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Diene synthesis and related reaction types

*Nobel Lecture, December 12, 1950*

The Precursors

Since the Nobel Foundation was first established, the Royal Swedish Academy of Sciences has deemed two advances in the field of organic chemical synthesis worthy of distinction by the award of a Nobel Prize. These were V. Grignard's discovery of the organomagnesium compounds and their application for preparative purposes, and P. Sabatier's discovery of catalytic hydrogenation, i.e. the addition of elementary hydrogen to unsaturated compounds by means of contact catalysts. Both methods were very soon introduced into all laboratories, where they became indispensable for the everyday preparative work (which would now be unthinkable without them), and both - especially the latter - have been introduced, in progressively improved form, ever more widely into industrial technology.

There has also been a third advance in the preparative field, namely diene synthesis, which is now a routine working method in organic chemistry. And it is for the discovery and development of this process that my colleague Diels and I have this year received the highest honour in the form of the Nobel Prize for Chemistry.

Two substances and their behaviour seem to me to be particularly suited for a description of the situation which served as the point of departure for the developments initiated by Diels and myself in 1927, namely cyclopentadiene and isoprene.

Cyclopentadiene (I) is characterized, as far as its reactive properties are concerned, by two factors: the presence of two (conjugated) double bonds, and the mobility of its hydrogen atoms in the methylene group. This theory is based on general experience, gained at an early date, in the conversion of this substance with agents such as bromine and alkali metals. When subsequently (1906) it was discovered that the hydrocarbon derivative quinone undergoes addition with extreme facility, the most obvious thing was to attribute this process to the same factors and to discuss the following possibilities $(\alpha-\gamma)$.

(1)
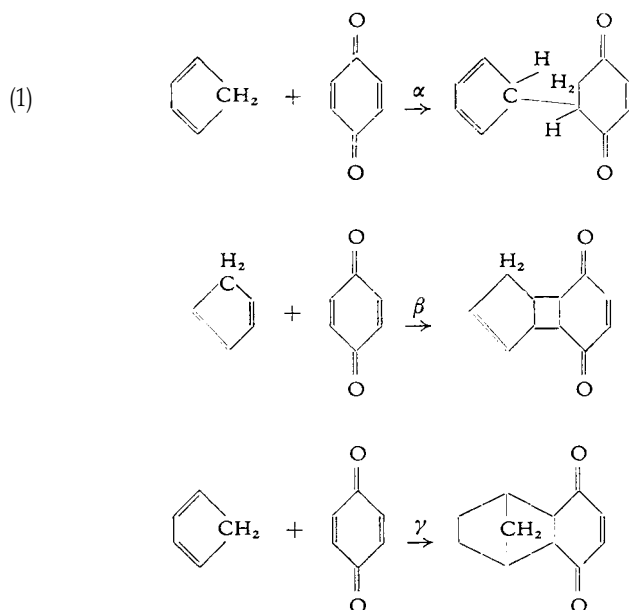
The formula (α) first recommended by its discoverer[1] is based on the assumption that a methylenic hydrogen atom is displaced from the cyclopentadiene range to the quinone range, whereas the subsequently suggested interpretations β and γ assume the interplay between the double bonds of the two partners to be - each in its own way - a case of straightforward addition. As there was no proof of the constitution of the addition product, there was equal justification for all the hypotheses so long as they rested only on unreliable analogies.

True, in the light of a further observation on cyclopentadiene the choice appeared temporarily to lie between reactions α and γ. The mutual formation of two double bonds and the formation of a four-membered carbon ring (III) was proved in the case of an addition product of dimethylketene (II) with cyclopentadiene[2]:
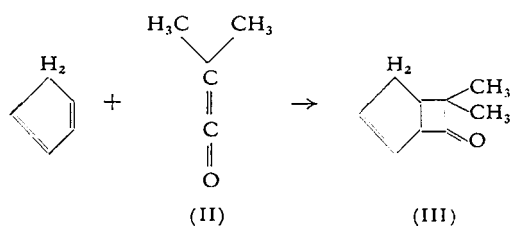
The parallel between these two processes seems obvious, but in fact does not hold. Only very much later was it shown that this reaction is very largely confined to ketenes and that it cannot be carried over to the addition of quinone to cyclopentadiene or to the addition of cyclopentadiene to similar substances, i.e. to the polymerization of cyclopentadiene.

This discovery was, however, the fruit of later work. For the time being the addition of ketene seemed quite obvious as a paradigm for the other additions accompanied by the formation of C-C bonds. Indeed, even at that time, other analogies showed that a reaction in accordance with formula γ was possible, in particular the addition of azodicarboxylic ester to cyclopentadiene, which can be proved to take place in accordance with formula y although it is accompanied by formation not of C-C but of C-N bonds[3].

Two observations on isoprene (IV) pointed in the same direction. The classical dipentene synthesis (V) dating from 1885[4] requires relatively high temperatures and gives poor yields. This may account for the fact that for decades it was regarded as an exceptional case.
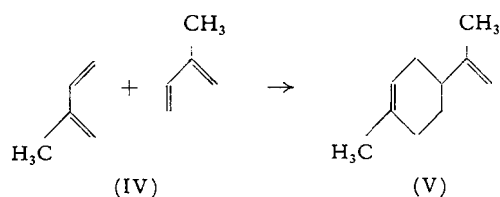
It was not until 1920[5] that as a second contribution of this kind the addition of two molecules of isoprene to quinone - in a very smooth reaction - was described and the process was given the substantially correct although as yet unproved formula[6].
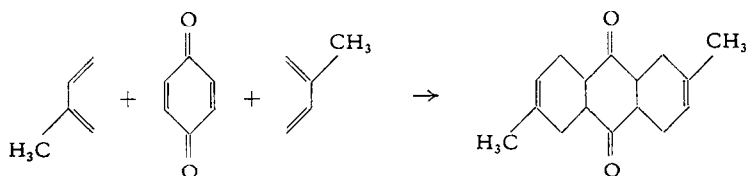

In view of this situation - three types of reaction side by side, with an indefinite boundary between them - a need for classification and systematization was inevitably felt. There was only one certain way of achieving this objective, namely by establishing the constitution of the addition products by direct proofs. Today, now that we have highly developed methods of

proof and plenty of reliable cases to draw on, it is difficult to imagine that at that time it was the search for provable cases which necessitated a variation of the two addenda - cyclopentadiene or isoprene on the one hand and quinone on the other. The shift of interest to the prototype of the dienes, butadiene, and the important step from quinone to maleic acid, which was later followed by those to acrylic acid and acrolein, led so inevitably to the goal[7] that our principle of a successive structural modification of the components remained the "leitmotiv" of our joint work. Subsequently, contributions on the same subject, though occasioned by the widest variety of causes, have been made on a rapidly increasing scale by many other authors, and have gradually built up a complete picture of these reactions.

The General Formula

The feature common to all these processes is the formation of a six-membered carbon ring by a direct union, i.e. a union without adjuvant substances, of two unsaturated partners. One of these, the diene component, is the carrier of a system of conjugated double bonds whilst the other, the "philodiene", must have at least one double bond. The addition usually takes place in accordance with the following scheme:

Diene   Philodiene   Addition product
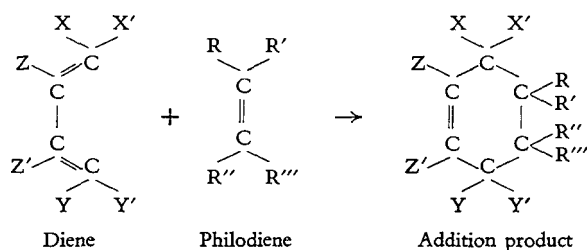
This basically uniform picture acquires its undreamed-of wealth of variations of all kinds thanks to the individual peculiarities of the reaction partner, in other words: thanks to the different substituents. These substituents are variables which, with the well-known profusion of forms of organic molecules, are available in true abundance.

From the great variety of these possibilities a large number have been realized by very many different authors in the course of over twenty years' development. Their results can be summarized by saying that in the overwhelming majority of cases they follow this basic formula, irrespective of

whether they belong to the ideal cases which proceed with absolute ease or whether they require high temperatures, and irrespective of whether their addition products are stable or sensitive to heat. For them the 6-ring formation is undoubtedly a law.

The diene component

In this lecture I shall not dwell on the normal cases, for I can scarcely take up your time with matters which today are learnt by any beginner and have to a large extent been tested and proved and therefore no longer have the attraction of novelty.

However, in order to give at least a very rough idea of the scope of the basic formula and of the nature and multiplicity of the substituents, I have summarized in two tables the primary types of the cases hitherto investigated. In these tables, wherever a representative of the one reacts with a representative of the other, this reaction is in accordance with the formula of diene synthesis.

The range of validity of the basic formula is very wide; it extends from the simplest case of butadiene and of the acyclic dienes (VI) to the alicyclic combinations, in which both double bonds are situated in one ring (VII), or are spread over a ring and a side-chain (VIII) or two rings (IX). In addition to this, various empirical findings have shown that the basic formula does not lose its validity even if, as in the case of styrene (X), methylene anthrone (XI) or other "semi-aromatics", one of the double bonds of the conjugated system belongs to an aromatic nucleus or if, as in the case of the anthracene type (XIV), both double bonds belong to an aromatic system. No diene syntheses have so far been observed with mononuclear benzene derivatives (XII), and according to very recent findings[8] they do not occur in the case of binuclear derivatives of the naphthalene type, unless at least one of the two nuclei is highly alkylated. Heterocyclic dienes of the furan type (XVI) and of the coumalin type (XV) give diene synthesis, but simple derivatives of thiophen (XVII) do not. We shall be discussing the behaviour of pyrrole (XVIII) later on (p. 277).

Acyclic tri- and tetraenes - in the simplest case hexatriene (XIX) - show normal behaviour with diene synthesis, i.e. they too add philodienes in accordance with the formula of the 6-ring formation. The predictable formation of higher-membered rings by 1,6- or 1,8-addition has not yet been confirmed empirically, at least not with acyclic tri- or polyenes, on which

Table of dienes

(VI)   (VII)   (VIII)   (IX)   (X)

(XI)   (XII)   (XIII)   (XIV)

(XV)   (XVI)   (XVII)   (XVIII)   (XIX)

(XX)   (XXI)
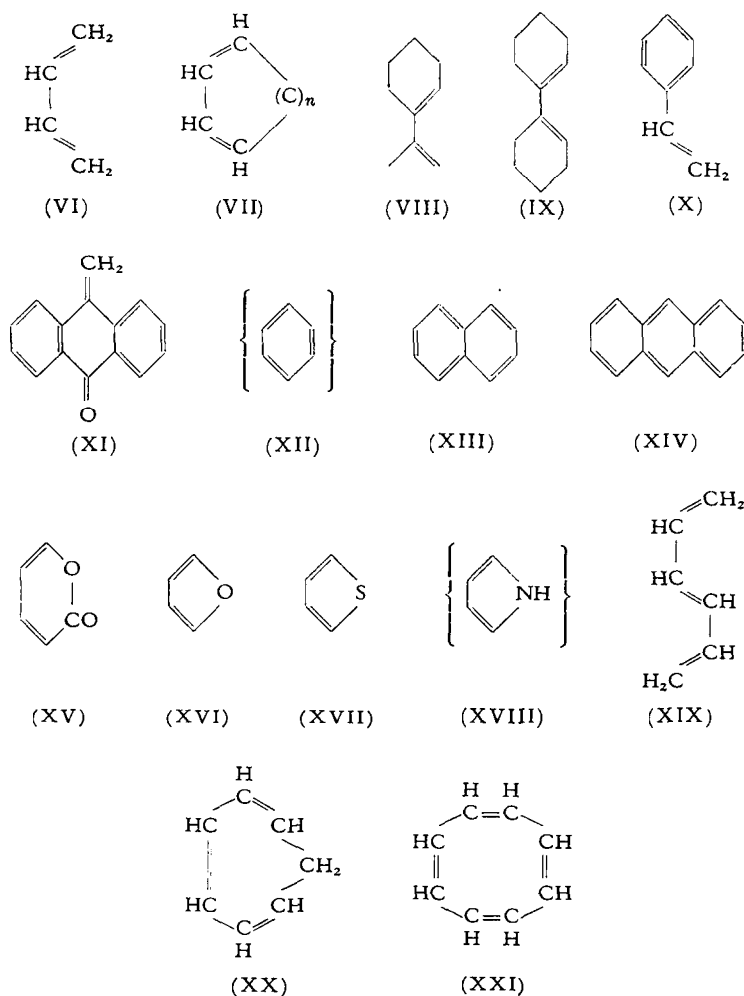
extensive experimental data[9,10] are available. Their cyclic analogues such as cycloheptatriene(XX)[11] and cyclooctatetraene (XXI)[12] are likewise capable of diene synthesis - indeed, to a very impressive extent - thanks to the nature of their double-bond systems.

The philodiene partner

The basic formula of addition characterizes the philodiene as a derivative of ethylene. Precisely in this group, extensive experience has shown that not

every olefine bond adds equally rapidly, but that the absorption capacity of the bonds depends to a large extent on constitutional conditions.

The α, β-unsaturated carbonyl compounds (XXII-XXX) are at the head of the entire group. They provide optimum conditions for adaptation to diene synthesis. Recognition of this fact, especially in the case of the *p*-qui none series (XXII), maleic anhydride (XXIII), acrylic acid (XXIV) and acrolein (XXV), constituted the decisive step in the discovery of the new method[7]. Subsequently these compounds also played a decisive part in the efforts to arrive at a thorough understanding of diene synthesis, and work on the adaptation of it to industrial purposes was, and still is, based primarily on them.

Table of philodienes

(XXII) (XXIII) (XXIV) (XXV)

(XXVI) (XXVII) (XXVIII) (XXIX) (XXX)

(XXXI) (XXXII) (XXXIII)
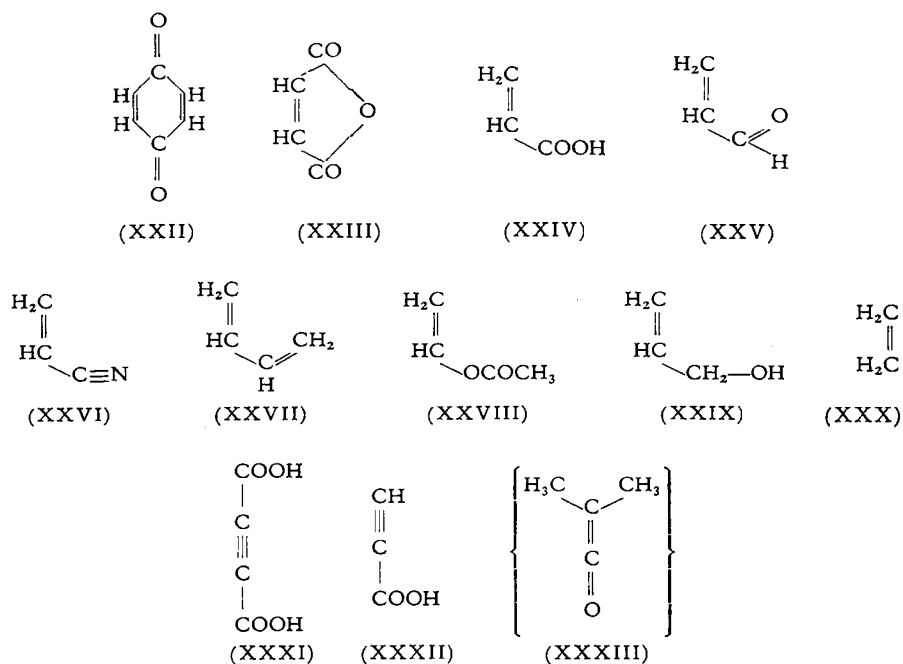
I must confine myself here to a brief survey of the philodiene class, with a rapid glance at its principal representatives, without attempting to go into any details.

Beside the α,β-unsaturated carbonyl compounds there are also the nitriles of α,β-unsaturated carboxylic acids (XXVI). The great tendency of many dienes to dimerize in accordance with the formula of the "partial 1,4-addi-

tion" explains why the simple dienes C=C-C=C (XXVII) can also act as philodienes.

Vinyl compounds (XXVIII), such as are now being produced industrially on a large scale for other purposes from acetylene react like allyl compounds (XXIX) with dienes in accordance with the diene synthesis formula; the same applies to hydrocarbons such as styrene, indene, propylene, and the simplest structure of this type, ethylene (XXX) - last but certainly not least of the series of philodiene components.

Within this wide range of olefine compounds the ketenes must be specially mentioned as the only exception so far known. They add dienes with the mutual elimination of one double bond each and with formation of derivatives of cyclobutane (XXXIV):

(XXXIV)
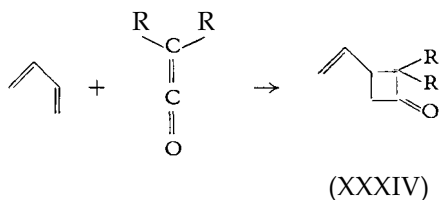
This rare case, which is undoubtedly due to the characteristic accumulation of double bonds in the ketene system, was first observed and defined long before diene synthesis was recognized as a general principle. The formation of four-membered rings from ketene and dienes has recently been confirmed many times over[13]. It is clearly an addition form typical of the ketenes, or in other words the ketenes cannot act as philodienes in the above-defined sense. Whether and to what extent this rule also applies to the allenes $H_2C=C=CH_2$, which are closely related to the ketenes, is a question which still remains to be answered.

On the other hand, the derivatives of acetylene also fit without limitation into the general formula for diene synthesis:
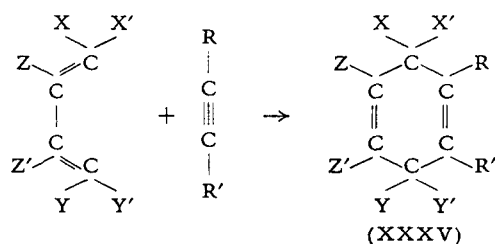
(XXXV)

Acetylene dicarboxylic acid (XXXI), propiolic acid (XXXII), and other acetylene derivatives have proved themselves to be very productive philodienes. Their doubly unsaturated addition products (XXXV) constitute a supplement - for many purposes ideal - to the addition products of the olefine series.

The role of maleic and fumaric acid

The results obtained from and the problem raised by diene synthesis from the point of view of general methodology are the subject of my lecture. I shall therefore not go into details on the many applications - which in course of time this method has made possible - for the analysis and determination of the constitution of organic compounds, and for preparative and industrial purposes. Instead, allow me here to make a brief observation.

I have already implied that, with regard to method, the step from quinone to maleic anhydride was of decisive importance in the development of diene synthesis. The propensity of maleic anhydride, and with it of related substances, to act as philodienes, which this revealed, is so complete that it could not escape our attention. The suspicion that this was the case was subsequently confirmed, and indeed is continually being strengthened as experience grows, and I should scarcely be going too far if I said that the suitability of substances of this type for preparative chemistry was discovered only with diene synthesis - almost exactly a hundred years after maleic acid and its close relative fumaric acid had first been isolated from plant material. Several decades after their discovery they became the focus of theoretical discussions, when the ideas of Van 't Hoff and Le Bel on the arrangement of the atoms in space threw the first light on their hitherto problematic relations to one another. Having been recognized as examples of *cis-* and *trans-*isomeric forms, and accepted as classical types, they ceased to be of immediate interest, until some decades later, fumaric acid - after being found by Thunberg and Wieland to be a transitional product in the metabolism of carbohydrates - attracted the attention of physiologists.

Despite this importance with regard to theoretical and biochemical problems, maleic and fumaric acid remained laboratory and academic preparations, which were more or less difficult to produce, and provided scarcely any greater incentive to efforts in the field of synthetic organic chemistry than any other olefine.

In the history of chemistry there can be few similar cases where sub-

stances which during a hundred years' existence were repeatedly in the fore-
front of scientific development and then suddenly revealed a latent capacity
and - so to speak, overnight - attracted the interest not only of a few spe-
cialists but of a wide range of workers in pure and applied organic chem-
istry. Thus, today it is difficult to find a type of unsaturated compound whose
reaction with maleic anhydride has not been investigated, at least provi-
sionally. The interest shown by industry in this development is reflected in
the number of applications for patents based on combinations of maleic and
fumaric acid, their homologues and functional derivatives, with an extreme-
ly wide variety of unsaturated compounds. Present efforts to develop in-
expensive methods of producing maleic and fumaric acid from substances
such as benzene, crotonaldehyde, and furfural originated in the needs which
have arisen from the new applications of these substances.

After this diversion I should like to turn my attention to the nature of the
reaction. Here, too, the importance of maleic and fumaric acid will re-
peatedly find expression - even in the extreme case of pyrrole, which I shall
now discuss.

Substituting Addition

Substituting addition to the double bond

One of our series of investigations was concerned with testing the reactions
of the systems

(XXXVI)   (XXXVII)   (XXXVIII)   (XXXIX)
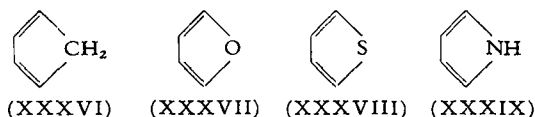
with maleic anhydride. The similarity is obvious: true pentacyclic systems,
all characterized by the presence of a pair of conjugated double bonds, the
first belonging to the isocyclic, the rest to the heterocyclic series.

It had already been established that cyclopentadiene (XXXVI) adds maleic
anhydride with unusual facility and that this process constitutes the ideal case
of diene synthesis.
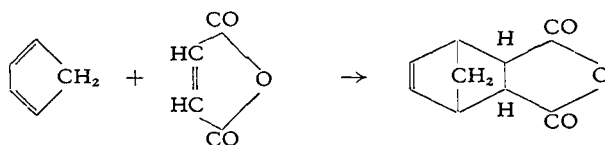
Furan (XXXVII), on the other hand, showed only differences of degree. The product of addition to maleic anhydride was less stable, and a determination of its constitution left no doubt that in its formation the same principle was at work as in the case of cyclopentadiene.

Thiophen (XXXVIII) under the same external conditions does not react at all with maleic anhydride, a result which it has so far been impossible to alter even by forcing the experimental conditions. However, thiophen may not be such an exceptional case as this might suggest. It is well known that in thiophen interaction between the double bonds and the sulphur atom brings about an internal equilibrium which can be compared with that of benzene and which expresses itself in a startling similarity in chemical and physical behaviour between the two substances. Benzene is likewise incapable of diene synthesis. But in the same way as the benzene system assumes the character of a diene with more highly condensed types, i.e. it acquires a capacity for attaching maleic anhydride in the 1,4 position, so the arrangement of the thiophen, when embedded in relatively complex systems, attains the same capacity for true diene synthesis.

The situation with pyrrole (XXXIX) is different[14]. This substance reacts very readily with maleic anhydride. These additions, however, are not diene syntheses, but rather result in the setting-up of only one double bond while at the same time displacing a hydrogen atom from the range of the one component to that of the other. According to their products, these, like diene syntheses, are additions; according to their nature they are undoubtedly substitution processes. I have therefore suggested for them the name "substituting addition".
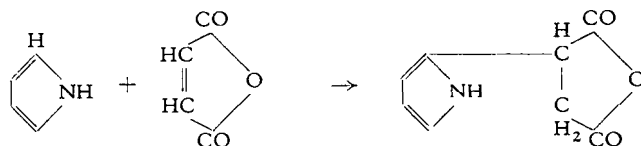
It was subsequently found that maleic anhydride reacts in accordance with the formula of substituting addition not only with pyrrole but also with many other nitrogen-containing heterocyclics, such as pyrazole, glyoxaline, indole, etc. The study of this vast subject is not yet complete, and we shall not be examining it in any further detail here. The main result lies in the proof that maleic anhydride is not only an ideal philodiene in diene synthesis but is also particularly suitable as a hydrogen acceptor in substituting additions.

We describe this category of substituting addition - namely where a hydrogen atom of the group C=CH is detached - as "substituting addition at the double bond", thus distinguishing it from processes of a similar kind, which will now be discussed.

### Substituting addition in the allyl position

The beginnings of this development were prompted by statements in the patent literature, according to which maleic anhydride can be added even to singly unsaturated hydrocarbons at 150-250°C[16]. This gives rise to addition products which contain the components in the molar ratio of 1 : 1, and which at first were all classified as "substituted succinic acids".

For an understanding of the phenomenon of substituting addition we considered it important that these statements should be supplemented by systematic experiments and that the constitution of the addition products should be determined for certain.

We established that ethylene itself is not capable of forming a simple addition product with maleic anhydride, at least not under the same conditions as those under which other olefines are transformed more or less easily. The next higher homologue, propylene (XL), reacts with maleic anhydride and was found to give allyl succinic acid (XLI) as its typical and only reaction product.
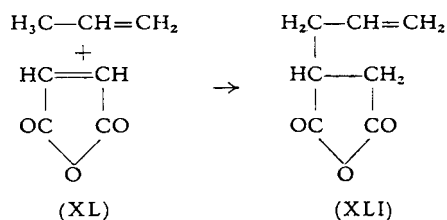
Analogous behaviour was shown by the following olefines:
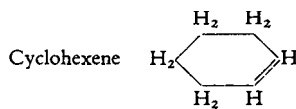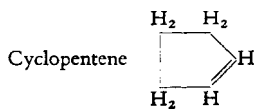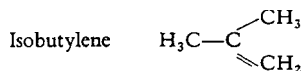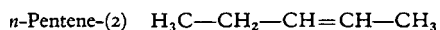
As a result of these experiments, therefore, we found that the additions of maleic anhydride in these cases were the same as the additions to pyrrole and other nitrogen-containing heterocyclics in so far as, like them, they constituted "substituting additions", but that they took place not at a carbon atom of the double bond but at the carbon atom adjacent to it, i.e. in the allyl position.

$$\overset{1}{C}=\overset{2}{C}-\overset{3}{C}H + M \overset{a}{\rightarrow} \overset{1}{C}=\overset{2}{C}-\overset{3}{C}MH \quad \left\{ M = \begin{array}{c} -HC\text{---}CH- \\ | \quad\quad | \\ OC \quad CO \\ \diagdown\diagup \\ O \end{array} \right\}$$
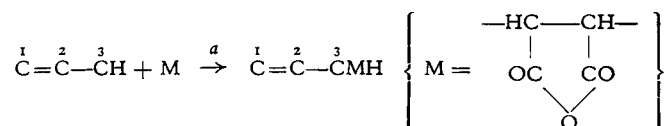
Thus, the processes of this class seemed to obey a general rule, namely that hydrogen atoms in the vicinity of the double bond are "loosened", and that in the case of substitution reactions - e.g. as a result of the action of Cl_2, O_2 and SeO_2 - they usually tend to be eliminated.

And yet this interpretation of our experiments on the action of maleic anhydride on mono-olefines is incorrect in one vital respect - a conclusion to which extension of our experimental work gradually led us. I will anticipate the result in order to avoid unnecessary digressions.

Our experimental results, which are summarized above, are also susceptible of a different interpretation with the same degree of probability: substituting addition of maleic anhydride to the olefine need not necessarily take place at C_3, but may also take place at C_1, provided that in this case the double bond "shifts" from the C_1, C_2 into the C_2, C_3 position. In this case, too, the hydrogen is detached from C_3:

$$\overset{1}{C}=\overset{2}{C}-\overset{3}{C}H + M \overset{b}{\rightarrow} HM-\overset{1}{C}-\overset{2}{C}=\overset{3}{C}$$
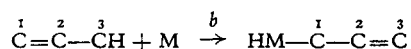
There is scarcely any need to point out that in the cases so far mentioned both assumptions, which we distinguish as *direct (a)* and *indirect (b) substituting addition*[17], are equally justified. This applies in general to all olefines, in which the "shift" of the double bond leads to a substance identical with the original:

$$\overset{1}{C}=\overset{2}{C}-\overset{3}{C}H \overset{\rightarrow}{\underset{\leftarrow}{}} H\overset{1}{C}=\overset{2}{C}-\overset{3}{C}$$
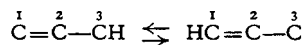
Differentiation is possible only where this condition is no longer fulfilled.

We came upon the first case of this type with allylbenzene (XIII). Here the structures to be expected in accordance with *a* or *b* are different from

one another. An investigation shows clearly that the reaction proceeds in accordance with formula *b*.

(XLII)

$$C_6H_5\overset{1}{-}CH_2\overset{2}{-}CH\overset{3}{=}CH_2$$
$$+$$
$$HC\overset{}{=\!\!=}CH$$
$$\quad\mid\quad\quad\mid$$
$$OC\quad CO$$
$$\diagdown\diagup$$
$$O$$

$\overset{a}{\rightarrow}$

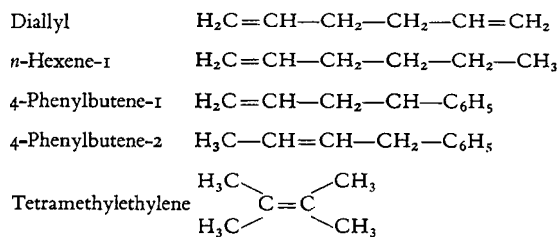$$C_6H_5\overset{1}{-}CH\overset{2}{-}CH\overset{3}{=}CH_2$$
$$\mid$$
$$HC\!-\!\!-\!\!CH_2$$
$$\quad\mid\quad\quad\mid$$
$$OC\quad CO$$
$$\diagdown\diagup$$
$$O$$

$$C_6H_5\overset{1}{-}CH_2\overset{2}{-}CH\overset{3}{=}CH_2$$
$$+$$
$$HC\overset{}{=\!\!=}CH$$
$$\quad\mid\quad\quad\mid$$
$$OC\quad CO$$
$$\diagdown\diagup$$
$$O$$

$\overset{b}{\rightarrow}$

$$C_6H_5\overset{1}{-}CH\overset{2}{=}CH\overset{3}{-}CH_2$$
$$\mid$$
$$H_2C\!-\!\!-\!\!CH$$
$$\quad\mid\quad\quad\mid$$
$$OC\quad CO$$
$$\diagdown\diagup$$
$$O$$
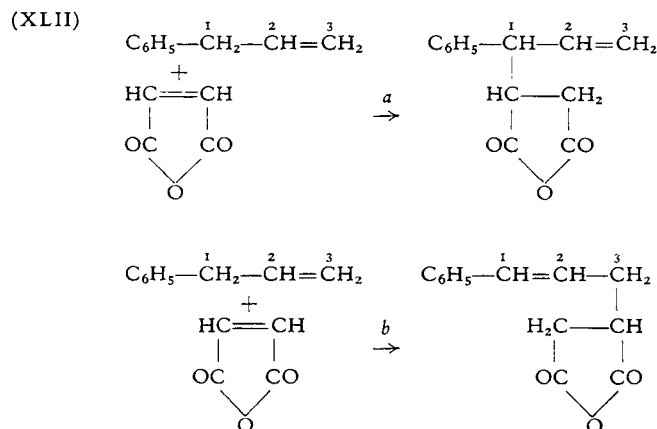
We transferred this finding to other olefines of the allylbenzene type, e.g.

Diallyl	$H_2C=CH-CH_2-CH_2-CH=CH_2$
n-Hexene-1	$H_2C=CH-CH_2-CH_2-CH_2-CH_3$
4-Phenylbutene-1	$H_2C=CH-CH_2-CH-C_6H_5$
4-Phenylbutene-2	$H_3C-CH=CH-CH_2-C_6H_5$
Tetramethylethylene	$\begin{array}{c}H_3C\diagdown\quad\diagup CH_3\\ \quad C=C\\ H_3C\diagup\quad\diagdown CH_3\end{array}$

In all these cases the process of "indirect substituting addition", which is accompanied by "shifting" of the double bond, always occurs, even where it cannot, for formal reasons, be distinguished from the alternative of a "direct substituting addition", at least in so far as additions of maleic anhydride are concerned[17].

   This finding opens up important prospects for our subject and for its future development. It enables the two processes of diene synthesis and substituting addition, which appear to be essentially different, to be examined from the same viewpoint. Diene synthesis is an ideal addition process based on inter-action between the double-bond systems of two partners. In view of the migration of the double bond in the substituting addition processes, which has regularly been observed, it can be concluded that these processes are based on a similar effect and that here the group C=C-C-H assumes the func-tion of the conjugated system C=C-C=C in diene synthesis.

A comparison of the two processes:
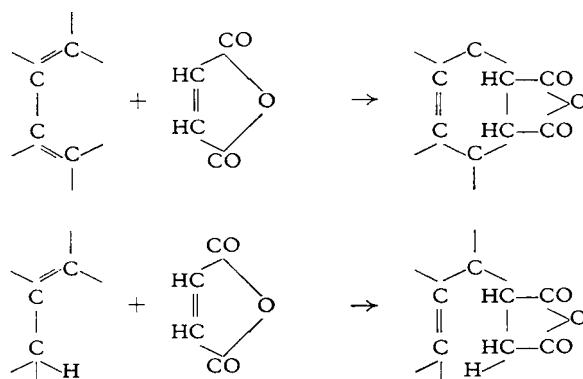
brings out their similarity: in both cases the double bond remaining after the addition process occupies the same position, and in both cases three bonds, i.e. six electrons, change their function. Instead of cyclization, as in diene synthesis, dislocation of the hydrogen atom occurs in substituting addition. It is well known that the dualism (addition-substitution) has always aroused the interest of those whose aim it has been to develop organic chemical methods and to improve and perfect means of describing them. A first attempt to deal with this dualism was made by Kekulé, who put forward the theory that every substitution is preceded by an addition. I cannot help thinking that the substituting addition of maleic anhydride is better suited than that of the substances previously studied to fit in with this view and to bring us closer to an understanding of the nature of substitution.

Combination of Diene Synthesis and Substituting Addition

In view of the existence of two definite forms of reaction of maleic anhydride it was possible to foresee cases where both would occur jointly with one another. Two of these seem to me worth special mention - divinylmethane and styrene.

The divinylmethane type

In the first case (XLIII) the maleic anhydride reaction begins, as might be expected, with a substituting addition *(a)*.

$$H_2C=CH—CH_2—CH=CH_2 \xrightarrow{a} H_2C=CH—CH=CH—CH_2—CH—CH_2 \xrightarrow{b}$$

(XLIII)   (XLIV)
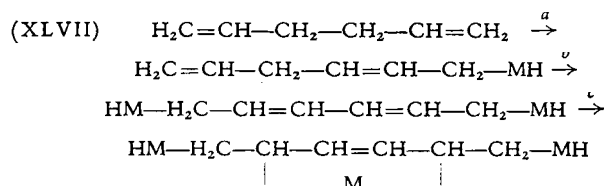
(XLV)
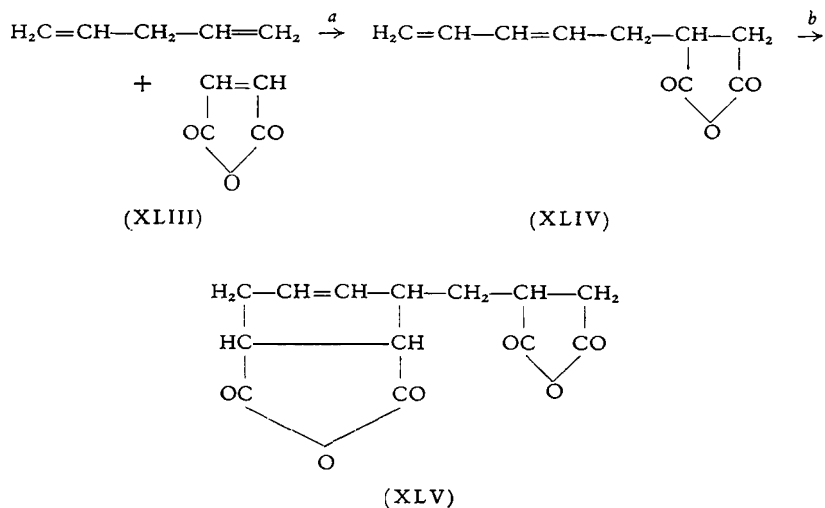
The "shift" of the double bond connected with this, leads to the formation of a conjugation and thus creates the condition necessary for subsequent diene synthesis (b). Since the first reaction is slower than the second, it is impossible to isolate the primary product (XLIV). The result[18] of this transformation sequence is the addition product (XLV), which constitutes a combination of acyclic and cyclic succinic acid. The dianhydride (XLV) - as we have now found - is for its part capable of further characteristic intramolecular changes, a discussion of which would be out of place here.

As prototype of the cyclic divinylmethane types we also investigated 1,4-dihydrobenzene (XCVI) from the same viewpoints, and with the same results[18].
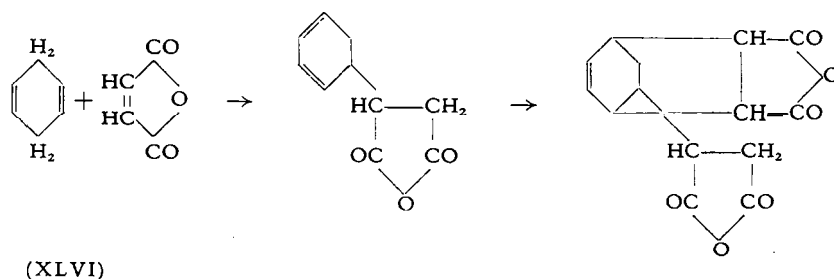
(XLVI)

The coupling of substituting addition and diene synthesis can, with a donor of given constitution, take place on a still larger scale. Thus, diallyl (XLVII) can accumulate up to three, α-allylnaphthalene (XLVIII) as many as four, molecules of maleic anhydride:
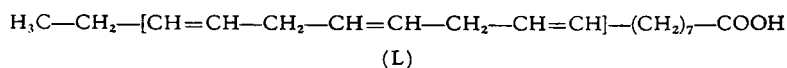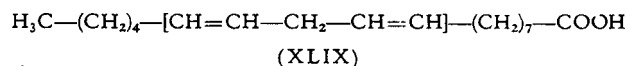
(XLVII) $H_2C=CH-CH_2-CH_2-CH=CH_2$ $\overset{a}{\rightarrow}$

$H_2C=CH-CH_2-CH=CH-CH_2-MH$ $\overset{v}{\rightarrow}$

$HM-H_2C-CH=CH-CH=CH-CH_2-MH$ $\overset{\iota}{\rightarrow}$

$HM-H_2C-CH-CH=CH-CH-CH_2-MH$

|_____M_____|

In the first case there are successively two substituting additions *(a and b)* and one diene synthesis *(c)* ; in the second, one substituting addition *(a)* and three diene syntheses *(b, c, d)*.

(XLVIII)
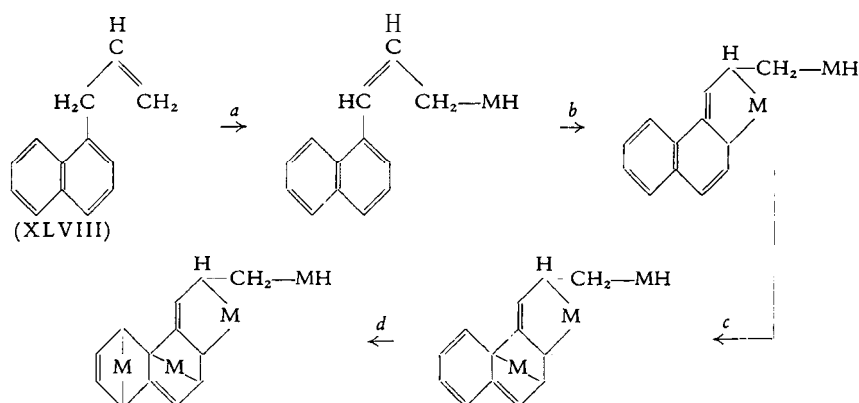
The successive dissolution of the bond system in the naphthalene of the side-chain is particularly significant here[19].

The reaction of the simple divinylmethane types with maleic anhydride also provides the key to an understanding of chemical processes which had hitherto been carried out on account of their industrial importance[20] without so far having led to defined chemical products; I refer here to the effects of maleic anhydride on linseed oil and other oils of the same type. Their common feature is their drying property, i.e. their ability, when in a thin layer, to form a film under the influence of the oxygen of the air. As is well known, this property is dependent on the linoleic (XLIX) and linolenic acid (L) content of these oils.

$H_3C-(CH_2)_4-[CH=CH-CH_2-CH=CH]-(CH_2)_7-COOH$

(XLIX)

$H_3C-CH_2-[CH=CH-CH_2-CH=CH-CH_2-CH=CH]-(CH_2)_7-COOH$

(L)

A glance at their structural formulae shows that these, too, are derivatives of divinylmethane. There can therefore be scarcely any doubt about the nature of their reaction with maleic anhydride. In its basic features it will very probably be the same as we found it in the simplest type of this reaction.

The fact that thanks to maleic anhydride these new modifications of drying oils have acquired, and are about to acquire, industrial importance is perhaps of less interest here than the fact that the reaction of divinylmethane with maleic anhydride tells us a great deal about the drying process itself.

The styrene type

Diene syntheses can be seriously affected if the diene or philodiene component or even both tend to change into pure or mixed macromolecular polymers. Unlike diene syntheses, these processes are chain reactions and are therefore easily influenced by catalysts. Suitable activators trigger them off, effective inhibitors will restrain or even completely suppress them. The boundaries between this kind of process and diene synthesis can be seen very clearly from the example of styrene, and indeed not only in systems where the styrene assumes the function of the philodiene but also in those where it fulfils the role of diene.

It is well known that the system styrene (LI) and butadiene is changed into macromolecular compounds under the influence of peroxide catalysts, these compounds being the basis of a valuable industrial rubber, "Buna S". There is no need for us to examine these complicated processes in detail in order to show how they differ from diene synthesis - both in the structural formula of the reaction products and in the dynamics of the reaction process. Being a typical chain reaction, polymerization can easily be suppressed, by the addition of inhibitors, to a point where the system can find its spontaneous equilibrium, i.e. the equilibrium no longer forced by catalysts. The diene synthesis which then occurs, results in a partially hydrogenated diphenyl (LII):

(LI)   (LII)   (LIII)
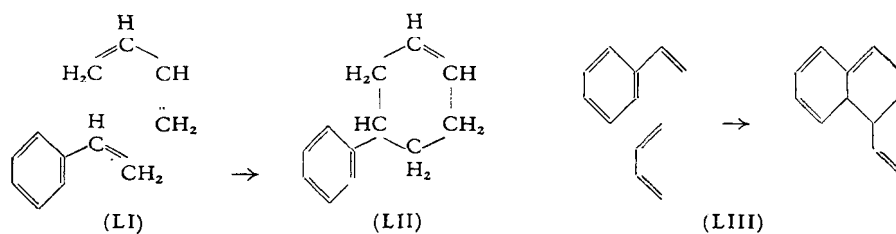
carbon, a process during which the bond structure of the phenyl nucleus is broken. There are two possible ways in which the unstable primary product (LIV) can become stabilized. One of these (*b*) is distinguished by the fact that the disintegration of the benzene formation which has been initiated is continued by a second diene synthesis with maleic anhydride. We obtained here for the first time a basic type of an addition product (LV), many variants of which had long been known thanks to the work of other authors[22]. These were obtained from styrene derivatives, in which the tendency to polymerize is not so pronounced as in styrene itself.

A second process (*c*) whereby the primary product (LIV) is stabilized is based on its tendency towards reclosure of the ring. Ideally this takes place by attachment of a second molecule of maleic anhydride in accordance with the formula of "indirect substituting addition". The characteristic "shift" of the double bond and the formation of (LVI), together result in restoration of the aromatic state.

In the case of styrene the second alternative (*c*) occurs more readily than the first (*b*), whereas with α-phenylstyrene the first process is demonstrably the only one which occurs. With substituting styrenes all conceivable intermediate forms between these two processes exist. A study of the connection between the rate at which the two processes occur and the nature and position of the substituents should help towards a thorough understanding of the relationships here.

A detailed examination of the arguments on which our proof is based would be outside the scope of this survey. Mention of the styrenes reminds me that, owing to the imperfections of the methods of organic chemistry, the study of these substances has been a question of patient seeking and cautious groping, and that where styrenes are concerned the clarification of a single detail often requires much time and effort.

The nature and extent of this problem become fully evident only when we remember that it is still not solved even when we have determined the structure of the addition products. The structural formulae of the molecules are merely simplified projections symbolizing the succession of the atoms and the way in which they are linked together. As far as their arrangement in space is concerned they tell us very little until we apply the principles of stereochemistry to them.

In the case of diene synthesis of styrene with maleic anhydride, which we have just been describing, the problem is then as follows: The addition product (LV) has seven asymmetrical carbon atoms which are of unequal valency

owing to the absence of certain molecular symmetrical forms and which are therefore capable of giving rise to the full number of $N = 2^7 = 128$ stereo-isomers. These constitute 64 pairs of enantiomorphous forms - racemic compounds. Even when allowance is made for the fact that - in the light of a special stereochemical experiment*, details of which will not be discussed here - in our case the number of isomers is again reduced by half, 32 isomers are still conceivable.

For the second structural isomer (LVI) with four centres of asymmetry, similar considerations give the impressive number of 16 isomers. In all, therefore, no less than 32 + 8 racemic forms are possible within the framework of the established structural formula. Experimentally we found three - one belonging to structural type (LV), and two to (LVI).

These examples illustrate three-dimensionally a characteristic feature of diene synthesis, a feature which is linked in the most intimate way with its nature - namely its pronounced steric selective properties. Of the reaction courses which are formally possible, only a few are taken, and frequently only one.

This peculiarity is one of the decisive factors determining the value of diene synthesis as a method. The fact that it can be used as a means of isolating and separating substances from mixtures, and that it is uniquely suitable as a means of determining the character of specific types of substance, could otherwise never have been known, for even the most highly developed methods of separating substances would be bound to fail in face of the difficulty of the problem to be solved here.

Diene Synthesis as a Stereochemical Phenomenon

The above examples of the peculiar steric nature of diene synthesis are better suited - since two successive additions are involved - to a definition rather than to a solution of the problem in question.
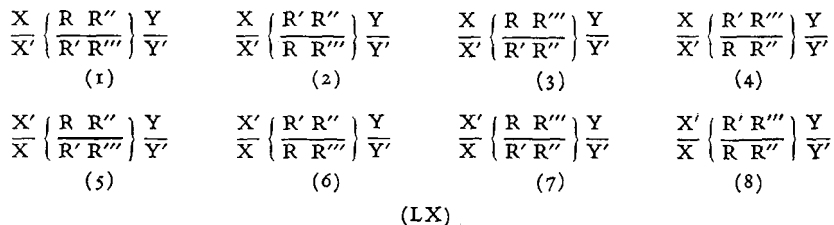
The steric preference for certain reaction courses among the many normally left open by the structural formula is a universal characteristic of diene synthesis, the peculiar nature of which we can see from the basic structural formula. This representation is simple and at the same time has the merit of maximum universality:

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* Trans-"bridge"-links are out of the question as they could not exist.

$$\text{(LVII)} \qquad \text{(LVIII)} \qquad \text{(LIX)}$$
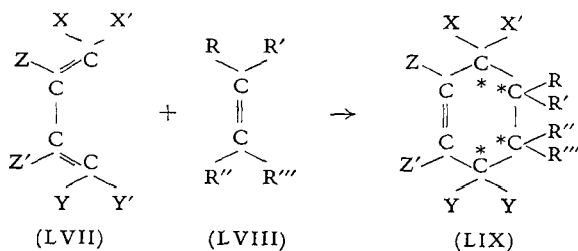
Upon addition of diene and philodiene the four addition centres usually become asymmetrical carbon atoms, which are of different valencies among themselves, and which formally can give rise to $2^4 = 16$ stereoisomeric addition products or eight pairs of enantiomorphous forms (racemic compounds)*.

These can be symbolized very clearly. The carbon ring formed by diene synthesis describes very roughly a plane, which we shall represent as a horizontal line. We then get the following eight possibilities (LX, 1-8) for the distribution of the substituents X, X', Y, Y', R, R', R'' and R''' on both sides of the ring plane**:

$$\frac{X}{X'}\left\{\frac{R\ \ R''}{R'\ R'''}\right\}\frac{Y}{Y'} \qquad \frac{X}{X'}\left\{\frac{R'\ R''}{R\ \ R'''}\right\}\frac{Y}{Y'} \qquad \frac{X}{X'}\left\{\frac{R\ \ R'''}{R'\ R''}\right\}\frac{Y}{Y'} \qquad \frac{X}{X'}\left\{\frac{R'\ R'''}{R\ \ R''}\right\}\frac{Y}{Y'}$$
$$(1) \qquad\qquad (2) \qquad\qquad (3) \qquad\qquad (4)$$

$$\frac{X'}{X}\left\{\frac{R\ \ R''}{R'\ R'''}\right\}\frac{Y}{Y'} \qquad \frac{X'}{X}\left\{\frac{R'\ R''}{R\ \ R'''}\right\}\frac{Y}{Y'} \qquad \frac{X'}{X}\left\{\frac{R\ \ R'''}{R'\ R''}\right\}\frac{Y}{Y'} \qquad \frac{X'}{X}\left\{\frac{R'\ R'''}{R\ \ R''}\right\}\frac{Y}{Y'}$$
$$(5) \qquad\qquad (6) \qquad\qquad (7) \qquad\qquad (8)$$
$$\text{(LX)}$$

As is well known, the two components - diene and philodiene - (which have just formed) occur, in their turn, in various geometrical isomers: the diene in the most universal case in four (LXI, 1-4), the philodiene in two (LXII, I-2).

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* This number is reduced when substituents are identical with one another. It increases when the diene and/or the philodiene are carriers of further centres of asymmetry. In this case the steric problems of diene synthesis touch those of asymmetrical synthesis[24].
** Owing to the non-existence of a "*trans*-cyclohexane" the substituents Z and Z' do not normally contribute to the formation of steric forms unless they possess their own centres of isomerism.

(LXI)

(LXII)
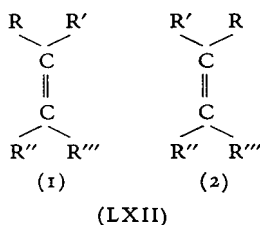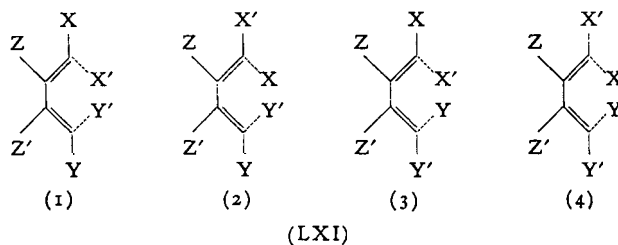
The problem of the steric course of diene synthesis boils down to the following three questions:

1. Does a relationship exist between the configuration of the philodiene and the arrangement of its substituents in the addition product?

2. Is there a similar relationship in the case of the diene component?

3. What relations apply to the mutual orientation of the two partners?

The «cis»-principle

A clear answer to the first question is given by comprehensive factual data.

The designation cis and trans for configurations in the olefine, characterizes the position of the substituents R, R', R" and R"' relative to the double bond. By the addition of a diene, this double bond is eliminated and the two carbon atoms, which it links together, become parts of a ring. Experience shows that the relative position of the substituents remains unchanged during this process. It is the same in relation to the ring as previously in relation to the double bond. One of the forms (LX, 1, 4, 5, 8) regularly arises from the isomers (LXII, 1), whereas (LXII, 2) can only result in the types (LX, 2, 3, 6, 7), but not vice versa.

From this unequivocal correlation in the configurations of philodiene and addition product, it can be inferred that diene synthesis constitutes a pure cis-addition which takes place at the double bond of the philodiene (cis-principle)[23,24].

Retention of the diene configuration

Considerations similar to those just described in the case of the philodiene components can be transferred - mutatis mutandis - to the diene. As in the former case, *cis* and *trans* additions are formally possible with the 1,4-addition in the latter case, just as they are with the 1,2-addition in the former case, and should result in addition products of different configuration. Our experiments showed that here, too, the addition of the philodiene to the diene takes place in accordance with the *cis*-addition formula, and that therefore an analogous steric retention principle applies here:

The diene enters the addition product with unaltered configuration, i.e. both *cis* substituents of the diene and both its *trans* substituents are situated on the same side of the ring in the addition product*. In the case of the diene (LXI, 1), for instance, only the forms (LX, 1-4) of the addition product satisfy this condition, the rest (LX, 5-8) conflict with it.

Whereas the *cis* principle, which was formulated at an early date, is now[24] supported by a vast body of experimental evidence, it is only recently[25] - owing to the inaccessibility of stereoisomeric dienes - that we have succeeded in confirming in a few characteristic cases, the "principle of the retention of the diene configuration".

Diene synthesis and free rotation

In the preceding section we made a tacit assumption which requires some justification. As is well known, in classical stereochemistry, the principle of "free rotation" was postulated in order that the number of asymmetrical ethane derivatives demanded by the model might be kept in accord with

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* The fact that the position of the substituents X′ and Y′ on the one hand, and that of X and Y on the other, are spatially equivalent, can probably be seen best if one imagines
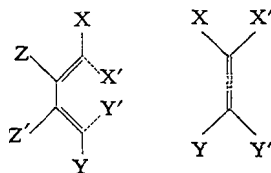
that carbon atoms 2 *and* 3 of the diene are taken out, and the two remaining parts of the diene are reunited. Both pairs then assume a *cis*-position relative to one another. In this way the analogy of the *cis*-principle with the principle of retention of the diene configuration becomes particularly clear.

empirical findings. According to this principle carbon atoms linked singly with one another can rotate round the C-C axis.

In the case of the diene component this would mean that between the two planar configurations - the "bent" one (LXIV) with addition centres as close together as possible, and the "stretched" one (LXIII) - all possible nonplanar transitions are conceivable:

trans-arrangement	*cis*-arrangement
(LXIII)	(LXIV)
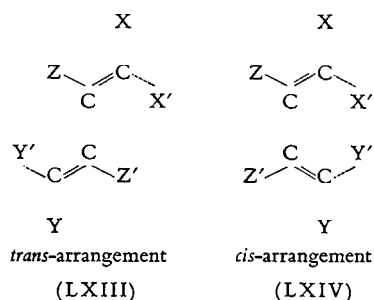
So far, we have been assuming that diene synthesis takes place from arrangement (LXIV). There are several different arguments for this hypothesis, some of which we will now cite[26].
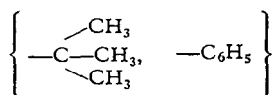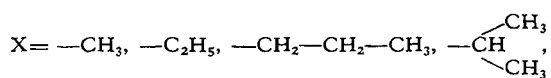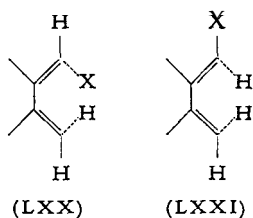
By means of constitutional factors it is possible to eliminate "free rotation" and also to define the "stretched" as well as the "bent" arrangement. It is found here that the first category, (LXV) and (LXVI), is unable to add philodienes, whereas compounds such as (LXVII-LXIX) are capable of diene synthesis:

(LXV)   (LXVI)

(LXVII)   (LXVIII)   (LXIX)
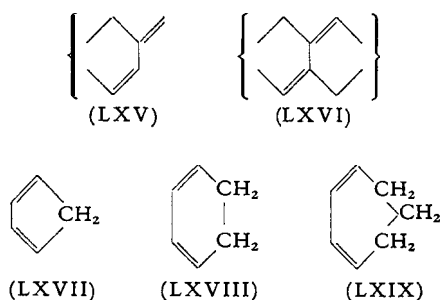
Significantly the reactivity optimum is with five-membered rings, which, thanks to their valency angle, by their very nature represent ideally the rigid planar diene. As the distance increases, so - according to the model - the mobility, and with it the possibility of deviation from the planar arrangement, increases. At the same time the reactive capacity decreases.

From a host of further arguments, I will point out that voluminous substituents Z and Z′, as well as a blocking X′ (or Y′) are capable of suppressing approximation to the "bent" planar form (LXIV), which is necessary for addition, to such an extent that addition no longer occurs.

In this connection the behaviour of the two series (LXX) and (LXXI) is informative:

(LXX)   (LXXI)

$$X= --CH_3,\ --C_2H_5,\ --CH_2--CH_2--CH_3,\ --CH \begin{smallmatrix} CH_3 \\ CH_3 \end{smallmatrix},$$

$$\left\{ --C \begin{smallmatrix} CH_3 \\ CH_3 \\ CH_3 \end{smallmatrix},\quad --C_6H_5 \right\}$$

With the *cis*-diene type (LXX) the capacity for addition declines as the branching and space-filling of the substituent X increase. According to empirical findings to-date it is totally eliminated with *tert.*-butyl and with phenyl. Significantly the analogous *trans*-dienes (LXXI) are without exception capable of diene synthesis, and the facility with which they react is substantially the same in all cases within this group. It is greater than with all analogues of the *cis*-series (LXX). The two hydrogen atoms in the *cis* position of (LXXI) obviously hinder least the coming into being of the "bent" arrangement, which is necessary for the reaction.

In order to express the formal similarity of the acyclic dienes in their bent arrangement to the cyclic dienes, e.g. (LXVIII), we have called the former "quasicyclic". The relations existing between free rotation and the course of diene synthesis can be reduced to the simple formula: cyclic and acyclic dienes show the same behaviour during diene synthesis, since the acyclic dienes come to reaction in their "quasicyclic" arrangement[26].

The universal orientation formula

In their simplicity, the steric rules so far described may to some extent be

apparent if not perfectly obvious. However, this is not the case with the relationship now about to be discussed, which deals with the question of whether the two partners are orientated in relation to one another. A long and difficult journey had to be travelled before this steric law, the "universal orientation formula", was recognized and proved. Within the framework of this lecture I can only sketch very briefly a few of the stages on this road.

Its starting-point was the study of thermal polymerization of cyclopenta-diene[27]. When heated, this hydrocarbon - as had been shown earlier - yields a polymerically homologous series, to whose formation the following uniform law seemed to apply:

$$n = 1, 2, 3$$
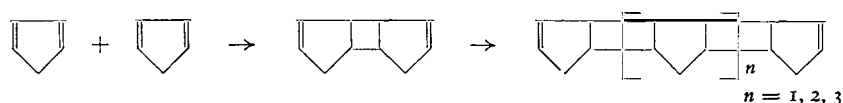
Our first contribution consisted of a review of this fascinatingly simple structural formula. The principle of the formation of four-membered rings had to be replaced by the formula for diene synthesis. The polymerization of cyclopentadiene should be formulated as follows:


(LXXII)

(LXXIII)

$$n = 1, 2, 3$$
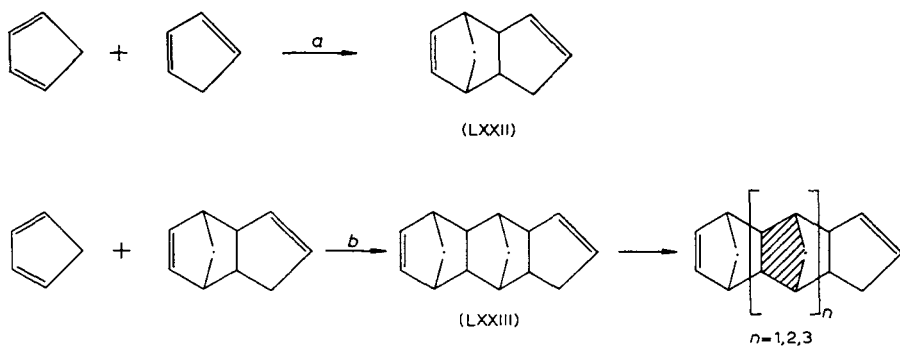
Here for the first time it was found necessary to include the stereochemical as well as the structural aspect in the study of diene synthesis. This was occasioned by the isolation of two trimeric cyclopentadienes (LXXIII). Breakdown of these led to the important conclusion that the two trimers were already based on two dimers (LXXII), or in other words that process *a* must already occur in two directions.

These two directions (α and β) are foreseen by the model, and this question could have been regarded as settled with the isolation of a second β-dicy-clopentadiene in addition to the α-form, which had long since been known,

and with the correlation of both with the configuration given by the model. That it was not, is due to one particular circumstance. The transitions which have been described take place at elevated temperature. The picture is very much simplified when one studies the changes undergone by monomeric cyclopentadiene at room temperature. The liquid hydrocarbon changes into the camphor-like mass of α -dicyclopentadiene within a few days. Structurally and sterically this process is completely uniform. Structurally it means nothing more than the first phase *(a)* of the above-described formation of a polymerically homologous series which at room temperature breaks off after the first member.

Its steric uniformity, however, inevitably seemed extremely remarkable, since it was obvious that only one of the possible courses α and β was taken at low temperature.

(LXXII, *a*)   (LXXII,β)
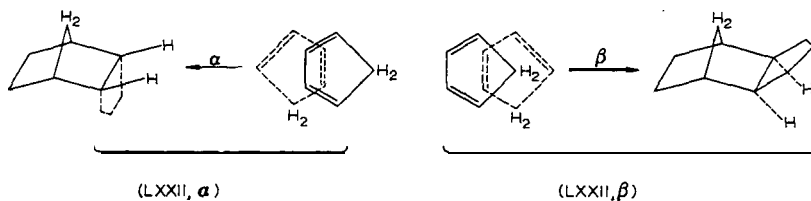
Experiments soon convinced us that this phenomenon was by no means confined to dimerization of cyclopentadiene. Thus, addition of cyclopentadiene to maleic anhydride proceeds in only one direction sterically, and this direction is demonstrably the same as that found with dimerization of cyclopentadiene.

With regard to the question whether α or β was the preferred steric course, a very precise answer in favour of α could be given from the addition product - cyclopentadiene and maleic anhydride.

A comparison between the addition products formed in accordance with formula α and formula β shows quite clearly that the above-explained retention principles apply in both cases, and that consequently they alone are not sufficient to account for the observed steric selection.

On the contrary, a new selection principle must be operating here, a principle which can with advantage be described with the aid of "orientation complexe". If one imagines the two partners - diene and philodiene - so close to one another that the four centres of addition* are situated on a

* Or, to be more accurate, their projection on the drawing-plane.

straight line, one recognizes that with α all the double bonds come to lie on one side of this line, whereas with β they are distributed on both sides. To put it another way: with diene synthesis, addition is entirely or predominantly steric when it is from an orientation complex with maximum accumulation of the double-bond systems of both partners (LXXII, α), but is entirely or predominantly non-steric when it is from the minimum-density arrangement of these systems (LXXII, β)[23].

(LXXIV, α)   (LXXIV, β)
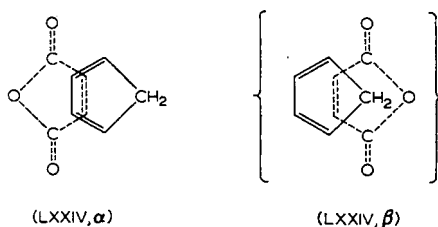
This statement holds good in a wide range of cases. We deduced it for many diene syntheses, in the first place in very great detail for the additions of maleic anhydride, which - for instance, with cyclopentadiene - always adds in accordance with formula (LXXIV, α) and not in accordance with (LXXIV, β). This picture is not materially changed if we go from the cyclic to the acyclic dienes, since these, as explained in the preceding section, react in their "quasicyclic" arrangement. The same applies if we go from maleic anhydride to acrylic acid, or to philodienes of the vinyl acetate type, where the uncombined electron pairs obviously assume the function of the double bond.

On the other hand, as was to be expected, the "universal orientation formula" ceases to be valid where the demand for maximum accumulation of the double-bond systems of both partners ceases to be unequivocal, which is the case in the diene class, e.g. with the fulvenes (LXXV, α and β), and in the philodiene series, e.g. with the diene syntheses of fumaric acid (LXXVI, α and β).
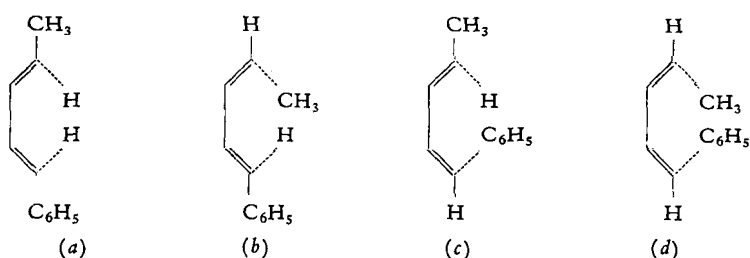

(LXXV, α)   (LXXV, β)

(LXXVI,*a*)   (LXXVI,β)
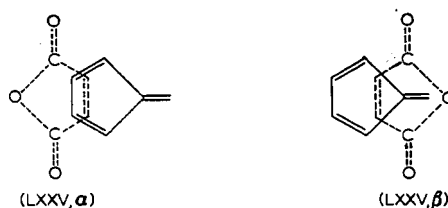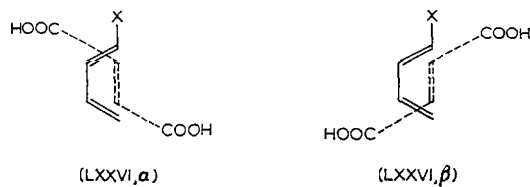
Here neither of the two orientation complexes is distinguished from the other, and the addition is steric in both directions.

An example

1-Phenyl-4-methylbutadiene exists in four forms (*a-d*), of which three (*a-c*) are well known.

(*a*)   (*b*)   (*c*)   (*d*)

As is to be expected from our empirical findings, form (*c*) can enter into no diene synthesis, since the phenyl group prevents the necessary approximation to the planar arrangement. Both forms (*a*) and (*b*) are capable of diene syntheses, and, as we know from experience, (*a*) participates more readily in these reactions than does (*b*).

Structurally diene synthesis of 1-phenyl-4-methylbutadiene with maleic anhydride or fumaric acid presents the following picture:
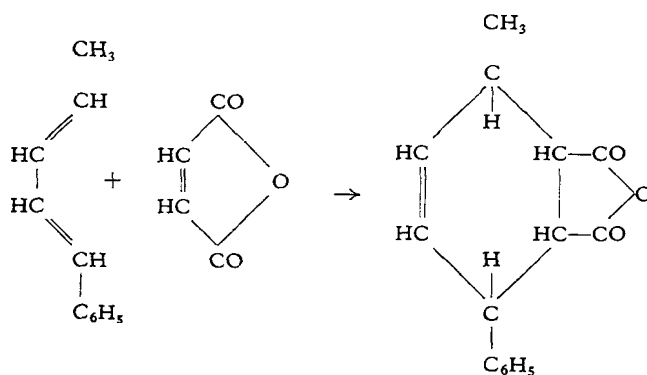
Sterically the forms (1-8) are possible.

CH₃ COOH COOH C₆H₅	CH₃ COOH C₆H₅	CH₃ COOH C₆H₅
	COOH	COOH
(1)	(2)	(3)

CH₃   C₆H₅   COOH COOH C₆H₅   COOH   C₆H₅

COCH COOH   CH₃   CH₃   COOH

(4)   (5)   (6)

COOH C₆H₅   C₆H₅

CH₃ COOH   CH₃ COOH COOH

(7)   (8)
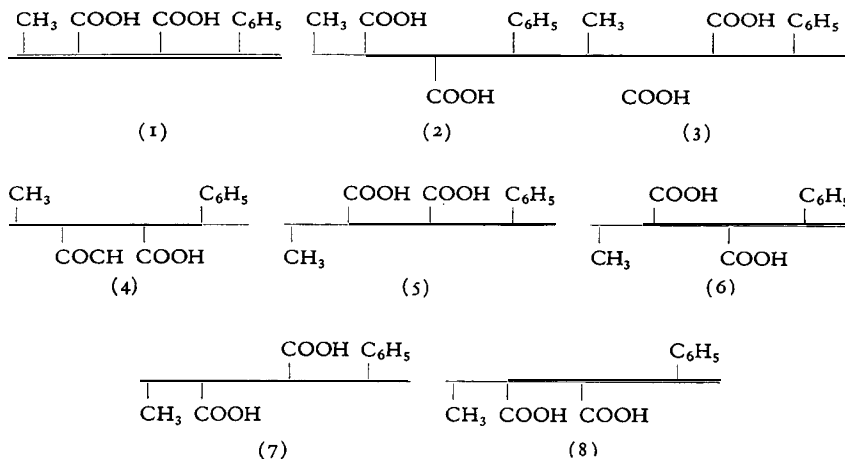
Case I : *trans, trans*-form *(a),* and maleic anhydride.

The *cis*-principle, which demands retention of the philodiene configuration, rules out (2), (3), (6), and (7); (5), (6), (7), and (8) are incompatible with the principle of retention of the diene configuration in the addition product. Of the remaining alternatives (1) and (4), the universal orientation formula decides in favour of (1). In accord with empirical findings, only one of the eight possible forms - namely the *all-cis* form (1) - arises.

Case II: *trans, cis-* form (b), and maleic anhydride.

In this case, by the same reasoning it can be predicted that form (5) will be the reaction product, in accord with empirical findings.

Case III: *trans, trans*-form (a), and fumaric acid ester yield, as predictable, forms (2) and (3) side by side.

Diene syntheses with asymmetrical addenda

The above steric interpretation does not conclude the discussion of the universal structural formula for diene synthesis. On the contrary, the structural formula confronts us with a further question: What course do diene syntheses take when the structural asymmetry of the two partners permits two alternative reactions? The two following combinations of an asymmetrical philodiene with a diene substituted in the α- or β-position represent the simplest processes of this type:

(LXXVII)

(LXXVIII)
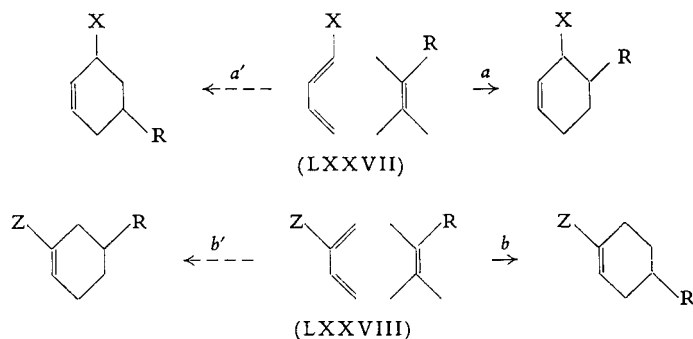
The empirical data recently obtained from these and more complex examples show selectivity again here, in that in the first case ortho-forms *(a)* and in the second para-forms (b) tend to arise before formation of meta-types *(a', b')*, since these types occur only as by-products, if at all.

In the light of our experience to-date, these findings, and this is most remarkable, are largely independent of the nature of the substituents X and R.

From the many results to hand I should like to point out one in particular which is very informative, namely the addition of *trans*-butadiene-1-carboxylic acid (X = COOH) to acrylic acid (R = COOH). Despite the polar character of the same substituents, structurally they move in close to one another and yield the ortho-form (LXXVII). This clustering of two groups of equal polarity is as complete here as possible, for it is found that - entirely in accordance with the steric rules described above - the *cis*-form of the ortho-series is the main product of this diene synthesis[24].

Observations on the mechanism of diene synthesis

Diene synthesis of butadiene-1-carboxylic acid with acrylic acid is in no way an exceptional case as far as its course is concerned. On the contrary, we have encountered other cases where groups of equal polarity crowd in as close as possible together during addition. I draw particular attention to this fact here because it provides me with an occasion for a remark on the mechanism of diene synthesis.

So far I have confined myself to the means of expression of classical structural chemistry - valency line, double bond, and asymmetrical carbon atom - in my descriptions of results. The fascinating simplicity of the new reaction, long ago prompted experiments with a view to a definition of it in the light of the modern theory of linkage[28].

At first it was suggested that diene synthesis was a (crypto-) ionic process. It was thought that displacements of the charge both in the system of the diene and also in that of the philodiene, induced polarities, and that the driving force for their union lay in their intermolecular equilibrium.

Our experimental results, obtained during a study of asymmetrical addenda, showed this interpretation of diene synthesis to be highly improbable - at least that it is not the determining factor governing the course of the addition process. The same nature of substituents X and R and their same position in the double-bond system of both partners ought to induce the same charge formula in both, and the equilibrium of this formula ought inevitably to give the same meta-type. This is obviously at variance with experimental   findings.

The fact that polar solvents and catalysts have relatively little effect on diene syntheses likewise points away from an ion reaction mechanism.

The strongest argument against such a mechanism lies in the fact that it in no way appears to obey the laws which govern diene synthesis structurally and sterically.

Structurally it is the formation of six-membered rings, the laws governing these being particularly striking where there is an opportunity for rings of relatively large width to arise. Since first being posed, with regard to the polyenesa, this problem has been repeatedly examined - on the last occasion[10] by means of addition of maleic anhydride to 1, 1, 12, 12-tetraphenyl-dodecahexaene.
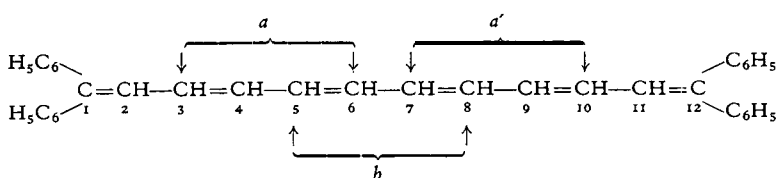
As is indicated by the sketch of the addition centres in the 3,6- and the 7,10-position on the one hand (a, a') and in the 5,8-position on the other (b), the 6-ring formation also dominates the field here. The (crypto-) ionic interpretation does not account for this phenomenon; on the contrary, the regular formation of six-membered rings directs our attention to another relationship.

From the point of view of the electron theory of valency, the total balance-sheet of diene synthesis lies in an interplay between the functions of the

six π-electrons of the two partners. Two of them retain - although in a changed position - their character as π-electrons, whereas the remaining four are used in pairs for the formation of two σ-bonds in the 6-ring. Both factors, i.e. the six π–electrons and the six-membered carbon ring, point to similarities between the linkage system of benzene and that of the aromatic hydrocarbons.

As is well known, compared with a cyclohexatriene with double bonds visualized as being localized, benzene is a relatively stable structure from the chemical and the energy aspect. Extensive experimental work has shown this "aromatic character" to be confined to the number 6, and according to the quantum theory it can be ascribed to a closed inner sextet of bonding **π–electrons.**

An identical - or at least very similar - group of six bonding electrons of "aromatic resonance" is by all appearances also at work during diene synthesis; indeed it is thought to be the triggering factor. As the two partners - diene and philodiene - approach one another, the electron sextet forms as a result of reciprocal decoupling of their π-electron systems, the energy required for this decoupling being supplied from the gain in resonance energy.

We can therefore supplement the universal reaction formula for diene synthesis by inserting an unstable complex-type structure (LXXX) as a transition between the initial system of the two partners (LXXIX) and the final stage of the stable product of addition (LXXXI).

Since the components already occupy spatially well-defined positions in this structure, we named these intermediate combinations "orientating complexes". The cohesion is effected by a sextet of electrons supplied jointly and proportionally to both partners. The conversion of this sextet into two σ-bonds, which complete cyclization, and into a double bond, which occupies a specific position, brings the addition process to a close.

(LXXIX)   (LXXX)   (LXXXI)
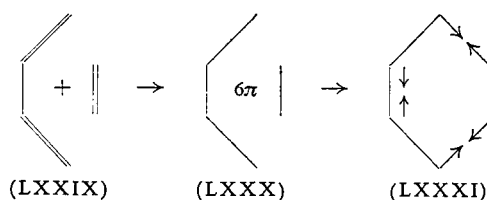
On the basis of this hypothesis diene synthesis is not a (crypto-) ionic but a (crypto-) radical process where the course of the reaction is determined by those factors which are decisive in the decoupling of electron pairs. Inductive

effects emanating from polar groups and manifesting themselves as charge displacements through the carbon chains will undoubtedly be present, although, being forces of relatively low magnitude, they will not usually be decisive - in complete contrast to the resonance forces exerted by multiple bonds upon one another or in their interplay with non-proportionate electron pairs of polar groups. I must confine myself here to stating that among the laws characterizing the picture of diene synthesis, none has yet been found which conflicts with the interpretation put forward above.

I am aware that this rough sketch merely suggests the direction in which an explanation of the peculiarities of diene synthesis is probably to be sought. Its structural and steric selectivity makes possible an enormous number of π-electron systems of both partners - and in fact not only of the substituents participating directly in the addition process but also those of "activating" substituents. This fact will have to be the starting-point of a detailed discussion of the configuration of the π-electron systems in the orientating complexes.

Diene Synthesis and Substituting Addition as a Special Case among General Reaction Types

Over the 23-year period during which diene synthesis was being developed, a vast body of experimental data accumulated, but despite the variety and abundance of individual cases, certain general laws are discernible among all the results obtained. These laws are clearly the expression of the fact that these are pure and direct interactions between electron systems of two partners - in other words, effects which are not complicated by the participation of accessory agents.

It is not surprising that processes of this type should not be confined to pure carbon systems but that other arrangements of atoms with suitable electron configurations show a tendency towards similar conversions. Cases of this type have become known in increasing numbers, so far primarily with the elements oxygen and nitrogen. Thus, instead of the arrangement C=C -C=C, the groups C=C-C=O and N=C-C=N can also act as dienes, whereas in addition to the classical philodienes, >C=C< and -C=C-, combinations such as >C=O, -N=N-, -C=N, and -N=O are capable of fundamentally the same effects. This second group is rounded off by molecular oxygen. Developments during the past few years have shown

ever more clearly the similarity of this substance to maleic anhydride in its reactions with dienes and olefines. The merging of diene synthesis and of substituting addition, on the one hand, with the apparently completely heterogeneous phenomena of autoxidation, on the other, into a homogeneous group of processes will presumably be only one stage in this development. It is very probable that in the majority of cases the additions of diazomethane, of diazoacetic acid, of organic azides, etc., to unsaturated systems, are triggered off and are determined, as far as their course is concerned, by resonance phenomena between the π-electron systems of the two partners The task now is to investigate such effects of unsaturated substances upon one another from aspects which have become evident for the first time during the study of diene synthesis as the ideal type of this reaction.

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