatment with an appropriate base. Table 1.1, taken from House (1965), shows the pK_a values for some compounds of this type and for some common solvents and reagents.

The acidity of the C—H bonds in these compounds is due to a combination of the inductive electron-withdrawing effect of the unsaturated groups and resonance stabilisation of the anion formed by removal of a proton (1.1). Not all groups are equally effective in 'activating' a neighbouring CH_2 or CH_3; nitro is the most powerful of the common groups and thereafter the series follows the approximate order $NO_2 > COR > SO_2R > CO_2R > CN > C_6H_5$. Two activating groups reinforce

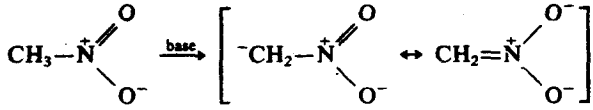
Table 1.1. *Approximate acidities of active methylene compounds and other common reagents*

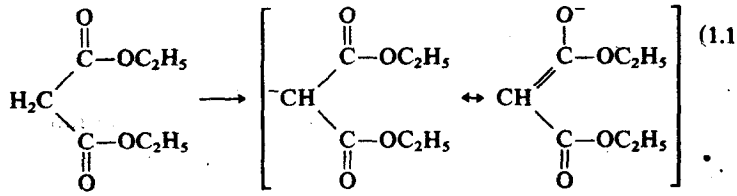
Compound	pK_a	Compound	pK_a
$CH_3CO_2\underline{H}$	5	$C_6H_5COC\underline{H}_3$	19
$C\underline{H}_2(CN)CO_2C_2H_5$	9	$CH_3COC\underline{H}_3$	20
$C\underline{H}_2(CO.CH_3)_2$	9	$C\underline{H}_3SO_2C\underline{H}_3$	~23
$C\underline{H}_3NO_2$	10	$C\underline{H}_3CO_2C_2H_5$	~24
$CH_3COC\underline{H}_2CO_2C_2H_5$	11	$CH_3\underline{CO}_2^-$	~24
$C\underline{H}_2(CO_2C_2H_5)_2$	13	$C\underline{H}_3CN$	~25
$CH_3O\underline{H}$	16	$C_6H_5N\underline{H}_2$	~30
$C_2H_5O\underline{H}$	18	$(C_6H_5)_3C\underline{H}$	~40
$(CH_3)_3CO\underline{H}$	19	$C\underline{H}_3SOC\underline{H}_3$	~40

(Acidic hydrogen atoms are underlined)

H. O. House, *Modern synthetic reactions*, copright 1972, W. A. Benjamin, Inc. Menlo Park, California.

each other, as can be seen by comparing diethyl malonate ($pK_a \approx 13$) with ethyl acetate ($pK_a \approx 24$). Acidity is also increased slightly by electron-withdrawing substituents (e.g. sulphide), and decreased by alkyl groups, so that diethyl methylmalonate, for example, has a slightly less acidic C—H group than diethyl malonate itself.

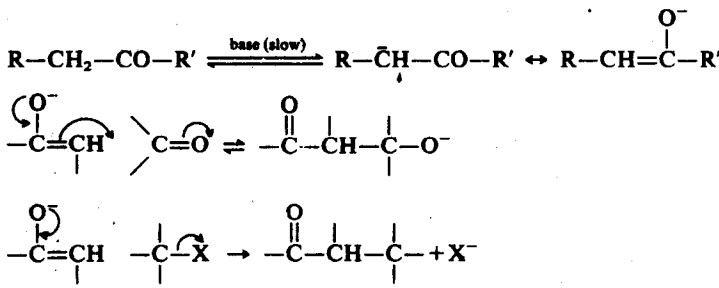




(1.1)

By far the most important activating groups in synthesis are the carbonyl and carboxylic ester groups. Removal of a proton from the α-carbon atom of a carbonyl compound with base gives the corresponding enolate anion, and it is these anions which are involved in base-catalysed condensation reactions of carbonyl compounds, such as the aldol condensation, and in bimolecular nucleophilic displacements (alkylations) (1.2).

The enolate anions should be distinguished from the enols themselves, which are always present in equilibrium with the carbonyl compound. Most monoketones and esters contain only small amounts of enol (< 1



(1.2)

per cent) at equilibrium, but with 1,2- and 1,3-dicarbonyl compounds much higher amounts of enol (>50 per cent) may be present. In the presence of acid catalysts monoketones may be converted largely into the enol form, and enols are concerned in many acid-catalysed condensations of carbonyl compounds in the presence of acidic or basic catalysts (1.3).

(1.3)

The formation of the enolate anion results from an equilibrium reaction between the carbonyl compound and the base. A competing equilibrium involves the enolate anion and the solvent. Thus, with diethyl malonate in solvent SolH in presence of base B^-, we have

$$\begin{aligned} CH_2(CO_2C_2H_5)_2 + B^- &\rightleftharpoons {}^-CH(CO_2C_2H_5)_2 + BH \\ {}^-CH(CO_2C_2H_5)_2 + SolH &\rightleftharpoons CH_2(CO_2C_2H_5)_2 + Sol^-, \end{aligned} \tag{1.4}$$

and to ensure an adequate concentration of the enolate anion at equilibrium clearly both the solvent and the conjugate acid of the base must be much weaker acids than the active methylene compound. The correct choice of base and solvent is thus of great importance if the subsequent alkylation, or other, reaction is to be successful. Reactions must normally be effected under anhydrous conditions since water is a much stronger acid than the usual activated methylene compounds and, if present, would instantly protonate any carbanion produced. Another point of importance is that the solvent must not be a much stronger acid than the conjugate acid of the base, otherwise the equilibrium

$$B^- + SolH \rightleftharpoons BH + Sol^- \tag{1.5}$$

will lie too far to the right and lower the concentration of B^-. For example,

sodamide can be used as base in liquid ammonia or in benzene, but, obviously, not in ethanol. Base–solvent combinations commonly used to convert active methylene compounds into the corresponding anions include sodium methoxide, sodium ethoxide and sodium or potassium t-butoxide in solution in the corresponding alcohol, or as suspensions in ether, benzene or dimethoxyethane. Potassium t-butoxide is a particularly useful reagent, since it is a poor nucleophile and its solutions in different solvents have widely different basic strengths; it is most active in solution in dry dimethyl sulphoxide (Pearson and Buehler, 1974). Metallic sodium or potassium, or sodium hydride, in suspension in benzene, either or dimethoxyethane, sodamide in suspension in an inert solvent or in solution in liquid ammonia, and solutions of sodium or potassium triphenylmethyl in ether or benzene have also been used with the less 'active' compounds.

For many purposes, however, these traditional bases have now been superseded by the lithium salts of certain sterically hindered secondary amines, particularly lithium diisopropylamide and lithium 2,2,6,6-tetramethylpiperidide (Olofson and Dougherty, 1973) or the alkali metal salts of bis(trimethylsilyl)amine, $HN(SiMe_3)_2$ (Colvin, 1978; Smith and Richmond, 1983). These strong amide bases are only weakly nucleophilic, so that they do not themselves attack susceptible functional groups, and they have the added advantage that they are soluble in non-polar, even hydrocarbon, solvents. The insolubility of the traditional bases in most common organic solvents seriously limits their usefulness.

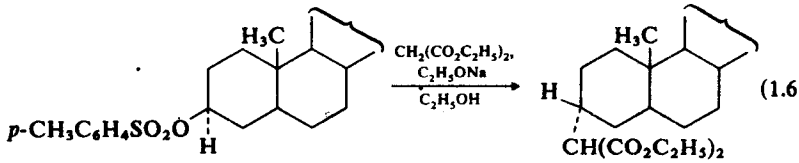
1.2. Alkylation of relatively acidic methylene groups

In order to effect a reasonably rapid reaction it is, of course, necessary to have a high concentration of the appropriate carbanion. Because of their relatively high acidity (see Table 1.1) compounds in which a C—H bond is activated by a nitro group or by two or more carbonyl, ester or cyano groups can be converted largely into their anions with a comparatively weak base such as a solution of sodium ethoxide in ethanol. An alternative procedure is to prepare the enolate in benzene or ether, using finely divided sodium or potassium metal or sodium hydride, which react irreversibly with compounds containing active methylene groups with formation of the metal salt and evolution of hydrogen. β-Diketones can often be converted into their enolates with alkali metal hydroxides or carbonates in aqueous alcohol or acetone.

Much faster alkylation of enolate anions can often be achieved in dimethylformamide, dimethyl sulphoxide, 1,2-dimethoxyethane or hexamethylphosphoramide than in the usual protic solvents. This appears to be due to the fact that the former solvents do not solvate the enolate

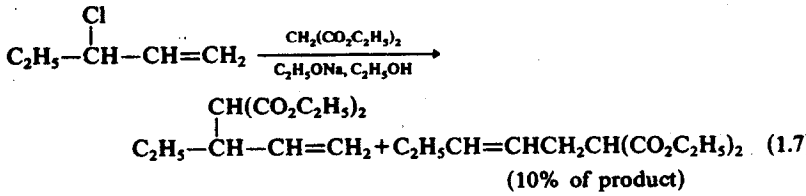
anion and thus do not diminish its reactivity as a nucleophile. At the same time they are able to solvate the cation, separating it from the cation–enolate ion pair and leaving a relatively free enolate ion which would be expected to be a more reactive nucleophile than the ion pair (Parker, 1962). Reactions effected with aqueous alkali as base are often improved in the presence of a phase-transfer catalyst such as a tetraalkylammonium salt (cf. Makosza and Jończyk, 1976).

Alkylation of enolate anions is readily effected with alkyl halides or other alkylating agents. Both primary and secondary alkyl, allyl or benzyl halides may be used successfully, but with tertiary halides poor yields of alkylated product often result because of competing dehydrohalogenation of the halide. It is often advantageous to proceed by way of the toluene-*p*-sulphonate or methanesulphonate rather than a halide. The sulphonates are excellent alkylating agents, and can usually be obtained from the alcohol in a pure condition more readily than the corresponding halides. Epoxides have also been used as alkylating agents, generally reacting at the less substituted carbon atom. Attack of the enolate anion on the alkylating agent takes place by an S_N2 pathway and thus results in inversion of configuration at the carbon atom of the alkylating agent.



(1.6)

With secondary and tertiary allylic halides or sulphonates, reaction of an enolate anion may give mixtures of products formed by competing attack at the α- and γ-positions (1.7).



(1.7)

A difficulty sometimes encountered in the alkylation of active methylene compounds is the formation of unwanted dialkylated products. During the alkylation of diethyl sodiomalonate, the monoalkyl derivative formed initially is in equilibrium with its anion as indicated in the first equation of (1.8). In ethanol solution, dialkylation does not take place to any appreciable extent because ethanol is sufficiently acidic to reduce

the concentration of the anion of the alkyl derivative, but not that of the more acidic diethyl malonate itself, to a very low value.

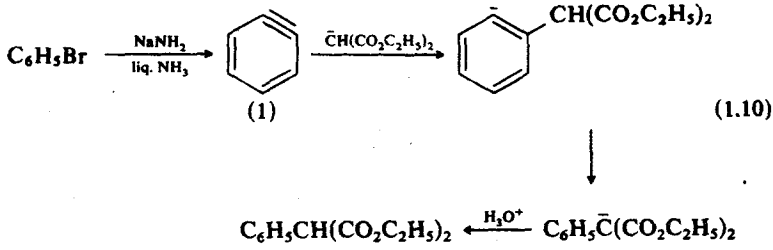
$$\begin{aligned} RCH(CO_2C_2H_5)_2 + \bar{C}H(CO_2C_2H_5)_2 &\rightleftharpoons R\bar{C}(CO_2C_2H_5)_2 + CH_2(CO_2C_2H_5)_2 \\ R\bar{C}(CO_2C_2H_5)_2 + C_2H_5OH &\rightleftharpoons RCH(CO_2C_2H_5)_2 + C_2H_5O^- \end{aligned} \quad (1.8)$$

However, replacement of ethanol by an inert solvent favours dialkylation, and dialkylation also becomes a more serious problem with the more acidic alkylcyanoacetic esters, and in alkylations with very reactive compounds such as allyl or benzyl halides or sulphonates.

Dialkylation may, of course, be effected deliberately if required by carrying out two successive operations, using either the same or a different alkylating agent in the two steps. Thus, alkylation with $\alpha\omega$-polymethylene dihalides, and intramolecular alkylation of ω-haloalkylmalonic esters provides a useful route to three- to seven-membered ring compounds. Non-cyclic products are frequently formed at the same time by competing intermolecular reactions and conditions have to be carefully chosen to suppress their formation (1.9).

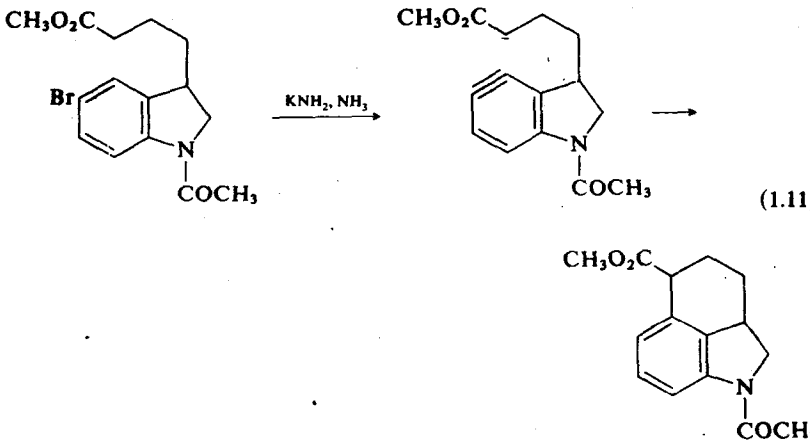
$$Br(CH_2)_3Br + CH_2(CO_2C_2H_5)_2 \xrightarrow[C_2H_5OH]{NaOC_2H_5} \begin{matrix} CO_2C_2H_5 \\ CO_2C_2H_5 \end{matrix} + \begin{matrix} CH(CO_2C_2H_5)_2 \\ CH(CO_2C_2H_5)_2 \end{matrix} \quad (1.9)$$

Under ordinary conditions aryl or vinyl halides do not react with enolate anions, although aryl halides with strongly electronegative substituents in the *ortho* and *para* positions do. 2,4-Dinitrochlorobenzene, for example, with ethyl cyanoacetate gives ethyl (2,4-dinitrophenyl)cyanoacetate in 90 per cent yield by an addition–elimination, not an S_N2, pathway. Unactivated aryl halides may also react with enolates under more vigorous conditions. Reaction of bromobenzene with diethyl malonate, for example, takes place readily in presence of an excess of sodium amide in liquid ammonia, to give diethyl phenylmalonate in 50 per cent yield. The reaction is not a direct nucleophilic displacement, however, but takes place by an elimination–addition sequence in which benzyne is an intermediate (1.10). Similar reactions can be effected intramolecularly and provide a good route to some cyclic systems (1.11). Vinyl derivatives of active methylene compounds can be obtained indirectly from alkylidene derivatives by moving the double bond out of conjugation as illustrated in (1.12). Kinetically controlled alkylation of the delocalised anion takes place at the α-carbon atom to give the

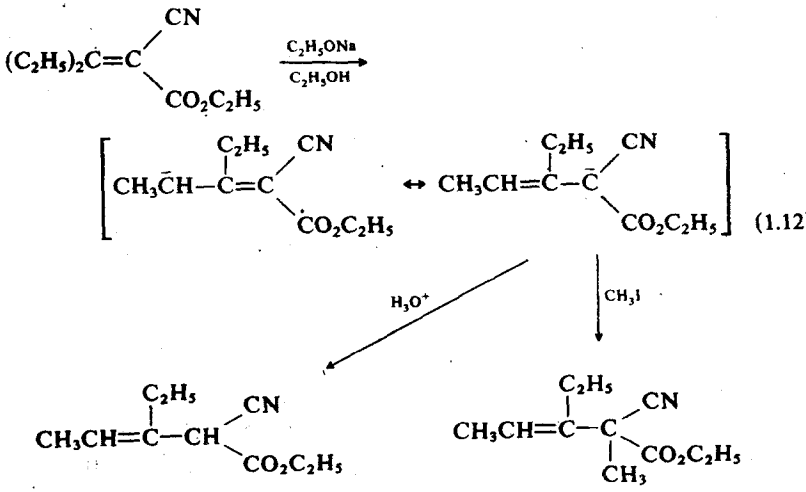


(1.10)

$\beta\gamma$-unsaturated compound directly. A similar course is followed in the kinetically controlled protonation of such anions.



(1.11)



(1.12)

A wasteful side reaction which frequently occurs in the alkylation of 1,3-dicarbonyl compounds is the formation of the *O*-alkylated product. Thus, reaction of the sodium salt of cyclohexan-1,3-dione with butyl bromide gives 37 per cent of 1-butoxycyclohexen-3-one and only 15 per cent of 2-butylcyclohexan-1,3-dione. In general, however, *O*-alkylation competes significantly with *C*-alkylation only with reactive methylene compounds in which the equilibrium concentration of enol is relatively high, as in 1,3-dicarbonyl compounds and phenols. Phenols, of course, generally undergo predominant *O*-alkylation.

Alkylation of malonic ester, cyanacetic ester and β-keto esters is useful in synthesis because the alkylated products on hydrolysis and decarboxylation or, better, by direct decarbalkoxylation under neutral conditions with an alkali metal salt (for example, lithium chloride) in a dipolar aprotic solvent such as dimethylformamide (Krapcho, 1982) afford carboxylic acids (esters) or ketones. From alkylated malonic or cyanoacetic esters, substituted acetic acids or esters are obtained, and alkylated acetoacetic esters give methyl ketones.

1.3 γ-Alkylation of 1,3-dicarbonyl compounds; dianions in synthesis

Alkylation of a 1,3-diketone or a β-keto-ester at a 'flanking' methyl or methylene group instead of at the doubly activated methylene or methine does not usually take place to any significant extent under 'ordinary' conditions. It can be accomplished selectively and in good yield, however, by way of the corresponding *dianion*, itself prepared from the diketone and two equivalents of a suitable strong base such as sodamide or lithium diisopropylamide, by reaction with one equivalent of alkylating agent (Harris and Harris, 1969). Thus, 2,4-pentanedione is converted into 2,4-nonanedione in 82 per cent yield (1.13) by reaction at the more reactive less resonance-stabilised carbanion and 1,6-diphenyl-1,3-pentanedione is obtained in 77 per cent yield by reaction of the dianion of benzylacetone with benzyl chloride. Keto acids and triketones can also be obtained by reaction of the dianions with carbon dioxide or with esters.

$$\mathrm{CH_3COCH_2COCH_3} \xrightarrow[\text{liq. } \mathrm{NH_3}]{\text{2 equivs } \mathrm{KNH_2}} \mathrm{CH_3CO\bar{C}HCO\bar{C}H_2} \leftrightarrow \mathrm{CH_3\overset{O^-}{\overset{|}{C}}{=}CH{-}\overset{O^-}{\overset{|}{C}}{=}CH_2}$$

$$\downarrow \begin{matrix}(1)\ C_4H_9Br \\ (2)\ H_3O^+\end{matrix}$$

$$\mathrm{CH_3COCH_2COCH_2C_4H_9}\quad (82\%) \qquad (1.13)$$

With unsymmetrical diketones which could apparently give rise to two different dianions, it is found in practice that in most cases only one is formed, and a single product results on alkylation. Thus, with 2,4-