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Cyclic Compounds as Configurational Models for Stereoregular Polymers

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It is possible to draw analogies between linear polymers and cyclic compounds. Stereo-chemical considerations developed in this connection led to the recognition of new aspects of importance for the systematic classification of both classes of compounds; for example, asymmetric structures can be predicted which had hitherto never been suspected. — The concept of "diasteric centers" is introduced, and the definition of an "asymmetric center" is expressed in more general terms.

Determination of the crystal structure of many stereo-regular polymers has led to an independent formulation of the principles for configurational and conformational analysis of polymers with respect to other types of organic compounds [1].

This approach is possible because linear polymers can be considered essentially as monodimensional molecules, *i.e.* the order necessary for a crystalline structure to develop is determined in one dimension by the succession rules existing within the macromolecule, In addition, the configurational sign (D or L) often loses its meaning; instead, the relationship between the configurations (no matter how defined) of atoms belonging to the same macromolecular chain becomes important.

In this paper, a method is outlined for considering polymeric structures from a configurational point of view. An attempt is made to point out analogies between macromolecules and the low molecular-weight molecules usually considered in classical organic stereochemistry. In particular, some analogies between the configurational properties of linear macromolecules and those of cyclic compounds are described.

1. Polymeric Chains, Their Lengths, and Cyclic Models

Studies of the configurational properties of polymers are remarkably simplified by considering polymeric chains of infinite length [2]; from several points of view, this extrapolation seems justified and useful. Various para-

meters in macromolecular chemistry, such as melting and transition points [3a] depend asymptotically on the molecular weight, *i.e.* above certain molecular weights their value is constant and practically equal to that of a polymer of infinite chain length. The configurational properties of polymers also exhibit this asymptotic dependence on molecular weight, as shown below.

The tertiary carbon atoms in an ideal isotactic polymer of infinite length derived from a vinyl monomer cannot be considered as asymmetric [2]. An isotactic vinyl polymer chain of finite length with identical end groups is usually considered as a *meso*-form, having two sequences of atoms with opposite configurations (DDD...DDLL...LLLL). In reality, there is no sharp transition in the central region, since each asymmetric atom differs from the preceding one and becomes less asymmetric the nearer it is to the center of the molecule ($D_1D_2D_3$... $D_{n/2}L_{n/2}$...$L_3L_2L_1$). The data reported in the literature concerning the influence exerted by the length of a substituent on the optical activity of an asymmetric atom show that such influence diminishes rapidly and that the molar optical activity soon tends to constant values (possibly zero).

This is illustrated in Figure 1, where Curve I represents schematically the situation occurring in compounds of the tartaric acid type (*meso*-forms with only two asymmetric atoms), Curve II represents that of a *meso*-compound having four or more similar asymmetric atoms, and Curve III refers to an isotactic vinyl polymer. Here the major portion of the macromolecule has no measurable asymmetry and can therefore be described by the model of infinite length (Curve IV).

The model of infinite length may be conveniently replaced by a cyclic model, if the concept of an unlimited chain is taken instead of that of an infinite chain.

A line closed on itself, in particular a circumference, has the property in common with an infinite straight line of being unlimited. The straight line is infinite and unlimited (in one dimension), while a circumference is a finite though unlimited figure. Analogous remarks apply to a segmented line

[1] G. Natta and P. Corradini, Suppl. Nuovo Cimento [10] *15*, 9 (1960); Chim. e Ind. *45*, 299 (1963).

[2] G. Natta, P. Pino, and G. Mazzanti, Gazz. chim. ital. *87*, 528 (1957).

[3a] P. J. Flory: Principles of Polymer Chemistry. Cornell University Press, Ithaca, N.Y., 1953, p. 571.
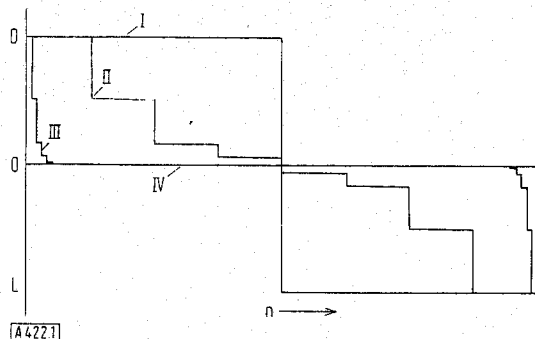
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Fig. 1. Schematic representation of the asymmetry of each asymmetric atom in *meso*-tartaric acid (I), in a *meso*-compound with several homo-substituted atoms (II), in an isotactic polymer with equal terminal groups (III), and in an isotactic polymer of infinite length (IV).

Abscissa: number of carbon atoms.

Ordinate: asymmetric character

with an infinite number of segments and to a polygon. On this basis, it is possible, to use a cyclic model to describe and to make predictions about polymers.

The concept of a polymer as an unlimited structure without end groups has recently also been developed by other authors: "In a strict sence, only a macrocyclic compound is a real polymer" [4]. Only a cyclic polymer can consist exclusively of one type of structural unit; a linear polymer of finite length always contains end groups with a structure different from those in the chain. For linear polymers, the monomeric units are all the same only when the chains are of infinite length.

Analogies between the physical properties of cyclic compounds and those of linear polymers can be observed only when the cycles are large enough. For instance, it has long been known that macrocyclic hydrocarbons crystallize in long straight segments similar to linear hydrocarbons [5]. It can also be expected that cyclic and linear compounds, whose molecules have the same distance between subsequent folds of the chain in the crystals will have similar melting points.

It must be remembered that, although compounds consisting of small cycles differ in their physical properties from those consisting of large cycles, the configurational properties of both are the same. It thus follows that the configurational properties of linear polymers can be predicted very simply by considering cyclic structures comprising only a few structural units either equal or equivalent to those in the corresponding linear polymer.

It is interesting to note that the hypothesis of cyclic structures for polymers was long supported by a number of workers owing to the difficulty in distinguishing by chemical means between linear macromolecules and cyclic compounds — even of small size — with analogous structures [3b].

2. Types of Representation and Symmetry Elements

In order to facilitate the configurational analysis proposed, simple and consistent representations of the two series of compounds (cycles and chains) must be chosen.

We have therefore chosen a regular plane polygon for the cyclic compounds and Fischer projection formulae for the chains [6a]. Complete rotation of substituents around the bonds is admitted, so that they can be symbolized by a letter and treated in symmetry operations as spheres, unless they are asymmetric, when the mirror image of the generic substituent D is then L.

Passage from one series of compounds to the other, *i.e.* from cycles to chains and *vice versa*, involves transformation of the symmetry elements inherent in the type of representation selected and valid only from a configurational point of view. Table 1 reports the relationships existing between the symmetry elements of a cyclic model with n sides and of the corresponding polymeric chain represented according to the Fischer convention.

Table 1. Correlation among the symmetry elements of a linear polymer chain (represented according to the Fischer convention) and of its cyclic models.

Cyclic model with n sides	Fischer projection
m-fold rotational axis perpendicular to the ring	Repetition period equal to n/m
Two-fold axis in the plane of the ring	Two-fold axes normal to the projection, placed at a distance of n/2 from each other
Mirror plane in the plane of the ring [a]	Mirror plane containing the chain axis and normal to the projection [a]
Mirror plane normal to the ring (one-fold alternating axis)	Mirror planes normal to the chain axis, placed at a distance of n/2
Center of symmetry (two-fold alternating axis)	Glide plane containing the chain and perpendicular to the projection, with a period of n/2
Four-fold alternating axis	Glide plane containing the chain and perpendicular to the projection, with a period of n/4

[a] Absence of stereoisomerism in both series.

It can be observed that no independent symmetric element corresponding to the four-fold alternating axis exists in linear polymers: a cyclic model containing such an axis, can always be reduced to one half; in this case it has a center of symmetry.

The relationships indicated in Table 1 suggest that the conditions for predicting the optical activity in low molecular-weight compounds, *i.e.* the absence of alternating axes of the 1st, 2nd and 4th order [6b,7], must be modified in the case of linear macromolecules. Here, the existence of configurational enantiomorphous forms is in fact connected with the absence, in the Fischer projection, of mirror planes normal to the chain axis and of glide planes containing the chain and being perpendicular to the projection.

These conclusions complete and put into a systematic form some considerations recently made by *Arcus* [8].

[3b] See [3a], Chapter I.

[4] W. Kern and R. C. Schulz in Houben-Weyl: Die Methoden der organischen Chemie. Thieme, Stuttgart 1963, Vol. XIV/1, p.4.

[5] A. Müller, Helv. chim. Acta 16, 155 (1933).

[6a] G. W. Wheland: Advanced Organic Chemistry. 3rd Edit., Wiley, New York 1960, p. 249.

[6b] See [6a], p. 211.

[7] E.L. Eliel: Stereochemistry of Carbon Compounds. McGraw-Hill, New York 1962, p. 7.

[8] C. L. Arcus in P. B. D. de la Mare and W. Klyne: Progress in Stereochemistry. Butterworths, London 1962, p. 264.

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3. Models of Stereoregular Structures and "Diasteric" Centers

cis-Hexamethylcyclohexane, cis-1, 3, 5 - trimethylcyclohexane, and cis-1,4-dimethylcyclohexane are configurational models of isotactic polymers (Fig. 2); trans-hexamethylcyclohexane, trans-1,4-dimethylcyclohexane, and trans-tetramethylcyclobutane are models of syndiotactic polymers [*].

All the models contain at least a plane of symmetry, the trans-models also possess a center of symmetry or a four-fold alternating axis; correspondingly, all the polymers have symmetry planes normal to the chain, and the syndiotactic polymers also have glide planes parallel to the chain.
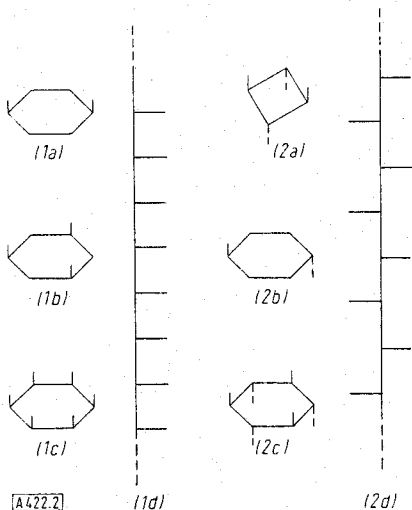
Fig. 2. Cyclic models and Fischer projection formulae of isotactic (1) and syndiotactic polymers (2).

The tertiary carbon atoms of the models are not asymmetric: we therefore deduce that the tertiary atoms of the macromolecule are not asymmetric either. In both cases, however, these atoms are centers of diastereoisomerism in the sense that inversion of the disposition of the substituents at some of these centers leads to a different stereoisomer, which is not enantiomorphous with the original compound. This is the situation involved in the transition from cis- to trans-substituted cyclohexanes, or from isotactic to syndiotactic polymers.

These diastereoisomerism phenomena are not necessarily connected with the presence of asymmetric or pseudo-asymmetric atoms, as can be seen from the models already discussed. It is proposed that the general term "diasteric" (i.e. capable of diastereoisomerism) be used to describe an atom, independently of its asymmetry, when interchange of two substituents on this atom causes the molecule to be transformed into one of its diastereoisomers (non-enantiomorphous stereoisomers). It can be shown that if a diasteric carbon atom is neither asymmetric nor pseudo-asymmetric, it must necessarily be part of a cycle or of an infinite chain.

A case similar to that of the vinyl polymers is that of the di-isotactic and di-syndiotactic polymers obtained from 1,2-disubstitued ethylenes of the type CHA=CHB.

[*] For a correlation of the terms isotactic and cis, and syndiotactic and trans, see [1].

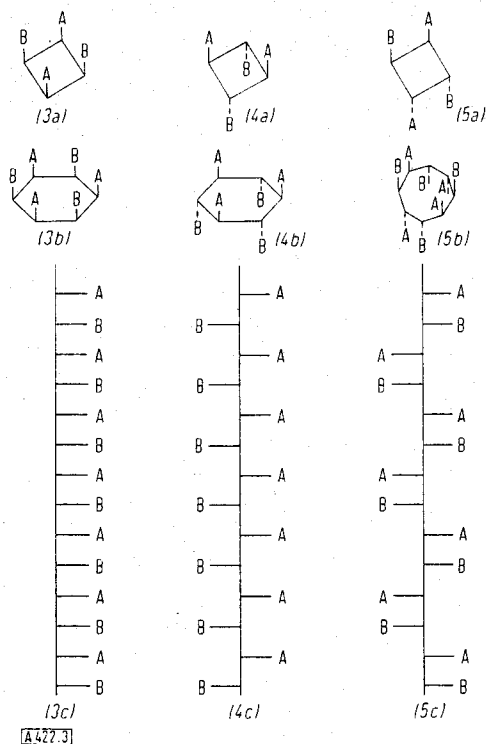Figure 3 shows the cyclic models for all possible forms (erythro- and threo-di-isotactic, and di-syndiotactic polymers).

Fig. 3. Cyclic models and Fischer projection formulae of erythro-di-isotactic (3), threo-di-isotactic (4), and di-syndiotactic polymers (5).

It must be observed that no planes of symmetry exist in the models of di-syndiotactic polymers, but only a center or a fourfold alternating axis of symmetry. In the corresponding polymer chain, in agreement with the correlations reported above, there is only a glide plane parallel to the chain axis.

Incidentally, it is noteworth that the octagonal model in Figure 3 represents the simplest cyclic compound with no asymmetric substituents which possesses an alternating axis of the fourth order as the only alternating configurational axis.

4. Optical Activity in Polymers

The symmetry of the structures just examined excludes the possibility of the existence of optical antipodes for all isotactic, syndiotactic, di-isotactic, and di-syndiotactic macromolecules. This fact is widely known [2, 8–10], but even recently some misunderstandings have arisen with regard to this question. Several classes of optically active polymers have been obtained to date: poly(propylene oxide) [11], poly-(3-methylpentene) and other polyolefins with asymmetric substituents [12], polysorbates and other substituted poly(pentadienoic

[9] G. Natta, M. Farina, and M. Peraldo, J. Polymer Sci. 43, 289 (1960); Chim. e Ind. 42, 255 (1960); Makromolekulare Chem. 38, 13 (1960).

[10] C. Schuerch, J. Polymer Sci. 40, 533 (1959).

[11] C. C. Price and M. Osgan, J. Amer. chem. Soc. 78, 4787 (1956).

[12] P. Pino, G. P. Lorenzi, and L. Lardicci, J. Amer. chem. Soc. 82, 4745 (1960).

esters) [13], polybenzofuran [14], polypentadiene [15], *etc.* Examination of the polymeric structures and cyclic models of all of these compounds reveals the absence of planes or centers of symmetry and alternating axes of the fourth order in the models, and of perpendicular planes and glide planes of symmetry parallel to the chain in the polymers.

Such optically active polymers are of two types: 1. polymers of the vinyl type with asymmetric substituents, and 2. compounds with asymmetric atoms in the main chain.

In the former type, the tertiary atoms in the chain are diasteric, but not asymmetric. Some polymers of the latter type are derived from monomers that contain asymmetric atoms, *e.g.* propylene oxide, others are obtained by asymmetric synthesis from monomers that do not contain centers of optical stereoisomerism, *e.g.* 1-monosubstituted or 1,4-disubstituted butadienes and cyclic olefins [13,16].

Using cyclic models, it can be seen that neither cyclobutene nor 1,5-cyclooctadiene, which are models of the 1,4-polybutadiene chains, possess configurational asymmetry [*].

The recent isolation of the antipodes of *trans,trans*-1,5-cyclooctadiene by *Cope* [18] does not invalidate this observation because here the stability of the asymmetric conformations is due solely to steric hindrance to rotation around the C—C bonds.

Figure 4 shows some optically active substituted cyclobutenes and 1,5-disubstituted cyclooctadienes and the corresponding isotactic and di-isotactic polymeric forms. The active forms are of the *threo*-type if the substituents are equal, and of both the *erythro*- and *threo*-type if they are different.

Analogously, it is possible to predict the existence of enantiomorphous forms for di-isotactic polymers of cyclic olefins: of the *threo*-type *(10)* for cycloolefins with identical substituents, and of the *erythro*- *(12)* and *threo*-type *(11)* for the more general case of different substituents (cf. Fig. 5) [16]. Figure 5 also shows the corresponding polycyclic compounds: *trans-anti-trans (10b)* for cycles with identical substituents, and *trans-anti-trans* and *cis-syn-cis* for cycles with different substituents. It is difficult to find examples of these models as the polycyclic compounds represented in Figure 5 are not well known.

[13] G. Natta, M. Farina, M. Peraldo, and M. Donati, Chim. e Ind. *42*, 1363 (1960); G. Natta, M. Farina, and M. Donati, Makromolekulare Chem. *43*, 251 (1961).

[14] G. Natta, M. Farina, M. Peraldo, and G. Bressan, Chim. e Ind. *43*, 161 (1961); Makromolekulare Chem. *43*, 68 (1961).

[15] G. Natta, L. Porri, A. Carbonaro, and G. Lugli, Chim. e Ind. *43*, 529 (1961); G. Natta, L. Porri, and S. Valenti, Makromolekulare Chem. *67*, 225 (1963).

[16] C. L. Arcus, J. chem. Soc. (London) *1955*, 2801.

[*] Cyclobutene is not only a model of the polybutadiene chain but 1,4-polybutadiene can actually be obtained from it [17]. In this reaction and all other polymerizations involving ring opening, the symmetry properties of the monomer can be transferred to the polymeric chain using the rules already developed, provided that the configurational repetition period is equal to only one monomeric unit, and that there are no inversions of configuration during the polymerization.

[17] G. Dall'Asta, G. Mazzanti, G. Natta, and L. Porri, Makromolekulare Chem. *56*, 224 (1962).

[18] A. C. Cope, C. F. Howell, and A. Knowles, J. Amer. chem. Soc. *84*, 3190 (1962).
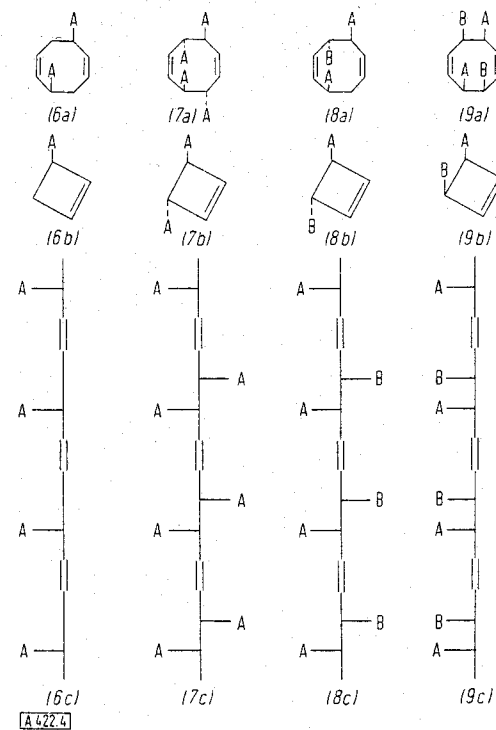
Fig. 4. Optically active polymers. Models and Fischer projection formulae of substituted 1,4-polybutadienes: isotactic 1-substituted polybutadiene *(6)*, *threo*-di-isotactic 1,4-disubstituted polybutadienes *(7)* and *(8)*, *erythro*-di-isotactic 1,4-disubstituted polybutadiene *(9)* (only one antipode is shown).
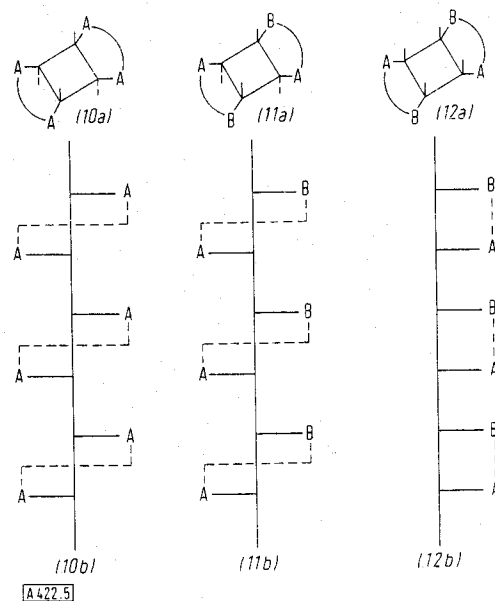

Fig. 5. Optically active polymers. Models and Fischer projection formulae of polymers of cyclic olefins: *threo*-di-isotactic polymers *(10)* and *(11)*, and *erythro*-di-isotactic polymers *(12)*.

From what has been stated so far it may seem impossible to obtain optically active polymers from α-olefins and from 1,2-disubstituted ethylenes which are not cyclic and which do not contain asymmetric groups. However, this is true only for simple repetitions, either isotactic or syndiotactic, but not if more complex structures are taken into account. Here the usefulness of the cyclic model is clearly seen. It is known that homocyclic compounds with 3, 4, or 5 atoms which are all equally substituted are optically inactive. Optically active isomers of this type exist only in the cyclohexane and

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higher series, e.g. inositols [see Fig. 6, (13a)]; the corresponding polymeric chains are also asymmetric, e.g. (13b). This type of structure can actually be obtained with six monomeric vinyl units, or with three units derived from monomers of the CHA=CHA type.
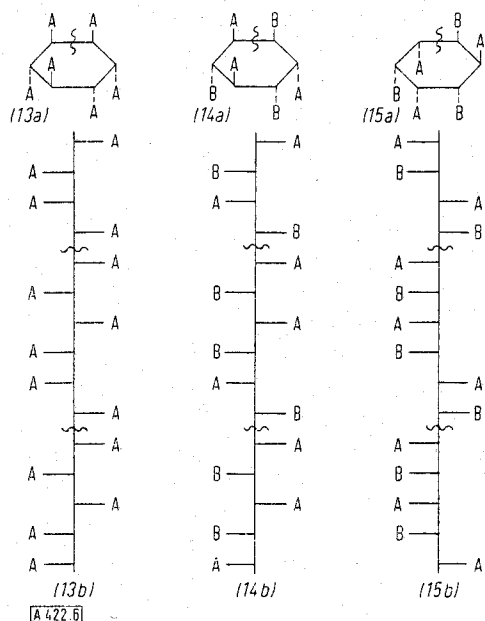

Fig. 6. Optically active polymers. Models and Fischer projection formulae of polymers derived from non-cyclic olefins.

It is also possible to foresee the existence of enantiomorphs for structures derived from monomers of the CHA=CHB type: the simplest have a configurational repetition period of three monomeric units and are represented in Figure 6. Structures (14) and (15) have an erythro-/threo-relationship. The threo-structure (14b) is analogous to the active structure obtained from monomers of the CHA=CHA type. It can be observed that the erythro-isomer (15b) has real asymmetry only when the threo-form is asymmetric and the substituents of the adjacent asymmetric atoms are different (Figs. 4, 5, and 6); otherwise, the erythro-form can be identified with a meso-form. In the optically active polymers of Fig. 6 all the tertiary carbon atoms are asymmetric, since the two chain portions bound to each atom are diastereoisomeric.

5. Polymeric Chains as Models of Cyclic Compounds

The formal analogy between polymeric substances and cyclic compounds has also contributed to the knowledge of certain classes of cyclic compounds.

Examination of the symmetry properties of the atoms in the chain of polybenzofuran shows that the definition of the asymmetric carbon atom commonly used is insufficient here [19], for each carbon atom of the polymeric chain is bonded to two substituents which are effectively

[19] G. Natta and M. Farina, Tetrahedron Letters 1963, 703.

identical if considered separately (Fig. 7). Such atoms seem to possess substitution of the C_{abdd} type. However, they differ substantially from the C_{abdd} atoms (e.g. a-CH_2-b) usually considered. In fact, in the structure under examination, the two substituents d are different
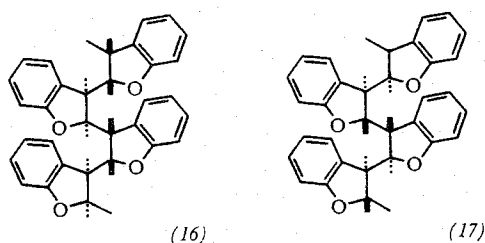

Fig. 7. Optically active polybenzofuran: erythro-di-isotactic (16) and threo-di-isotactic structures (17).

in their relationships to the atom considered: one belongs to the same cycle (endo-), whereas the other belongs to a different cycle (exo-) [14]. This therefore leads to a more general definition of the asymmetric carbon atom: the four substituents must be different either in themselves or at least in their relationships to the atom considered (e.g. exo- or endo-) [19].

The above discussion can be applied to the analogous cyclic compounds shown in Figure 6. As already mentioned, the chemistry of homocyclic or heterocyclic saturated compounds of this type is not well developed.

We have therefore synthesized one of these models, the trans-anti-trans-anti-trans isomer of perhydrotriphenylene [20]. It is a crystalline compound melting at 128 °C, and its configurational and conformational structure is

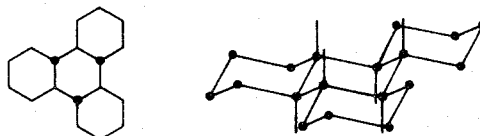Fig. 8. Structural and conformational formulae of (R)-trans-anti-trans-anti-trans-perhydrotriphenylene.

given in Figure 8. In spite of its high symmetry (1 threefold axis and 3 two-fold axes), it does not possess alternating axes of any order, hence it exists in two enantiomorphous forms, one of which is shown in Figure 8. The symmetry properties of the tertiary atoms are analogous to those of the tertiray carbons in polybenzofuran, of which perhydrotriphenylene represents the best model available at present. By applying the rule "endo precedes exo" recently proposed [19,21] to extend the Cahn-Ingold-Prelog nomenclature [22] to this compound, one finds that the six asymmetric atoms of the isomer shown in Figure 8 have all an absolute (R)-configuration.

[20] M. Farina, Tetrahedron Letters 1963, 2097.
[21] M. Farina and G. Bressan, Makromolekulare Chem. 61, 79 (1963).
[22] R. S. Cahn, C. K. Ingold, and V. Prelog, Experientia 12, 81 (1956).

6. Conclusions

The discussion of the analogies between cyclic and polymeric compounds reveals a substantial unity between classical organic and macromolecular stereochemistry. In our opinion, previous misunderstandings can easily be cleared up by adopting a cyclic model rather than by trying to extrapolate the configurational properties of macromolecular compounds from those of the low molecular-weight linear compounds.