

Chemical Graphs: Looking Back and Glimpsing Ahead

Alexandru T. Balaban

Polytechnic University, Organic Chemistry Department, 77207 Bucharest, Roumania, and Texas A&M University at Galveston, P.O. Box 1675, Galveston, Texas 77553-1675

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Graph-theoretical applications to chemistry are reviewed from a personal point of view in the context of the gradual acceptance of the value of such applications by the chemical and informational community. Initial problems involved enumerations of isomers that required the use of molecular (constitutional) graphs and techniques such as Polya's theorem, including valence isomers of annulenes, benzenoids, and diamond hydrocarbons (polymantanes). Problems connected with structural coding and retrieval of chemical information followed. Reaction graphs exemplify a different type of graphs. For QSAR/QSPR studies, global graph invariants (topological indices, TIs) have proved their usefulness; they are based on local vertex invariants (LOVIs) which until recently were exclusively integers, leading to high degeneracy of TIs. Newly introduced real-number LOVIs are briefly reviewed. This retrospective section ends with applications of graph theory (GT) to elemental carbon nets and to fullerenes. Then a few predictions are made for promising developments in the future: increasing use of GT for information processing, development of LOVIs and TIs incorporating stereochemical features, and increased use of TIs for molecular modeling and drug design, along with more sophisticated molecular graphics methods.

1. INTRODUCTION

The 1994 Herman Skolnik Award that the ACS Division of Chemical Information has bestowed upon me is an honor which makes me very happy: it recognizes achievements in chemical applications of graph theory by a scientist from an East European country where performing research was fraught with difficulties. Therefore I am grateful for this Award not only for me but also for the area in which I worked and for scientists from the part of the world I am from. I would like to thank the persons who nominated me and the ACS Division of Chemical Information for this prestigious Award.

Nine years ago, the *Journal of Chemical Information and Computer Sciences* featured a Silver Jubilee issue wherein several scientists published invited contributions. The feature article about the 25-year perspective of this journal was authored by H. Skolnik, after whom the Award of the Division is named. It is remarkable that ten of the authors of that 1983 issue are Herman Skolnik Awardees. These are (the year of the Award follows in brackets) as follows: H. Skolnik (1976),¹ E. Garfield (1977),² W. J. Wiswesser,³ R. Fugmann (1982),⁴ J. R. Rowlett, Jr. (1983),⁵ D. B. Baker (1986),⁶ D. R. Lide, Jr. (1988),⁷ M. F. Lynch (1989),⁸ J. E. Dubois (1992),⁹ and A. T. Balaban (1994).¹⁰

In 1993, at the request of Dr. S. V. Cyvin who was editing a special issue of *Mathematical Chemistry (MATCH)*, I wrote for that issue a very personal account about how I became interested in chemical graph theory.¹¹ To avoid repetition, the present paper will emphasize (of course, from a personal viewpoint) how graph theory has been used for chemistry and what the future may have in reserve for chemical graphs.

2. LOOKING BACK

2.1. Isomerism and Its Implications for Chemical Information. Most scientists agree that chemistry is the best

documented science when one wishes to learn if a certain chemical structure has been synthesized earlier and (if the answer is affirmative) where to find information about it. This is due to the fact that molecular formulas can be ordered and that isomers (sharing the same molecular formula but corresponding to different structures) can be represented by molecular graphs. In turn, these graphs can be searched according to algorithms developed by the Chemical Abstracts Service, the Beilstein Institute, and the Gmelin Institute. Other chemical searches and other sciences, basing the search on words, lack the uniqueness and the metric properties of chemical formulas compounded with graph-theoretical algorithms. The first, best known, and most important types of chemical graphs are the molecular or constitutional graphs mentioned above, whose nodes (vertices or points) correspond to atoms and whose edges (lines) correspond to covalent bonds. Multiple bonds and/or atoms of different nature are taken into account in special ways. For organic compounds which constitute the large majority of chemical substances, one usually ignores hydrogen atoms, and one obtains hydrogen-depleted (or hydrogen-suppressed) constitutional graphs.

In several of his stories, Sir Arthur Conan Doyle wrote the following principle that guided Sherlock Holmes in his investigations: "When you have eliminated the impossible, whatever remains, no matter how improbable, must contain the truth".

This "Sherlock Holmes Principle" can serve as a guide for chemists who wish to synthesize new structures belonging to a certain class of molecules: one enumerates all possible molecular graphs corresponding to the given class, then one deletes what is impossible on the basis of chemical data and/or intuition, and one is left with a set of structures which can provide insight into the vast inviting realm of the unknown.

A first application of such an idea happened before I knew I was applying graph theory (GT) to chemistry. This is still

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the case of most chemists and students of chemistry who, on enumerating isomers of any given class of molecules (e.g., alkanes), imitate Molière's "Bourgeois Gentilhomme" who was speaking in prose without knowing it. Actually, if all chemists could learn the few simple graph-theoretical equivalents of chemical terms, there would be a substantial mutual advantage for chemists and graph theorists. Since one of the origins of graph theory can be traced to Cayley's attempt to enumerate alkanes, and since there is a one-to-one correspondence between graphs and organic chemical formulas, GT has much to offer to chemists who know how to ask the right questions in the proper language that graph theorists can understand. In 1959, I attempted¹² a systematic approach to find all possible m -membered monocyclic aromatic systems $X_xY_yZ_z$ formed from first row elements X , Y , and Z obeying Hückel's $4k + 2$ π -electron rule. Pauli's principle allows only the above three sp^2 -hybridized atom types, having 2, 1, or 0 π -electrons, respectively, in their nonhybridized AO leading to the delocalized aromatic MOs. Chemical constraints due to atomic electronegativities and to multiple adjacencies of heteroatoms belonging to the same type were later taken into account.^{13,14} Thus one obtains two equations with three unknowns x , y , and z

$$x + y + z = m \quad (m = 3, 4, 5, \dots)$$

$$2x + y = 4k + 2 \quad (k = 0, 1, 2, \dots)$$

which yield several sets of solutions, and finding all circular arrangements of such "beads with three colors" is a typical graph-theoretical exercise known as the "necklace problem". Later, in a first joint work with Professor F. Harary¹⁵ (who authored¹⁶ a classical book on GT) this problem was solved using Pólya's powerful theorem and was extended to condensed bicyclic aromatics.¹⁷ This theoretical work had been generated by, and proved to be useful for, experimental work on heteroaromatics (boron-containing heterocyclics;¹⁸ during the work for my Ph. D. Thesis with C. D. Nenitzescu, I had found a new synthesis for pyrylium salts,¹⁹ and I am still interested in this field²⁰).

A second application, after I had read about GT, was connected with valence isomers of annulenes $(CH)_{2n}$.²¹⁻²⁴ Interestingly, the GT problem (enumeration of cubic graphs, i.e., of regular graphs all of whose vertices have degree 3) was unsolved at that time. The first multiply-connected valence isomer of an annulene had been synthesized in Bucharest and is called "Nenitzescu's hydrocarbon" $(CH)_{10}$. I found an algorithm for obtaining constitutional formulas of cubic graphs, and I believe I was the first to point out that bis(cyclopropenyl) was a legitimate valence isomer of benzene. Not only was GT useful for enumerating valence isomers and providing their structures but also it allowed a simple definition for them as graphs with the same partition of vertex degrees and, of course, the same nature of atoms symbolized by the vertices of the hydrogen-depleted graph. The structures of valence isomers of annulenes $(CH)_{2n}$ proved to be useful for chemists who were engaged in the synthesis of such compounds.

Trivial names such as cubane, cuneane, snoutene, pentaprismane, and bullvalene are evocative; on the other hand, the IUPAC nomenclature for bridged polycyclics based on von Baeyer's system is quite cumbersome. However, the numbers of chemically possible constitutional valence isomers of $[2n]$ annulenes (represented by planar graphs) increase so fast²⁵ (2 for $n = 2$; 5 for $n = 3$; 17 for $n = 4$; 71

for $n = 5$; 357 for $n = 6$; 2140 for $n = 7$) that the use of systematic names rather than trivial names should be the solution.

This work on cubic graphs occasioned my first publication, jointly with mathematicians, in a nonchemical journal.²⁶ In addition to valence isomers of annulenes, the same approach was applied to benzo- and polybenzoannulenes,^{27,28} heteroannulenes,²⁹ homoannulenes,³⁰ and monodehydro derivatives;³¹ the interconversions among such isomers which can proceed thermally, photochemically, or under catalysis by transition metal ions were surveyed in several papers in cooperation with M. Banciu,³²⁻³⁴ and eventually a three-volume book was published³⁵ on annulenes and benzo, hetero, homo derivatives and their valence isomers.

Not only molecules can be aromatic but also transition states can be aromatic; this was the basic idea that led to a systematic enumeration of all such six-membered systems³⁶ and to the prediction of possible degenerate Cope rearrangements involving valence isomers of annulenes;³⁷ some of the latter predictions were subsequently confirmed experimentally. Earlier ideas in this area had been advocated by Evans³⁸ and other authors³⁹ and later by Dewar,⁴⁰ Zimmermann,⁴¹ and Hendrickson.⁴² Of course, Woodward and Hoffmann's monumental work based on Fukui's frontier orbitals clarified not only this particular thermally-allowed case involving molecular ground states but also photochemical reactions as well as all the stereochemical implications.⁴³

Another encounter with an interesting GT problem was in the enumeration of all polycyclic benzenoid hydrocarbons corresponding to the unsolved GT problem of "hexagonal-cell animals". In a further cooperation with F. Harary,⁴⁴ the dualist graph (whose vertices are the centers of benzenoid rings and whose edges correspond to condensed rings) allowed a simple enumeration and provided definitions for cata/peri/corona-fused systems. A coding and nomenclature system can be devised.⁴⁵ Dualists are special graphs, because angles do matter. We discovered later that dualist graphs had been previously employed for benzenoids by F. T. Smith.⁴⁶ Two kinds of benzenoids exist: those which are portions of the graphite or honeycomb lattice ("in-plane benzenoids") and those which (like helicenes) have several atoms projecting onto the same node of the graphite network ("out-of-plane benzenoids"); this fact led later to disagreements in enumerations of benzenoids. Thanks to the cooperation of S. J. Cyvin, a consensus among those who subsequently contributed to this field was achieved in a multiauthored consolidated report.⁴⁷

In cooperation with Roumanian mathematicians (I. Tomescu and C. Artemi), algebraic formulas were published for enumerating certain classes of benzenoid catafusenes;⁴⁸⁻⁵² the longest linearly condensed portion of catafusenes determines their electronic properties such as absorption spectra⁵³⁻⁵⁵ and their chemical reactivity in the Diels-Alder reaction.⁵⁶ Accordingly, nonbranched catafusenes were enumerated by means of a computer program according both to their total number of benzenoid rings and to those in the longest linearly condensed portion.⁵⁷

So far, only molecular constitution has been tackled using GT. Stereoisomerism is still a hard nut to crack. However, in certain cases advances can be made. Annulenes larger than benzene can adopt several conformations, whose geometry can be encoded using three symbols for the three orientations of lines on the graphite lattice, or six if directions are also taken into account;⁵⁸ this idea was later developed

by Trinajstić, Knop, and their co-workers into a "boundary code" for benzenoids.⁵⁹

Since the best known chemical carcinogens are polycyclic aromatic hydrocarbons (PAHs) possessing bay-regions (a necessary but insufficient condition for carcinogenicity), it was natural to try the first enumeration of such PAHs using GT in a cooperation with U.S. scientists.⁶⁰ Since then, I maintained an interest in this area, publishing jointly with chemists and biochemists^{61,62} and being a coauthor of a book on mathematical modeling of cancer genesis and prevention.⁶³

From the two-dimensional graphite network, it was natural to go to the three-dimensional diamond lattice. Staggered rotamers of alkanes are portions of the latter lattice, and their numbers for linear or branched alkanes can be determined.⁶⁴ By considering polymantanes (diamond hydrocarbons such as adamantane, diamantane, etc.) as formed from condensed adamantane units, the centers of these units form a tridimensional dualist graph which is an alkane rotamer.⁶⁵ This idea led to a joint paper with P. v. R. Schleyer,⁶⁶ who was the first to prepare polymantanes using AlCl_3 -catalyzed isomerizations of saturated polycyclic hydrocarbons.

Further joint work with Harary and Robinson on GT applications to stereochemistry led to the enumeration of chiral and achiral alkanes.⁶⁷ A publication in *J. Chem. Educ.* with U.S. mathematicians, Quintas and Kennedy, outlined in simple language how Pólya's theorem works and enumerated for the first time constitutional isomers of alkanes both in terms of their total number of carbon atoms and that of carbons in the longest linear portion.⁶⁸ This is connected with IUPAC nomenclature based on the longest linear portion of alkane chains.

2.2. Coding and Retrieval of Chemical Structures. Specifically for chemical information, GT can provide many useful tools and insights. Indeed, Morgan's algorithm on whose basis *Chemical Abstracts* stores constitutional information for isomers uses extended connectivities.⁶⁹

In the preceding sections, several incidental naming/coding systems have been mentioned for valence isomers of annulenes and their congeners, for cata-condensed benzenoids, and for polymantanes (diamond hydrocarbons). Additionally, a specific effort was directed by our group toward applying GT for purposes of chemical information. In a fruitful cooperation with Drs. Bonchev and Mekenyan from Burgas (Bulgaria), we used hierarchically ordered extended connectivities (HOC) in trying to improve the systems proposed by Morgan⁶⁹ and later by Wipke and Dyott.⁷⁰ The results were published in a series of papers describing uniquely the constitution and stereochemistry of substances.^{71–74}

For alkanes, a simple code was devised more recently, leading to a canonical numbering of carbon atoms.⁷⁵ This code was further developed by my son and his co-workers,⁷⁶ using a computer program called GENLOIS which can generate all acyclic skeletons, testing for isomorphism and vertex equivalence by means of topological invariants. Unlike coding systems in which one starts from the center of the acyclic graph as proposed by Read,^{77,78} or as in the IUPAC system from one of the endpoints of the alkane molecular graph, in our code the highest priority is awarded to a vertex with the highest degree. A partly similar approach was recently followed by M. Randić, S. Nikolić, and N. Trinajstić, and their results are summarized in this issue.⁷⁹

It should be possible to use our code for 4-trees modeling alkanes (or the differcode which has only one-digit numbers) and also for polycyclic graphs, if one could find a unique assignment of a spanning tree in a polycyclic graph.

Another father-and-son cooperation in the area of chemical information involved an algorithm for enumerating all cycles in polycyclic graphs;⁸⁰ the underlining idea was homeomorphic reduction of hydrogen-depleted graphs by temporary removal of vertices with degree 2. This algorithm was subsequently developed by two other groups of authors^{81,82} (review⁸³).

Findig graph centers for polycyclic graphs is an open problem, and, if solved, it could provide a useful basis for chemical information systems. Partial success was achieved in special cases in joint work with Drs. M. Randić and D. Bonchev.^{84–88}

It had been advocated that the characteristic polynomial obtained from the adjacency matrix or its roots (its GT spectrum) might serve as a tool for storing constitutional information. Jointly with Harary, we showed that this is impossible because nonisomorphic graphs may have the same characteristic polynomial.⁸⁹ The area of such isospectral or cospectral graphs has been further developed by other authors and was well summarized by N. Trinajstić.⁹⁰

2.3. Reaction Graphs. A quite different kind of graphs from those discussed in the preceding sections are reaction graphs, whose vertices symbolize a chemical species (a molecule or reaction intermediate) and edges symbolize elementary reaction steps interconverting two such chemical species.

The first such reaction graph was published in 1966 for 1,2-rearrangements of pentasubstituted ethyl cations with five different substituents.⁹¹ If the two carbon atoms of the ethyl group are distinguished by isotopically labeling one of them, then the reaction graph is cubic with 20 vertices (the Desargues–Levi graph).

A shorthand notation for these cations using two unordered digits and one period is shown in Figure 1. The shortest pathway between complete exchange of the five ligands among the two carbon atoms (e.g., between species denoted as 13. and .13) involves five reaction steps, i.e., these two "antipodal vertices" are at the largest topological distances, equal to five (the graph diameter).

If no isotopic label exists, antipodal vertices are indistinguishable, the period vanishes from the shorthand notation, and a cubic reaction graph with 10 vertices results: it is the well-known Petersen graph, also called the five-cage because it is the smallest graph with girth $g = 5$; the girth of a graph is the length of its smallest circuit.

Interestingly, the same two graphs were discussed only two years later, in 1968, by Lauterbur and Ramirez⁹² and by Dunitz and Prelog⁹³ in the context of pseudorotations of pentacoordinated trigonal-bipyramidal phosphorus compounds with five different ligands. When enantiomerism is taken into account, one obtains the Desargues–Levi graph; when it is ignored, one obtains the Petersen graph. It was Mislow^{94,95} who pointed out the parallelism between the 1966 and 1968 papers. This fact shows the wide coverage of Mislow's documentation since many of my early papers on chemical graphs were published in English but in a Roumanian journal with limited circulation, whose French title (*Revue Roumaine de Chimie*) is due to traditional links between France and Roumania, which share Romance languages.

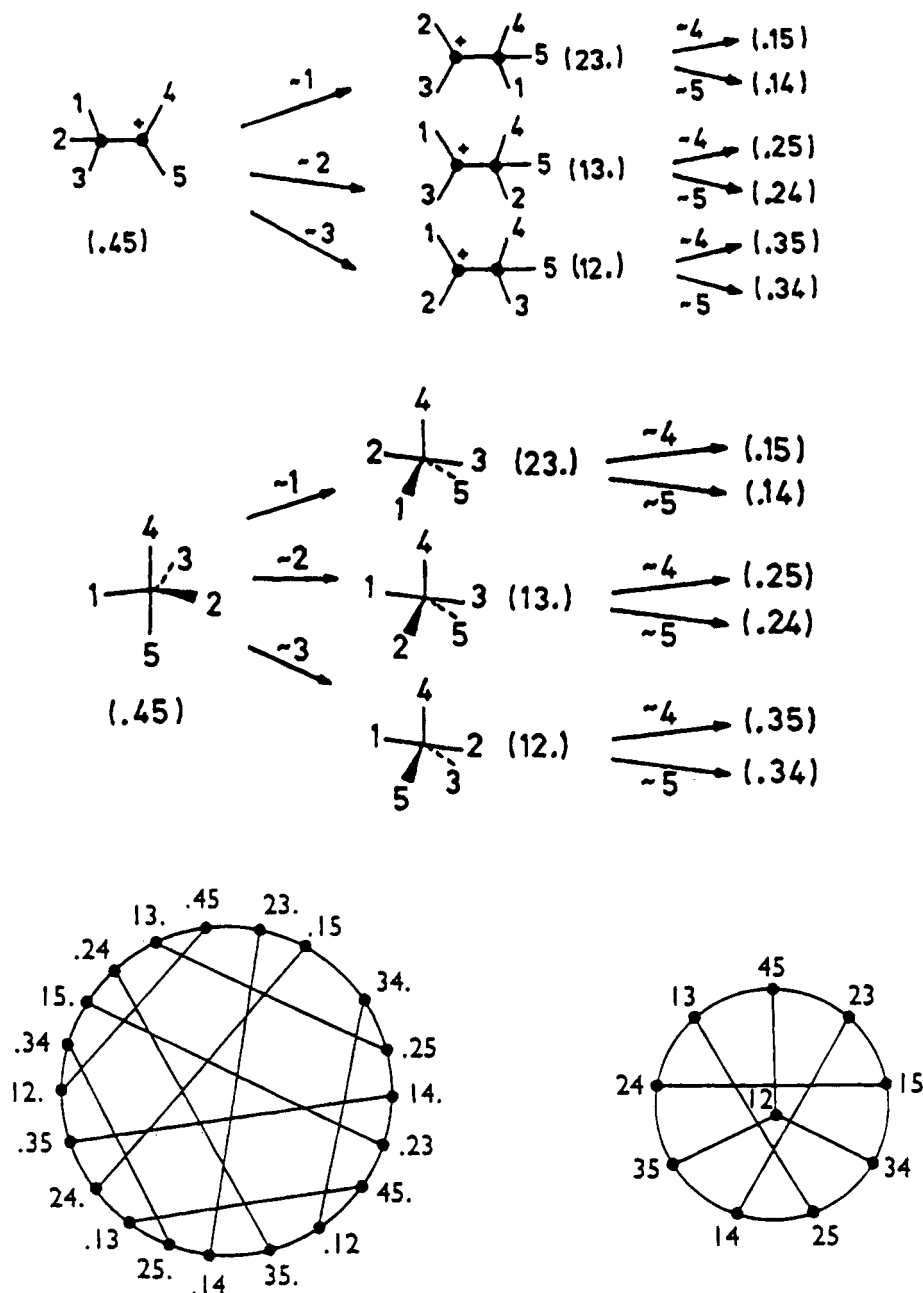


Figure 1. First row, portion of the reaction graph for the rearrangements of ethyl carbocations with five different groups; second row, portion of the reaction graph for pseudorotation of trigonal-bipyramidal compounds with five different ligands; third row, left and right, respectively: the Desargues-Levi graph and the Petersen graph with vertex notation corresponding to chemical interconversions indicated above.

Reaction graphs soon became an attractive field for several groups of theoretical chemists; the most active one was in the Free University of Brussels (ULB). Therefore, when I decided to edit the first book on *Chemical Applications of Graph Theory* (Academic Press, 1976),⁹⁶ I invited Dr. Gielen from ULB to write the chapter on chemical graphs⁹⁷ and Dr. Brocas from the same University to write the chapter on applications of GT in physical chemistry.⁹⁸ Mathematicians (Harary, Robinson, Palmer^{99,100} and Read¹⁰¹) as well as chemists contributed to that book: these latter authors included Drs. Ugi, Ramirez, Gillespie, Marquarding, and Dugundji on the logical structure of chemistry,¹⁰² Dr. Dubois on the DARC system,¹⁰³ Dr. Rouvray on GT matrices in quantum chemistry,¹⁰⁴ and Drs. Gordon and Temple on graphs as models for polymers.¹⁰⁵ I contributed with two chapters in this book.^{99,106}

Later, together with Dr. D. H. Rouvray whose reviews^{107,108} on applications of GT to chemistry had contributed substan-

tially to making this area better known, we wrote a chapter reviewing a few of these applications in a volume edited by mathematicians (R. J. Wilson and J. W. Beineke), along with chapters written by other authors for applications of GT to various other fields.¹⁰⁹

Personally, I followed up with exploring reaction graphs for other types of organic or inorganic reactions.¹¹⁰⁻¹¹³ A recent cooperation with Professor J. Brocas involved reaction graphs for rearrangement of xenon hexafluoride.¹¹⁴ Reaction graphs can be huge, such as the "monster-graph" for the automerization of bullvalene, an object of interest for several graph-theoretical chemists.^{115,116} In my recent review of reaction graphs,¹¹⁷ I included most of the published data, but regrettably I omitted the interesting contributions of Professor Gimarc.¹¹⁸⁻¹²⁰

A still different subclass of reaction graphs has directions on its edges and is of considerable assistance in simply solving some complicated kinetic equations. Such kinetic

directed graphs have been initiated earlier¹²¹ and then developed and reviewed by Bonchev and Temkin.^{122–125}

In parallel with chemical reaction graphs, I became fascinated with the unsolved GT problem of cages, and I published in mathematical journals the first of the three possible 10-cages,¹²⁶ and what is conjectured to be the 11-cage.¹²⁷ The problem of cages with $g = 9$ and $g > 12$ is still unsolved, but mathematicians now use powerful computer programs for this purpose.^{128–130}

2.4. Graph Invariants and Topological Indices for QSAR–QSPR. Quantitative structure–activity or structure–property relationships (QSAR and QSPR, respectively) are based on correlating physical, chemical, or biological properties (which are expressed as numerical data) with chemical structures (which are discrete, non-numerical data, modeled in most cases by hydrogen-depleted molecular graphs). To be able to make such correlations, various features of chemical structures have to be expressed also in numerical form: electronic or steric properties are obtained empirically (such as Hammett constants or Taft parameters) or via quantum-chemical calculations (orbital energies, polarizabilities, electron densities) or by both methods (dipole moments, molar volumes, pK_a values); hydrophobic or hydrophilic parameters;¹³¹ lately, molecular shape parameters or molecular modeling using sophisticated programs such as COMFA are also increasingly used for drug design.¹³²

Along with all these methods, GT has also provided tools for QSAR/QSPR. In 1947, H. Wiener^{133,134} published a series of several papers on global graph invariants, which were later called by Hosoya topological indices (TIs).¹³⁵ They are based on local invariants, in most cases local vertex invariants (LOVIs). In turn, these LOVIs usually start with one of the two symmetrical matrices associated with graphs: the adjacency matrix **A** whose entries a_{ij} are 1 for adjacent vertices i, j and 0 otherwise, or the distance matrix **D** whose entries d_{ij} are topological distances, i.e., the number of edges on the shortest path between the vertices i and j . The sum over row or column i of **A** yields LOVIs called vertex degree v_i ; the analogous sum for **D** yields distasums (initially called status) s_i .

Wiener's index for any connected nondirected simple graph *G* is the half-sum of all d_i values. Like other first generation TIs, it is an integer based on integer LOVIs, and thus has a fairly high degeneracy, i.e., more than one graph corresponds to the same TI value. Ideally, TIs should show high correlational ability and at the same time should have low degeneracy. A TI which would be completely nondegenerate would be a molecular code, or molecular ID number, and, in principle, one should be able to reconstruct the structure from the code. So far, for the general problem of any graph, this is still an open problem.

Among the second-generation TIs which are real numbers based on integer LOVIs, the index which proved to be most successful was Randić's molecular connectivity ${}^1\chi$ ¹³⁶

$${}^1\chi = \sum_{\text{edge } ij} (v_i v_j)^{-1/2}$$

followed shortly afterwards by related indices χ^v developed by Kier and Hall for paths of higher lengths and adapted to code heteroatoms of various valences v .^{137–139}

After having proposed a few first-generation TIs based on graph centers,¹⁴⁰ I developed several second-generation

TIs, namely the mean square distance index¹⁴¹

$$D = (\sum d_{ij}^2)^{-1/2}$$

and the average distance connectivity index^{141–143}

$$J = \frac{q}{\mu + 1} \sum_{\text{edge } ij} (s_i s_j)^{-1/2}$$

This last index (where μ denotes the cyclomatic number) has a lower degeneracy than ${}^1\chi$ and does not increase automatically with the number of graph vertices like most other TIs; interestingly, its asymptotic value for an infinitely long linear alkane¹⁴⁴ is $\pi = 3.14159$. Hence *J* can be considered to reflect only the "topological shape", i.e., the degree of branching and cyclicity of the molecule. It should be employed in multiparametric correlations, along with the number of vertices, for properties which are influenced also by the magnitude of the molecule, otherwise its performance is poor.¹⁴⁵ The index *J* has the advantage that it can easily be adapted for the presence of heteroatoms and/or multiple bonds, like all distance-based TIs:¹⁴⁶ the distance between atoms *i* and *j* connected by a bond with bond order *b* can be expressed as b^{-1} or (in a better correspondence with real interatomic distances)¹⁴⁷ as b^{-4} ; the nature of heteroatoms can be introduced by means of coefficients multiplying the LOVI denoted by s_i , and reflecting the atomic number,¹⁴⁸ the electronegativity, or the covalent radius (all of these relatively to carbon);¹⁴⁹ the last two properties are chemically more plausible, as they vary according to chemical periodicity.

Lately a third-generation of TIs was initiated by trying to find new real-number LOVIs, on which real-number TIs would be based. This idea was reviewed recently in this journal;¹⁵⁰ therefore, only a brief survey will be included here. In addition to the integer vertex degree v_i or distasums s_i on which practically all TIs have been based so far, we introduced the following six new real-number LOVIs.

(i) Solutions of linear equation systems obtained from the matrices **A** or **D** combined with two column vectors which provide chemical or topological information.¹⁵¹

(ii) Regressive vertex degrees¹⁵² or regressive distance sums,¹⁵³ adding to v_i or s_i progressively decreasing contributions of the more remote vertices.

(iii) Eigenvectors corresponding to selected eigenvalues of matrices **A** or **D**.¹⁵⁴

(iv) LOVIs based on information theory: the first information-theoretical applications were due to Bonchev and Trinajstić¹⁵⁵ who devised second-generation global TIs by using Shannon's formula. The field was reviewed by Bonchev.¹⁵⁶ Subsequent application of the same formula for devising LOVIs was performed independently by Basak et al.^{157–159} and by our group;^{160,161} recently, we joined our efforts in applying these LOVIs for obtaining TIs to be used in QSAR/QSPR studies.¹⁶²

(v) LOVIs with very low degeneracy obtained from sums and products of vertex degrees using sophisticated exponential operations;¹⁶³ this approach can be used for the whole graph or only for fragments (substituents);¹⁶⁴ earlier second- or first-generation LOVIs for fragments had been based on the *J* index¹⁴⁶ or, jointly with Drs. D. Bonchev and O. Mekenyan, on a global approach toward the intersection between the graph and its subgraphs.¹⁶⁵

(vi) From LOVIs based on reciprocal distances¹⁶⁶ (indepen-
dently also introduced by Trinajstić and co-workers¹⁶⁷),
or on resistance distances introduced by Klein and Randić,¹⁶⁸
one can form by simple summation new TIs called Harary
numbers^{167,169} and Kirchhoff numbers, respectively.¹⁶⁹ The
resistance distance-based LOVIs and TIs for polycyclic
graphs have low degeneracy, but for acyclic graphs the LOVI
is s_i , and the Kirchhoff number is identical to the Wiener
number.

Since we were interested more in the methodology for
finding new LOVIs and TIs with low degeneracy than for
trying to apply them, we validated these new LOVIs by
intramolecular comparison and the new TIs by *intermolecu-*
lar comparison using as test structures the set of alkanes
with up to ten carbon atoms. We also checked the TIs for
intercorrelations¹⁷⁰ and tried to see what is the physical
meaning of TIs.¹⁷¹ A few reviews on TIs were also
published.¹⁷²⁻¹⁷⁴

Among the QSAR/QSPR studies that we performed, the
most numerous involved a physical property that was
universally and precisely measured for small molecules,
namely the normal boiling point, BP. We showed that BPs
of alkanes correlate well with many of the newly introduced
TIs in multiparametric or nonlinear equations.^{151,154,160,161} For
heteroatom-containing compounds, the corresponding modi-
fied index J performed well for sets of oxygen- or sulfur-
containing compounds devoid of hydrogen bonds.¹⁷⁵ BPs
of halogenated alkanes with one through four carbon atoms
show a nonlinear variation versus the number of halogens
(especially with fluorine);¹⁷⁶ therefore, we showed that
artificial neural networks allowed for such compounds better
modeling and satisfactory predictions of BPs¹⁷⁷ in agreement
with data published by Woolf.¹⁷⁸ Octane numbers for
alkanes, alkenes, and cycloalkanes also correlate with
TIs.^{179,180}

Another QSPR study correlated the chemical structure of
alkanes with their critical data and their parameters for the
Antoine equation relating vapor pressures to absolute tem-
peratures.¹⁸¹

To conclude this section, mention should be made of a
comparative study that tested several hundred molecular
descriptors: A. R. Katritzky and his co-workers found out
that TIs perform excellently as molecular descriptors for
QSPR involving physicochemical properties; for QSAR
involving biological activities, TIs have to be supplemented
with parameters, such as hydrophobicity or electronic density
parameters, that characterize the biological type of activ-
ity.^{182,183} The reader should not be left with the impression
that topological indices are good only for correlations
between chemical structure and thermodynamic properties;
their main usefulness will be shown for correlations with
biological activities in drug design.

2.5. Elemental Carbon. A separate section is reserved
in this topic because, unlike the finite molecular graphs
discussed so far, the traditional forms of elemental carbon
(diamond and graphite) are infinite molecular graphs, and
because the recent discovery of fullerenes raises interesting
problems for chemical information.

One of the first papers to discuss alternative planar or
tridimensional infinite networks for carbon, in addition to
the graphite or diamond networks, was published in 1968.¹⁸⁴
Energy estimates for a few of these possible networks formed
from either sp^2 - or sp^3 -hybridized carbon atoms were based

on approximate calculations. More reliable calculations for
planar systems formed from sp^2 -hybridized carbon have been
published recently.¹⁸⁵

Only later have carbon networks been considered in which
 sp^2 - and sp^3 -hybridized carbon atoms coexisted. Some of
these hypothetical networks with regular unit cells have
remarkable properties, as shown in joint papers with Roald
Hoffmann and his co-workers.^{186,187} In collaboration with
D. J. Klein, we published studies on what can be considered
as block-copolymers of diamond and graphite,¹⁸⁸ on fullero-
polycoronands¹⁸⁹ and on graphitic cones.¹⁹⁰ Interestingly, a
short time afterwards, one type of such graphitic cones was
discovered experimentally.¹⁹¹

Several other groups of authors published ideas on
alternative forms of elemental carbon, and the truncated
icosahedron was considered in a few of these.^{192,193} How-
ever, these ideas were not considered seriously till 1985 when
buckminsterfullerene C_{60} and some of its homologs (espe-
cially C_{70}) were discovered by Smalley, Kroto, and Curl.¹⁹⁴
After 1990 when Krätschmer, Huffman, and Fostiropoulos
reported on how to prepare larger amounts of these
fullerenes,¹⁹⁵ the structure of buckminsterfullerene was
unambiguously confirmed by ^{13}C -NMR and by other meth-
ods.¹⁹⁶

The research group at the Texas A&M University in
Galveston (with which I have a long-term cooperation)
published outstanding theoretical papers on fullerenes;¹⁹⁷⁻¹⁹⁹
we have published jointly in this area, including problems
on fullerene nomenclature,^{200,201} and the most recent paper
appears separately in this issue.

3. A GLIMPSE AHEAD

A guess on the probable directions in which graph theory
(GT) is likely to assist chemical research is as risky as
predicting the future by gazing into a crystal ball. Neverthe-
less, one may safely assert that GT will continue to prove
useful for (i) storage and retrieval of chemical information,
rational coding, and nomenclature; (ii) extending the ability
of TIs to model chemical structure by including information
on stereochemical features, molecular shape, and molecular
similarity; and (iii) QSAR/QSPR studies, especially in drug
design, since TIs can be easily computed for any known or
unknown structure, and since they can be selected to match
various structural features.

At the same time, the initial chemical application of GT,
namely enumeration of isomers, is nowadays superseded by
powerful computer programs such as heuristic DENDRAL
which use expert systems to delete from outputs chemically
impossible structures such as systems having more than two
adjacent oxygen atoms;²⁰² GT has proved its usefulness in
programs for computer-aided design of organic syntheses
initiated by Corey and Wipke,²⁰³⁻²⁰⁵ by dissecting stepwise
target molecules into all possible subgraphs for retrosynthetic
purposes. Synthon graphs²⁰⁶ are related graphs whose aim
is to improve yields by making use of convergent, rather
than sequential, approaches.

In the early 1980s I was invited to present plenary lectures
at IUPAC symposia on aromatics, and I chose to speak on
the challenging problems involving benzenoid poly-
cyclics.²⁰⁷⁻²⁰⁹ By means of dualist graphs it is easy to list
interesting and yet unknown structures which combine
stereochemical and topological challenges. A few of these

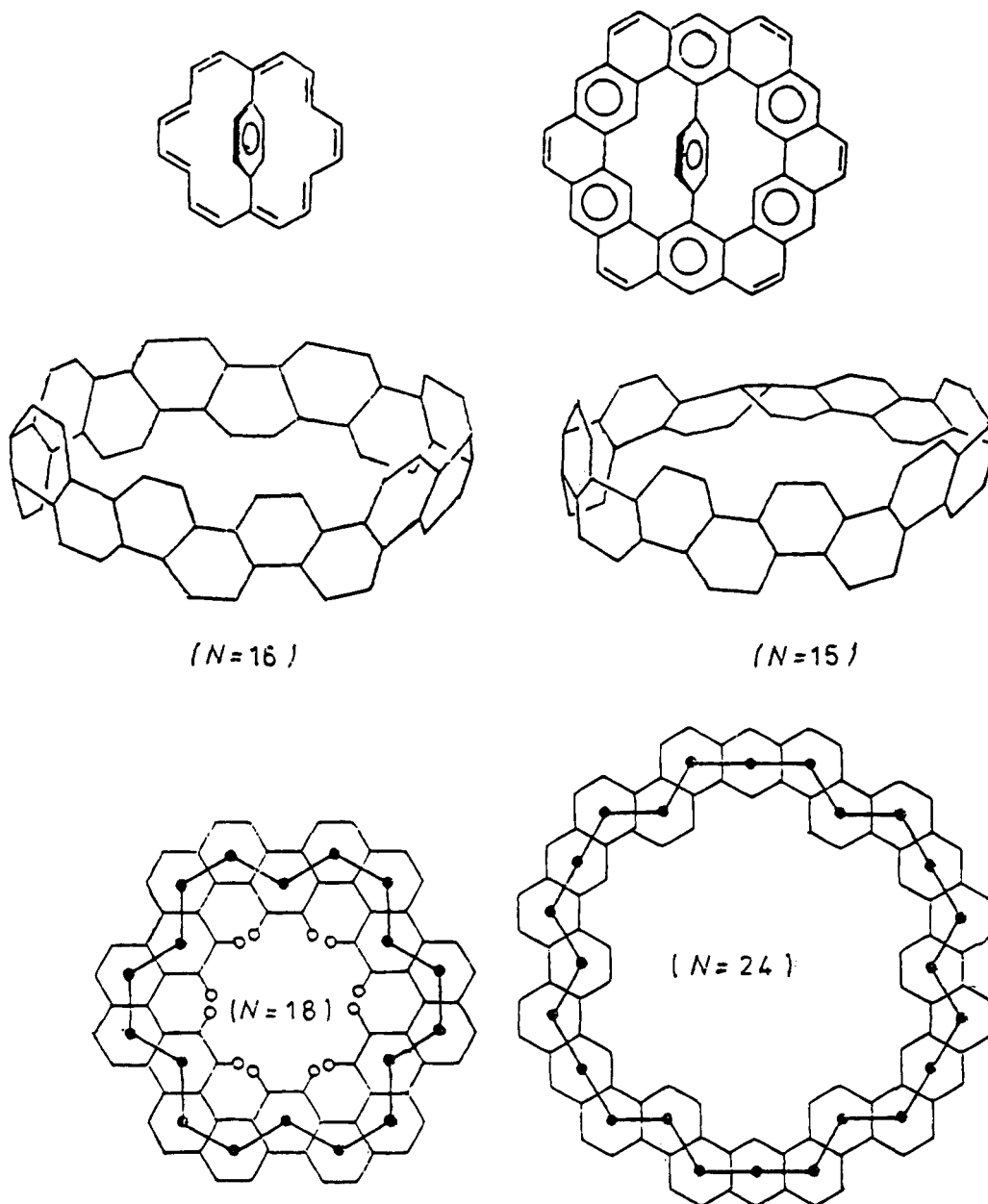


Figure 2. Challenging unknown aromatic hydrocarbons. First row, a “choker” annulene and its Kekulene counterpart; second row, a zigzag circum-catafusene and its Möbius counterpart; third row, zigzag coronoids with N benzenoid rings (dualist graph vertices are shown by black points and internal hydrogens by white points). Note that the system with $N = 24$ has anthracenic portions but less strain than the system with $N = 18$ which is devoid of such portions.

structures²⁰⁹ are shown in Figure 2 with all their carbon atoms, and other ones are presented in Figure 3 only by means of dualist graphs.

I was not allowed to attend the European Conference on Computer Algebra held in Austria in 1985 (EUROCAL-85, concentrating on symbolic and algebraic computation), but by lecture appeared in the conference volume.^{210,211} It was entitled “Numerical and Non-Numerical Methods in Chemistry: Present and Future”. After discussing promising areas such as synthesis design, the next paragraph continued as follows: “A closely related area is heuristic, discovery of unknown reactions: taking into account the large variety of chemical structures and the still larger variety (because of its combinatorial nature) of chemical reactions, one can conceive programs for discovering new reactions. By proceeding along similar lines as in the preceding paragraph, but with the difference that now the interest is to compare the data banks of known or named reactions with the outcome of the synthon assembly according to allowed

reactions, one can uncover new, yet unknown reactions. The history of reaction discovery reveals that many reactions were discovered serendipitously, while other ones were looked for deliberately. In the latter case, however, two-reagent or three-reagent combinations were usually investigated. If one takes into consideration other decisive factors such as catalyst, solvent and temperature, it is easy to see how large the ‘terra incognita’ of three- and four-reagent reactions is, and how a systematic search may be made by suitable computer programs.”

Confirming the above prediction, recent papers by Ugi²¹² and by Zefirov²¹³ with their co-workers did indeed discover thus new reactions.

Drs. Gimbel, Kennedy, and Quintas organized a symposium entitled “Quo Vadis, Graph Theory?” in 1992, and along with prominent graph theorists they invited users of GT; three of these, namely R. C. Read, M. Randić, and I, had applied GT to chemistry. In my talk,²¹⁴ I highlighted a few unsolved problems: generalized centers in cyclic graphs;

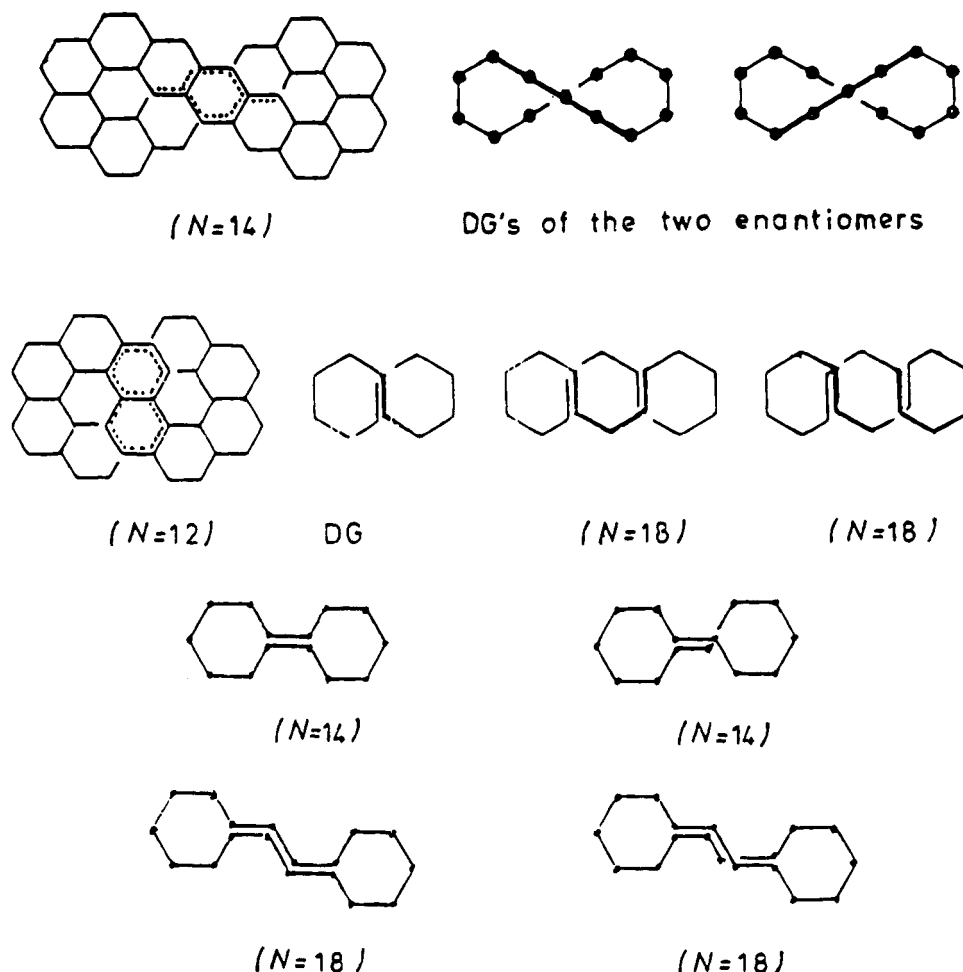


Figure 3. Challenging unknown topologically stereoisomeric benzenoids. First row, a benzenoid shaped like digit 8 with $N = 14$ rings, and the dualist graphs (DGs) of the two enantiomers; second row, a similar structure with $N = 12$ (devoid of long acenic portions which lower the stability) with its DG and two DGs of diastereomeric benzenoids which $N = 18$ (the last one is chiral); third and fourth rows, DGs of diastereomeric benzenoids with $N = 14$ and 18, respectively (the second ones in each row are chiral).

cages; spectral graph theory; and k -factorable graphs with $k > 1$. The last topic, for the particular case of structures formed from isopentenoid subunits, has obvious implications in the chemistry of natural products such as steroids or terpenes. In joint papers with S. Marcus and M. Barasch, we presented computer programs for finding if a given graph with $5k$ vertices is decomposable into k isopentenoid subgraphs and in the affirmative case for producing all the ways in which one can perform this decomposition.^{215,216} Picture grammars and push-down automata were also used for this purpose.²¹⁷

In a lecture presented at an international conference on chemical information,²¹⁸ I have outlined some recent advances and future trends on chemical information using topological and graph-theoretical models.

Already, chemical graphs under the form of structural formulas now appear in the Tables of Contents of many chemical journals for quick scanning of the papers. On a deeper level, literature search by means of Boolean operators and graphs and/or subgraphs (structure or substructure literature search) makes it possible to access in a very short time an immense data base (tasks that were unthinkable three decades ago). Chemical graphs have also proven their usefulness in computer-aided synthesis design,^{102,203–205,219} and I trust that such applications of chemical graphs, or different ones, will continue to be developed in the near future.

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REFERENCES AND NOTES

- Skolnik, H. The Journal for chemical information and computer scientists: a 25-year perspective. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 137–139.
- Garfield, E. History of citation indexes for chemistry: a brief review. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 170–173.
- Wiswesser, W. J. Historic Development of chemical notations. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 258–263.
- Fugmann, R. Peculiarities of chemical information from a theoretical viewpoint. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 174–179.
- Rowlett, R. J., Jr. Abstracts and other information filters. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 159–163.
- Baker, D. B. Chemical Abstracts Service's secondary chemical information services. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 186–191.
- Rumble, J. R., Jr.; Lide, D. R., Jr. Chemical and spectral databases: a look into the future. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 231–234.
- Lynch, M. F.; Barnard, J. M.; Welford, S. M. Generic structure storage and retrieval. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 264–270.
- Dubois, J. E.; Sobel, Y. DARC system for documentation and artificial intelligence in chemistry. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 326–333.
- Balaban, A. T. Applications of graph theory in chemistry. *J. Chem. Inf. Comput. Sci.* **1985**, 25, 334–343.
- Balaban, A. T. Confessions and reflections of a graph-theoretical chemist. *Math. Chem. (MATCH)* **1993**, 29, 3–17.
- Balaban, A. T. An attempt for the systematization of monocyclic aromatic compounds (in Romanian). *Acad. Repub. Pop. Rom. Stud. Cercet. Chim.* **1959**, 7, 257–295.
- Balaban, A. T.; Simon, Z. Aromaticity constants (Aromaticity. II) *Tetrahedron* **1962**, 18, 315–321.
- Balaban, A. T.; Simon, Z. Aromaticity, V. Stability of monocyclic aromatic compounds. *Rev. Roum. Chim.* **1965**, 10, 1059–1092.
- Balaban, A. T.; Harary, F. Chemical graphs. IV (Aromaticity. VI) Dihedral groups and monocyclic aromatic compounds. *Rev. Roum. Chim.* **1967**, 12, 1511–1515.
- Harary, F. *Graph Theory*; Addison-Wesley: Reading, MS, 1971.
- Balaban, A. T.; Palmer, E. M.; Harary, F. Chemical graphs. XXIX. Numbers of isomers with naphthalene and adamantane skeletons. *Rev. Roum. Chim.* **1977**, 22, 517–523.
- Bally, I.; Ciomei, E.; Vasilescu, A.; Balaban, A. T. Heterocyclic organoboron compounds. XVI. Chelated compounds with α,β -unsaturated β -aminoketones. *Tetrahedron* **1973**, 29, 3185–3187 and previous papers in the series.
- Balaban, A. T.; Nenitzescu, C. D. Reactions catalyzed by aluminium chloride. XXVII. A synthesis of pyrylium salts from acid chlorides and olefins (Pyrylium salts. I). *Liebigs Ann. Chem.* **1959**, 625, 74–88.
- Balaban, A. T.; Dinculescu, A.; Dorofeenko, G. N.; Fischer, G. W.; Koblik, A. V.; Mezheritskii, V. V.; Schroth, W. *Pyrylium Salts. Syntheses, Reactions and Physical Properties*; Adv. Heterocyclic Chem., Suppl. Vol. 2; Katritzky, A. R., Ed.; Academic Press: New York, 1982.
- Balaban, A. T. Chemical graphs. I. Valence isomerism of cyclo-polyenes. *Rev. Roum. Chim.* **1966**, 11, 1097–1116, (Erratum, *ibid.* **1967**, 12, No. 1, 103).
- Balaban, A. T. Chemical graphs. VIII. Valence isomerism and general cubic graphs. *Rev. Roum. Chim.* **1970**, 15, 463–485.
- Balaban, A. T. Chemical graphs. XIV. Valence isomers of [12]-annulene. *Rev. Roum. Chim.* **1972**, 17, 865–881.
- Balaban, A. T.; C. Deleanu, Chemical graphs. 47. Valence isomers of [14]annulene. *Rev. Roum. Chim.* **1987**, 32, 271–294.
- Balaban, A. T.; Vancea, R.; Motoc, I.; Holban, S. Chemical graphs. 43. Fortran IV program for computing the numbers of general cubic graphs on p vertices. *J. Chem. Inf. Comput. Sci.* **1986**, 26, 72–76.
- Balaban, A. T.; Davies, R. O.; Harary, F.; Hill, A.; Westwick, R. Cubic identity graphs and planar graphs derived from trees. *Austral. J. Math.* **1970**, 11, 207–215.
- Balaban, A. T. Chemical graphs. XXI. Valence isomers of benzoannulenes. *Rev. Roum. Chim.* **1974**, 19, 1185–1196.
- Deleanu, C.; Balaban, A. T. Chemical graphs. Part 53. Benzo- and polybenzo-derivatives of valence isomers of [12]annulene. *Rev. Roum. Chim.* **1990**, 35, 349–391.
- Balaban, A. T. Chemical graphs. XXII. Valence isomers of heteroannulenes or of substituted annulenes. Coisomeric cubic multi-graphs. *Rev. Roum. Chim.* **1974**, 19, 1323–1342.
- Balaban, A. T.; Chemical graphs. XXIII. General cubic graphs with one loop, and homovalenes or their derivatives. *Rev. Roum. Chim.* **1974**, 19, 1611–1619. Erratum, *Rev. Roum. Chim.* **1978**, 23, 311.
- Baciu, V.; Balaban, A. T. Chemical graphs. XXXIX. Valence isomers of monodehydro[n]annulenes. *Rev. Roum. Chim.* **1980**, 25, 1213–1220.
- Banciu, M.; Balaban, A. T. Schemes and transformations for benzo- and dibenzoderivatives of valence isomers of [10]annulene. *Chem. Scr.* **1983**, 22, 188–194.
- Balaban, A. T.; Banciu, M. Schemes and transformations for valence isomers of $(CH)_8$ and $(CH)_{10}$ hydrocarbons. *J. Chem. Educ.* **1984**, 61, 766–770.
- Banciu, M.; Popa, C.; Balaban, A. T. Schemes and transformations in the $(CH)_{2k}$ series. Valence isomers of [12]annulene. *Chem. Scr.* **1984**, 24, 28–37.
- Balaban, A. T.; Banciu, M.; Ciorba, V. *Annulenes, Benzo-, Hetero-, Homo-Derivatives and Their Valence Isomers*. CRC Press: Boca Raton, FL, 1986.
- Balaban, A. T. Chemical graphs. III. Reactions with cyclic six-membered transition states. *Rev. Roum. Chim.* **1967**, 12, 875–898. (Reprinted in "Recherches sur la Philosophie des Sciences", pp 207–230, Editura Academiei: Bucuresti).
- Balaban, A. T. Chemical graphs. XV. Degenerate Cope rearrangements of valence isomers of annulenes. *Rev. Roum. Chim.* **1972**, 17, 883–896.
- Evans, M. G. The activation energies of reactions involving conjugated systems. *Trans. Faraday Soc.* **1939**, 35, 824–834.
- Mathieu, J.; Valls, J.; Apeleff, P. Circular electron transfer in the interpretation of reactions of organic chemistry. *Bull. Soc. Chim. Fr.* **1957**, 1509–1541.
- Dewar, M. J. S. Aromaticity and pericyclic reactions. *Angew. Chem., Int. Ed. Engl.* **1971**, 10, 761–775.
- Zimmermann, H. E. In *Pericyclic Reactions*; Marchand, A. P., Lehr, R. E., Eds.; Academic Press: New York, 1977; Vol. 1, Chapter 2.
- Hendrickson, J. B. Variety of thermal pericyclic reactions. *Angew. Chem., Int. Ed. Engl.* **1974**, 13, 47–76.
- Woodward, R. B.; Hoffmann, R. The conservation of orbital symmetry. *Angew. Chem., Int. Ed. Engl.* **1969**, 8, 781–853.
- Balaban, A. T.; Harary, F. Chemical graphs. V. Enumeration and proposed nomenclature of benzenoid cata-condensed polycyclic aromatic hydrocarbons. *Tetrahedron* **1968**, 24, 2505–2516.
- Balaban, A. T. Chemical graphs. VII. Proposed nomenclature of branched cata-condensed benzenoid polycyclic hydrocarbons. *Tetrahedron* **1969**, 25, 2949–2956.
- Smith, F. T. Capacitive energy and the ionization of aromatic hydrocarbons. *J. Chem. Phys.* **1961**, 34, 793–801.
- Balaban, A. T.; Brunvoll, J.; Cioslowski, J.; Cyvin, B. N.; Syvin, S. J.; Gutman, I.; Wenchel, He.; Wenjie, He.; Knop, J. V.; Kovacevic, M.; Müller, W. R.; Szymanski, K.; Tosić, R.; Trinajstić, N. Enumeration of benzenoid and coronoid hydrocarbons. *Z. Naturforsch.* **1987**, 42C, 863–870.
- Balaban, A. T.; Tomescu, I. Chemical graphs. XL. Three relations between the Fibonacci sequence and the numbers of Kekulé structures for non-branched cata-condensed polycyclic aromatic hydrocarbons. *Croat. Chem. Acta* **1984**, 57, 391–404.
- Balaban, A. T.; Tomescu, I. Algebraic expressions for the number of Kekulé structures of isarithmic cata-condensed polycyclic hydrocarbons. *Math. Chem. (MATCH)* **1983**, 14, 155–182.
- Balaban, A. T.; Tomescu, I. Chemical graphs. XLI. Numbers of conjugated circuits and Kekulé structures for zigzag catafusenes and (j,k) -hexes; generalized Fibonacci numbers. *Math. Chem. (MATCH)* **1985**, 17, 91–120.
- Balaban, A. T.; Artemi, C.; Tomescu, I. Algebraic expressions for Kekulé structure counts in non-branched regularly cata-condensed benzenoid hydrocarbons. *Math. Chem. (MATCH)* **1987**, 22, 77–100.
- Tomescu, I.; Balaban, A. T. Decomposition theorems for calculating the number of Kekulé structures in coronoids fused via perinaphthyl units. *Math. Chem. (MATCH)* **1989**, 24, 289–389.
- Balaban, A. T. Chemical graphs. X. (Aromaticity. VIII). Resonance energies of cata-condensed benzenoid polycyclic hydrocarbons. *Rev. Roum. Chim.* **1970**, 15, 1243–1250.
- Balaban, A. T. Chemical graphs. XI. (Aromaticity. IX). Isomerism and topology of non-branched cata-condensed polycyclic conjugated non-benzenoid hydrocarbons. *Rev. Roum. Chim.* **1970**, 15, 1251–1262.
- Balaban, A. T. Chemical graphs. Part 50. Symmetry and enumeration of fibonacenes (unbranched catacondensed benzenoids isarithmic with helicenes and zigzag catafusenes). *Math. Chem. (MATCH)* **1989**, 24, 29–38.
- Balaban, A. T.; Biermann, D.; Schmidt, W. Chemical graphs. 42. Dualist graph approach for correlating Diels–Alder reactivities of polycyclic aromatic hydrocarbons. *Nouv. J. Chim.* **1985**, 9, 443–449.
- Balaban, A. T.; Artemi, C. Chemical graphs. Part 51. Enumeration of nonbranched catafusenes according to the numbers of benzenoid rings in the catafusene and in its longest linearly condensed portion. *Polycycl. Aromatic Compds.* **1990**, 1, 171–189.
- Balaban, A. T. Chemical graphs. XXVI. Codes for configurations of conjugated polyenes. *Rev. Roum. Chim.* **1976**, 21, 1045–1047.

- (59) Dzonova-Jerman-Blazic, B.; Trinajstić, N. Computer-aided enumeration and generation of the Kékulé structures in conjugated hydrocarbons. *Comput. Chem.* **1982**, *6*, 121–132.
- (60) Balasubramanian, K.; Kauffman, J. J.; Koski, W. S.; Balaban, A. T. Graph theoretical characterization and computer generation of certain carcinogenic benzenoid hydrocarbons and identification of bay regions. *J. Comput. Chem.* **1980**, *1*, 149–157.
- (61) Balaban, A. T.; Niculescu-Duvaz, I.; Simon, Z. Topological aspects in QSAR for biologically active molecules. *Acta Pharm. Jugosl.* **1987**, *37*, 7–36.
- (62) Niculescu-Duvaz, I.; Baracu, I.; Balaban, A. T., Alkylating agents, in *Chemistry of Antitumor Agents*; Wilman, D. E. V., Ed.; Blackie Publ.: London, 1990.
- (63) Voiculescu, N.; Balaban, A. T.; Niculescu-Duvaz, I.; Simon, Z. *Modeling of Cancer Genesis and Prevention*; CRC Press: Boca Raton, FL, 1990.
- (64) Balaban, A. T. Enumeration of catafusenes, diamondoid hydrocarbons, and staggered alkane C-rotamers. *Math. Chem. (MATCH)* **1976**, *2*, 51–61. Balaban, A. T. Chemical graphs. XXVII. Enumeration and codification of staggered conformations of alkanes. *Rev. Roum. Chim.* **1976**, *21*, 1049–1071.
- (65) Balaban, A. T.; Schleyer, P. R. Systematic classification and nomenclature of diamond hydrocarbons. I. Graph-theoretical enumeration of polymantanes. *Tetrahedron* **1978**, *34*, 3599–3609.
- (66) Schleyer, P. R.; Donaldson, M. M. The relative stability of bridged hydrocarbons. II. *endo*- and *exo*-Trimethylenenorbornane. The formation of adamantane. *J. Am. Chem. Soc.* **1960**, *82*, 4645–4650.
- (67) Robinson, R. W.; Harary, F.; Balaban, A. T. The number of chiral and achiral alkanes and mono-substituted alkanes. *Tetrahedron* **1976**, *32*, 355–361.
- (68) Balaban, A. T.; Kennedy, J. W.; Quintas, L. V. The number of alkanes having n carbons and a longest chain of length d . An application of a theorem of Polya. *J. Chem. Educ.* **1988**, *65*, 304–313.
- (69) Morgan, H. L. The generation of a unique machine description for chemical structures—a technique developed at Chemical Abstracts Service. *J. Chem. Doc.* **1965**, *5*, 107–113.
- (70) Wipke, W. T.; Dyott, T. M. Stereochemically unique naming algorithm. *J. Am. Chem. Soc.* **1974**, *96*, 4834–4842.
- (71) Balaban, A. T.; Mekenyan, O.; Bonchev, D. Unique description of chemical structures based on hierarchically ordered extended connectivities (HOC procedures). I. Algorithms for finding graph orbits and canonical numbering of atoms. *J. Comput. Chem.* **1985**, *6*, 538–551.
- (72) Mekenyan, O.; Bonchev, D.; Balaban, A. T. Unique description of chemical structures based on hierarchically ordered extended connectivities (HOC procedure). II. Mathematical proofs for the HOC algorithm. *J. Comput. Chem.* **1985**, *6*, 552–561.
- (73) Balaban, A. T.; Mekenyan, O.; Bonchev, D. Unique description of chemical structures based on hierarchically ordered extended connectivities (HOC procedure). III. Topological, chemical and stereochemical coding of molecular structure. *J. Comput. Chem.* **1985**, *6*, 562–569.
- (74) Ralev, N.; Karabunarliev, S.; Mekenyan, O.; Bonchev, D.; Balaban, A. T. Unique description of chemical structures based on hierarchically ordered extended connectivities (HOC procedure). VIII. General principles for computer implementation. *J. Comput. Chem.* **1985**, *6*, 587–591.
- (75) Balaban, A. T. Topological indices and their uses: a new approach for coding of alkanes. *J. Mol. Struct. (Theochem)* **1988**, *165*, 243–253.
- (76) Balaban, T. S.; Filip, P. A.; Ivanciuc, O. Computer generation of acyclic graphs based on local vertex invariants and topological indices. Derived canonical labelling and coding of trees and alkanes. *J. Math. Chem.* **1992**, *11*, 79–105.
- (77) Read, R. C. A new system for the designation of chemical compounds. 1. Theoretical preliminaries and the coding of acyclic compounds. *J. Chem. Inf. Comput. Sci.* **1983**, *23*, 135–149.
- (78) Read, R. C. A new system for the designation of chemical compounds. 2. Coding of cyclic compounds. *J. Chem. Inf. Comput. Sci.* **1985**, *25*, 116–128.
- (79) Randić, M.; Nikolić, S.; Trinajstić, N. Compact codes: on nomenclature of acyclic chemical compounds. *J. Chem. Inf. Comput. Sci.* (this issue).
- (80) Balaban, A. T.; Filip, P.; Balaban, T. S. Computer program for finding all possible cycles in graphs. *J. Comput. Chem.* **1985**, *6*, 316–329.
- (81) Qian, C.; Fisanick, W.; Hartzler, D. E.; Chapman, S. N. Enhanced algorithm for finding the smallest set of smallest rings. *J. Chem. Inf. Comput. Sci.* **1990**, *30*, 105–170.
- (82) Fan, T.; Panaye, A.; Doucet, J. P.; Barbu, A. Ring perception. A new algorithm for directly finding the smallest set of smallest rings from a connection table. *J. Chem. Inf. Comput. Sci.* **1993**, *33*, 657–662.
- (83) Downs, G. M.; Gillet, V. J.; Holliday, J. D.; Lynch, M. F. Review of ring perception algorithms for chemical graphs. *J. Chem. Inf. Comput. Sci.* **1989**, *29*, 172–187, and references cited therein.
- (84) Bonchev, D.; Balaban, A. T.; Mekenyan, O. Generalization of the graph centre concept and derived topological centric indices. *J. Chem. Inf. Comput. Sci.* **1980**, *20*, 106–113.
- (85) Bonchev, D.; Balaban, A. T.; Randić, M. The graph center concept for polycyclic graphs. *Internat. J. Quantum Chem.* **1981**, *19*, 61–82. Erratum, *Internat. J. Quantum Chem.* **1982**, *22*, 441.
- (86) Bonchev, D.; Balaban, A. T. Topological centric coding and nomenclature of polycyclic hydrocarbons. I. Condensed benzenoid systems (polyhexes, fusenes). *J. Chem. Inf. Comput. Sci.* **1981**, *21*, 223–229.
- (87) Bonchev, D.; Mekenyan, O.; Balaban, A. T. Iterative procedure for the generalized graph center in polycyclic graphs. *J. Chem. Inf. Comput. Sci.* **1989**, *29*, 91–97.
- (88) Bonchev, D.; Balaban, A. T. Central vertices versus central rings in polycyclic systems. *J. Math. Chem.* **1993**, *14*, 287–304.
- (89) Balaban, A. T.; Harary, F. The characteristic polynomial does not uniquely determine the topology of a molecule. *J. Chem. Doc.* **1971**, *11*, 258–259.
- (90) Trinajstić, N. *Chemical Graph Theory*; CRC Press: Boca Raton, FL, 1983; Vol. 1, Chapter 7, pp 97–119.
- (91) Balaban, A. T.; Farcasiu, D.; Banica, R. Chemical graphs. II. Graphs of multiple 1,2-shifts in carbonium ions and related systems. *Rev. Roum. Chim.* **1966**, *11*, 1205–1227.
- (92) Lauterbur, P. C.; Ramirez, F. Pseudorotation in trigonal-bipyramidal molecules. *J. Am. Chem. Soc.* **1968**, *90*, 6722–6726.
- (93) Dunitz, J. V.; Prelog, V. Ligand reorganization in trigonal bipyramid. *Angew. Chem., Int. Ed. Engl.* **1968**, *7*, 725–726.
- (94) Mislow, K. Role of pseudorotation in stereochemistry of nucleophilic displacement reactions. *Acc. Chem. Res.* **1970**, *3*, 321–333.
- (95) DeBruin, K. E.; Naumann, K.; Zon, G.; Mislow, K. Topological representation of the stereochemistry of displacement reactions at phosphorus in phosphonium salts and cognate systems. *J. Am. Chem. Soc.* **1969**, *91*, 7031–7040.
- (96) Balaban, A. T. Enumeration of cyclic graphs. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 63–105.
- (97) Gielen, M. Application of graph theory to organometallic chemistry. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 261–298.
- (98) Brocas, J. Some aspects of graph theory for intermolecular interactions in chemical physics. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 223–259.
- (99) Harary, F. An exposition of graph theory. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 5–9.
- (100) Harary, F.; Palmer, E. M.; Robinson, R. W.; Read, R. C. Polya's contributions to chemical theory. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 11–24.
- (101) Read, R. C. The enumeration of acyclic chemical compounds. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 25–61.
- (102) Dugundji, J.; Gillespie, P.; Marquarding, D.; Ugi, I.; Ramirez, F. Metric spaces and graphs representing the logical structure of chemistry. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 107–174.
- (103) Dubois, J. E. Ordered chromatic graph and limited environment concepts. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 333–370.
- (104) Rouvray, D. H. The topological matrix in quantum chemistry. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 175–221.
- (105) Gordon, M.; Temple, W. B. The graph-like state of matter and polymer science. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 299–332.
- (106) Balaban, A. T.; Harary, F. Early history of the interplay between graph theory and chemistry. In *Chemical Applications of Graph Theory*; Balaban, A. T., Ed.; Academic Press: London, 1976; pp 1–4.
- (107) Rouvray, D. H. Isomer enumeration methods. *Chem. Soc. Revs.* **1974**, *3*, 355–372.
- (108) Rouvray, D. H. Some reflections on topological structure of covalent molecules. *J. Chem. Educ.* **1975**, *52*, 768–773.
- (109) Rouvray, D. H.; Balaban, A. T. Chemical applications of graph theory. In *Applications of Graph Theory*; Wilson, R. J.; Beineke, L. W., Eds.; Academic Press: London, 1979; pp 177–221.
- (110) Balaban, A. T. Chemical graphs. XIX. Intramolecular isomerization of trigonal-bipyramidal structures with five different ligands. *Rev. Roum. Chim.* **1973**, *18*, 855–862.
- (111) Balaban, A. T. Chemical graphs. XVI. Intramolecular isomerization of octahedral complexes with six different ligands. *Rev. Roum. Chim.* **1973**, *18*, 841–854.
- (112) Balaban, A. T. Chemical graphs. XXX. Reaction graphs for degenerate rearrangements of homovalent cations. *Rev. Roum. Chim.* **1977**, *22*, 243–255.

- (113) Balaban, A. T. Chemical graphs. XXXIII. Graphs for intramolecular rearrangements of tetragonal-pyramidal complexes. *Rev. Roum. Chim.* **1978**, *23*, 733–746.
- (114) Balaban, A. T.; Brocas, J. Modes of rearrangements and reaction graphs for XeF_6 . *J. Mol. Struct. (Theochem)* **1989**, *185*, 139–153.
- (115) Gimarc, B. M.; Brant, A. R. Bullvalene: reaction graphs relating polysubstituted positional isomers. *J. Chem. Inf. Comput. Sci.* **1994**, *34*, 1167–1173. Gimarc, B. M.; Ott, J. J. Bullvalene: reaction graphs for rearrangements of heteroatomic and substituted positional isomers. *Croat. Chem. Acta* **1991**, *64*, 493–500.
- (116) Brocas, J. The reaction graph of the Cope rearrangement in bullvalene. *J. Math. Chem.* **1994**, *15*, 389–395.
- (117) Balaban, A. T. Reaction graphs. In *Graph Theory Approaches to Chemical Reactivity*; Bonchev, D., Mekenyan, O., Eds.; Kluwer Academic Publishers: Dordrecht, Netherlands, 1994.
- (118) Gimarc, B. M.; Ott, J. J. Graphs for chemical reaction networks: applications to the isomerizations among the carboranes. In *Graph Theory and Topology in Chemistry*; King, R. B., Rouvray, D. H., Eds.; Elsevier: Amsterdam, 1987; pp 285–301.
- (119) Gimarc, B. M.; Ott, J. J. Isomerization of carboranes by the diamond-square diamond rearrangement. *J. Am. Chem. Soc.* **1987**, *109*, 1388–1392.
- (120) Gimarc, B. M.; Ott, J. J. Details of the reaction graphs for intramolecular isomerizations of the carboranes. *J. Math. Chem.* **1990**, *5*, 359–380.
- (121) Temkin, M. I. Kinetic equations of complex reactions deduced by the theory of graphs. *Dokl. Akad. Nauk. SSSR.* **1965**, *165*, 615–618.
- (122) Zeigarnik, A. V.; Temkin, O. N. Graph-theoretical methods in the theory of complex reactions mechanisms: a graphical description of the mechanisms. *Kinet. Catal.* **1994**, *35*, 636–646, and further references therein.
- (123) Bonchev, D.; Temkin, O. N.; Kamenski, D. Graph theoretical classification and coding of chemical reactions with a linear mechanism. *J. Comput. Chem.* **1982**, *3*, 95–111.
- (124) Temkin, O. N.; Bonchev, D. Application of graph theory to chemical kinetics. Part 1. Kinetics of complex reactions. *J. Chem. Educ.* **1992**, *69*, 544–550.
- (125) Temkin, O. N.; Zeigarnik, A. V.; Bonchev, D. In *Graph Theoretical Approaches to Chemical Reactivity*. Bonchev, D., Mekenyan, O., Eds.; Kluwer: Dordrecht, The Netherlands, 1994.
- (126) Balaban, A. T. A trivalent graph of girth ten. *J. Combinatorial Theory, Ser. B* **1972**, *12*, 1–5.
- (127) Balaban, A. T. Trivalent graphs of girth nine and eleven, and relationships among cages. *Rev. Roum. Math. Pures Appl.* **1973**, *18*, 1033–1043.
- (128) Biggs, N. L.; Hoare, M. J. A trivalent graph with 58 vertices and girth 9. *Discrete Math.* **1980**, *30*, 299–301.
- (129) Evans, C. W. Second trivalent graph with 58 vertices and girth 9. *J. Graph Theory* **1984**, *8*, 97–99.
- (130) Wong, P. K. Cages—a survey. *J. Graph Theory* **1982**, *6*, 1–22.
- (131) Hansch, C.; Leo, A. J. *Substituent Constants for Correlation Analysis in Chemistry and Biology*; Wiley: New York, 1977.
- (132) Cramer, III, R. D.; Patterson, D. E.; Bunce, J. D. Comparative molecular field analysis (COMFA). 1. Effect of shape on binding of steroids to carrier proteins. *J. Am. Chem. Soc.* **1988**, *110*, 5959–5967.
- (133) Wiener, H. Structural determination of paraffin boiling points. *J. Am. Chem. Soc.* **1947**, *69*, 17–20.
- (134) Wiener, H. Correlation of heat of isomerization and difference in heat of vaporization of isomers among paraffin hydrocarbons. *J. Am. Chem. Soc.* **1947**, *69*, 2636–2638.
- (135) Hosoya, H. Topological index. A proposed quantity characterizing the topological nature of structural isomers of saturated hydrocarbons. *Bull. Chem. Soc. Jpn.* **1971**, *44*, 2332.
- (136) Randić, M. On characterization of molecular branching. *J. Am. Chem. Soc.* **1975**, *97*, 6609–6615.
- (137) Kier, L. B.; Hall, L. H. *Molecular Connectivity in Structure-Activity Studies*; Research Studies Press: Letchworth, England, 1986.
- (138) Kier, L. B.; Hall, L. H. *Molecular Connectivity in Chemistry and Drug Research*; Academic Press: New York, 1976.
- (139) Kier, L. B.; Murray, W. J.; Randić, M.; Hall, L. H. Molecular connectivity. V. Connectivity series concept applied to density. *J. Pharm. Sci.* **1976**, *65*, 1226–1230.
- (140) Balaban, A. T. Chemical graphs. XXXIV. Five new topological indices for the branching of tree-like graphs. *Theor. Chem. Acta* **1979**, *53*, 355–375.
- (141) Balaban, A. T. Topological indices based on topological distances in molecular graphs. *Pure Appl. Chem.* **1983**, *55*, 199–206.
- (142) Balaban, A. T. Highly discriminating distance-based topological index. *Chem. Phys. Lett.* **1982**, *80*, 399–404.
- (143) Balaban, A. T.; Quintas, L. V. The smallest graphs, trees, and 4-trees, with degenerate topological index. *J. Math. Chem. (MATCH)* **1983**, *14*, 213–233.
- (144) Balaban, A. T.; Ionescu-Pallas, N.; Balaban, T. S. Asymptotic values of topological indices J and J' (average distance sum connectivities) for infinite acyclic and cyclic graphs. *Math. Chem. (MATCH)* **1985**, *17*, 121–146.
- (145) Razinger, M.; Chretien, J. R.; Dubois, J. E. Structural selectivity of topological indexes in alkane series. *J. Chem. Inf. Comput. Sci.* **1985**, *25*, 23–27.
- (146) Balaban, A. T.; Filip, P. Computer program for topological index J (average distance sum connectivity). *Math. Chem. (MATCH)* **1984**, *16*, 163–190.
- (147) Balaban, A. T.; Bonchev, D.; Seitz, W. A. Topological chemical distances and graph centers in molecular graphs with multiple bonds. *J. Molec. Struct. (Theochem)* **1993**, *280*, 253–260.
- (148) Barysz, M.; Jashari, G.; Lall, R. S.; Srivastava, V. K.; Trinajstić, N. In *Chemical Applications of Topology and Graph Theory*; King, R. B., Ed.; Elsevier: Amsterdam, pp 222–227.
- (149) Balaban, A. T. Chemical graphs. 48. Topological index J for heteroatom-containing molecules taking into account periodicities of element properties. *Math. Chem. (MATCH)* **1986**, *21*, 115–122.
- (150) Balaban, A. T. Using real numbers as vertex invariants for third generation topological indexes. *J. Chem. Inf. Comput. Sci.* **1992**, *32*, 23–28.
- (151) Filip, P.; Balaban, T. S.; Balaban, A. T. A new approach for devising local graph invariants: derived topological indices with low degeneracy and good correlation ability. *J. Math. Chem.* **1987**, *1*, 61–83.
- (152) Diudea, M. V.; Minailiuc, O.; Balaban, A. T. Molecular topology. IV. Regressive vertex degrees (new graph invariants) and derived topological indices. *J. Comput. Chem.* **1991**, *12*, 527–535.
- (153) Balaban, A. T.; Diudea, M. V. Real number vertex invariants: regressive distance sums and related topological indices. *J. Chem. Inf. Comput. Sci.* **1993**, *33*, 421–428.
- (154) Balaban, A. T.; Ciubotariu, D.; Medeleanu, M. Topological indices and real vertex invariants based on eigenvalues or eigenvectors. *J. Chem. Inf. Comput. Sci.* **1991**, *31*, 517–523.
- (155) Bonchev, D.; Trinajstić, N. Information theory, distance matrix, and molecular branching. *J. Chem. Phys.* **1977**, *67*, 4517–4533.
- (156) Bonchev, D. *Information Theoretic Indices for Characterization of Chemical Structure*; Research Studies Press-Wiley: Chichester, 1993.
- (157) Basak, S. C. Use of molecular complexity indices in predictive pharmacology and toxicology. *Med. Sci. Res.* **1967**, *15*, 605.
- (158) Roy, A. B.; Raychaudhury, C.; Ghosh, A. A.; Ray, S. K.; Basak, S. C. Information-theoretic topological indices of a molecule and their applications in QSAR. In *Quantitative Approaches to Drug Design*; Dearden, J. C., Ed.; Elsevier: Amsterdam, pp 75–76.
- (159) Raychaudhury, C.; Ray, S. K.; Ghosh, J. J.; Roy, A. B.; Basak, S. C. Discrimination of isomeric structures using information-theoretic topological indices. *J. Comput. Chem.* **1994**, *5*, 581–588.
- (160) Balaban, A. T.; Balaban, T. S. New vertex invariants and topological indices of chemical graphs based on information on distances. *J. Math. Chem.* **1991**, *8*, 383–397.
- (161) Balaban, A. T.; Balaban, T. S. Correlations using topological indices based on real graph invariants. *J. Chim. Phys.* **1929**, *89*, 1735–1745.
- (162) Balaban, A. T.; Bertelsen, S.; Basak, S. C. New centric topological indexes for acyclic molecules (trees) and substituents (rooted trees), and coding of rooted trees. *Math. Chem. (MATCH)* **1994**, *30*, 55–72.
- (163) Balaban, A. T.; Catana, C. Search for nondegenerate real vertex invariants and derived topological indexes. *J. Comput. Chem.* **1993**, *14*, 155–160.
- (164) Balaban, A. T.; Catana, C. New topological indices for substituents (molecular fragments). *SAR QSAR Environ. Res.* **1994**, *2*, 1–16.
- (165) Mekenyan, O.; Bonchev, D.; Balaban, A. T. Topological indices for molecular fragments and new graph invariants. *J. Math. Chem.* **1988**, *2*, 347–375.
- (166) Ivanciuc, O.; Balaban, T. S.; Balaban, A. T. Design of topological indices. Part 4. Reciprocal distance matrix, related local vertex invariants and topological indices. *J. Math. Chem.* **1993**, *12*, 309–318.
- (167) Plavšić, D.; Nikolić, S.; Trinajstić, N.; Mihalić, Z. On the Harary index for the characterization of chemical graphs. *J. Math. Chem.* **1993**, *12*, 235–250.
- (168) Klein, D. J.; Randić, M. Resistance distance. *J. Math. Chem.* **1993**, *12*, 81–95.
- (169) Bonchev, D.; Balaban, A. T.; Liu, X.; Klein, D. J. Molecular cyclicity and centrality of polycyclic graphs. Part 1. Cyclicity based on resistance distances and reciprocal distances. *Int. J. Quantum Chem.* **1994**, *50*, 1–20.
- (170) Motoc, I.; Balaban, A. T.; Mekenyan, O.; Bonchev, D. Topological indices: inter-relations and composition. *Math. Chem. (MATCH)* **1982**, *13*, 369–404.
- (171) Motoc, I.; Balaban, A. T. Topological indices: intercorrelations, physical meaning, correlational ability. *Rev. Roum. Chim.* **1981**, *26*, 593–600.
- (172) Balaban, A. T.; Motoc, I.; Bonchev, D.; Mekenyan, O. Topological indices for structure-activity correlations. *Top. Curr. Chem.* **1983**, *114*, 21–55.

- (173) Balaban, A. T. Lowering the intra- and intermolecular degeneracy of topological invariants. *Croat. Chim. Acta* **1994**, *66*, 447–458.
- (174) Balaban, A. T. Local vs global (i.e. atomic vs molecular) numerical modeling of molecular graphs. *J. Chem. Inf. Comput. Sci.* **1994**, *34*, 398–402. Balaban, A. T. Real-number local (atomic) invariants and global (molecular) topological indices. *Rev. Roum. Chim.* **1994**, *39*, 245–257.
- (175) Balaban, A. T.; Kier, L. B.; Joshi, N. Correlation between chemical structure and normal boiling points of acyclic ethers, peroxides, acetals, and their sulfur analogues. *J. Chem. Inf. Comput. Sci.* **1992**, *32*, 237–244.
- (176) Balaban, A. T.; Joshi, N.; Kier, L. B.; Hall, L. H. Correlations between chemical structure and normal boiling points of halogenated alkanes. C₁–C₄. *J. Chem. Inf. Comput. Sci.* **1992**, *32*, 233–237.
- (177) Balaban, A. T.; Basak, S. C.; Colburn, T.; Grunwald, G. D. Correlation between structure and normal boiling point of haloalkanes C₁–C₄ using neural networks. *J. Chem. Inf. Comput. Sci.* **1994**, *34*, 1118–1121.
- (178) Woolf, A. A. Boiling point relations in the halogenated ethane series. *J. Fluorine Chem.* **1990**, *50*, 89.
- (179) Balaban, A. T.; Motoc, I. Chemical graphs. XXXVI. Correlations between octane numbers and topological indices of alkanes. *Math. Chem. (MATCH)* **1979**, *5*, 197–218.
- (180) Balaban, A. T.; Kier, L. B.; Joshi, N. Structure–property analysis of octane numbers for hydrocarbons (alkanes, cycloalkanes, alkenes). *Math. Chem. (MATCH)* **1992**, *28*, 13–27.
- (181) Balaban, A. T.; Ferioli, V. Correlation between structure and critical data or vapor pressures of alkanes by means of topological indices. *Reports Molec. Theory* **1990**, *1*, 133–139.
- (182) Katritzky, A. R.; Gordeeva, E. V. Traditional topological indices versus electronic, geometrical, and combined molecular descriptors in QSAR/QSPR research. *J. Chem. Inf. Comput. Sci.* **1993**, *33*, 835.
- (183) Murugan, R.; Grendze, M. P.; Toomey, J. E., Jr.; Katritzky, A. R.; Karelson, M.; Lobanov, V.; Rachwal, P. Predicting physical properties from molecular structure. *Chemtech* **1994**, *24*, 17–23.
- (184) Balaban, A. T.; Rentea, C. C.; Ciupitu, E. Chemical graphs. VI. Estimation of the relative stability of several planar and tridimensional lattices for elementary carbon. *Rev. Roum. Chim.* **1968**, *13*, 231–247. Erratum, *Rev. Roum. Chim.* **1968**, *13*, 1233.
- (185) Zhu, H.; Balaban, A. T.; Klein, D. J.; Zivković, T. P. Conjugated-circuit computation on two-dimensional carbon networks. *J. Chem. Phys.* **1994**, *101*, 5281–5292.
- (186) Hoffmann, R.; Eisenstein, O.; Balaban, A. T. Hypothetical strain-free oligoradicals. *Proc. Natl. Acad. Sci. U.S.A.* **1980**, *77*, 5588–5592.
- (187) Merz, K. M., Jr.; Hoffmann, R.; Balaban, A. T. 3,4-Connected carbon nets: through-space and through-bond interactions in the solid state. *J. Am. Chem. Soc.* **1987**, *109*, 6742–6751.
- (188) Balaban, A. T.; Klein, D. J.; Folden, C. A. Diamond-graphite hybrids. *Chem. Phys. Lett.* **1994**, *217*, 266–270.
- (189) Balaban, A. T.; Zhu, H.; Klein, D. Fullero-polycoronands. *Fullerene Sci. Technol.*, in press.
- (190) Balaban, A. T.; Klein, D. J.; Liu, X. Graphitic cones. *Carbon* **1994**, *32*, 357–359.
- (191) Ge, M.; Satler, K. Observation of graphitic cones. *Chem. Phys. Lett.* **1994**, *220*, 192–196.
- (192) Bochvar, D. A.; Galpern, E. G. Hypothetical systems: carbododecahedron, s-icosahedron, and carbo-s-icosahedron. *Dokl. Akad. Nauk SSSR* **1973**, *209*, 40–43.
- (193) Davidson, R. A. Spectral analysis of graphs by cyclic automorphism subgroups. *Theor. Chim. Acta* **1981**, *58*, 193–231.
- (194) Kroto, H. W.; Heath, J. R.; O'Brien, J. C.; Curl, R. F.; Smalley, R. E. C₆₀: Buckminsterfullerene. *Nature* **1985**, *318*, 162–163.
- (195) Krätschmer, W.; Lamb, L. D.; Fostiropoulos, K.; Huffman, D. R. Solid C₆₀. A new form of carbon. *Nature* **1990**, *347*, 354–358.
- (196) Kroto, H. W. C₆₀, fullerenes, giant fullerenes, and soot. *Pure Appl. Chem.* **1990**, *62*, 707–715. Space stars, C₆₀, and soot. *Science* **1988**, *242*, 1139–1145. Buckminsterfullerene. *Chem. Rev.* **1991**, *91*, 1213–1235.
- (197) Klein, D. J.; Schmalz, T. G.; Hite, G. E.; Seitz, W. A. Resonance in C₆₀ buckminsterfullerene. *J. Am. Chem. Soc.* **1986**, *108*, 1301.
- (198) Schmalz, T. G.; Seitz, W. A.; Klein, D. J.; Hite, G. E. Elemental carbon cages. *J. Am. Chem. Soc.* **1988**, *110*, 1113–1127.
- (199) Klein, D. J.; Liu, X. Theorems for carbon cages. *J. Math. Chem.* **1992**, *11*, 199–205.
- (200) Balaban, A. T.; Klein, D. J. W. R. Hamilton, his circuits, and IUPAC nomenclature for fullerenes. *J. Chem. Educ.*, in press.
- (201) Babic, D.; Balaban, A. T.; Klein, D. J. Nomenclature and coding of fullerenes. *J. Chem. Inf. Comput. Sci.*, in press.
- (202) Lederberg, J.; Sutherland, G. L.; Buchanan, B. G.; Feigenbaum, E. A.; Robertson, A. V.; Duffield, A. M.; Djerassi, C. Applications of artificial intelligence for chemical reference. I. The number of possible organic compounds. Acyclic structures containing C, H, O, and N. *J. Am. Chem. Soc.* **1969**, *91*, 2973–2976.
- (203) Corey, E. J.; Wipke, W. T. Computer-assisted design of complex organic syntheses. *Science* **1969**, *166*, 178–192.
- (204) Corey, E. J. The logic of chemical syntheses. Multistep syntheses of complex carbogenic molecules. *Angew. Chem., Int. Ed. Engl.* **1990**, *30*, 455–565.
- (205) Corey, E. J. *The Logic of Chemical Synthesis*; Wiley: New York, 1989.
- (206) Balaban, A. T. Chemical graphs. XXXVIII. Synthon graphs. *Math. Chem. (MATCH)* **1980**, *8*, 159–192.
- (207) Balaban, A. T. Is aromaticity outmoded? *Pure Appl. Chem.* **1980**, *52*, 1409–1492.
- (208) Balaban, A. T. Challenging problems involving benzenoid polycyclics and related systems. *Pure Appl. Chem.* **1982**, *54*, 1075–1096.
- (209) Balaban, A. T. Chemical graphs. Part 49: Open problems in the area of condensed polycyclic benzenoids: topological stereoisomers of coronoids and congeners. *Rev. Roum. Chim.* **1988**, *33*, 699–707.
- (210) Balaban, A. T. Numerical and non-numerical methods in chemistry: present and future. *Sigsam Bull.* **1984**, *18*, (2), 29–30.
- (211) Balaban, A. T. Symbolic computation and chemistry. In *EUROCAL-85, Lecture Notes in Computer Science No. 203*; Buchberger, B., Ed.; Springer: Berlin, 1985; pp 68–79.
- (212) Ugi, I.; Bauer, J.; Bley, K.; Baumgarten, R.; Fontaine, E.; Forstmeyer, D.; Lohnberger, S. Computer-assistance in the design of syntheses and a new generation of computer programs for the solution of chemical problems by molecular logic. *Pure Appl. Chem.* **1988**, *60*, 1573–1586.
- (213) Zefirov, N. S.; Gordeeva, E. V. Computer-assisted synthesis. *Usp. Khim.* **1987**, *56*, 1753–1772.
- (214) Balaban, A. T. Solved and unsolved problems in chemical graph theory. *Annals Discrete Math.* **1993**, *55*, 109–126. Reprinted in *Quo Vadis, Graph Theory?*; Gimbel, J., Kennedy, J. W., Quintas, L. V., Eds.; North Holland: Amsterdam, 1993.
- (215) Balaban, A. T.; Barasch, M.; Marcus, S. Computer program for the recognition of standard isoprenoid structures. *Math. Chem. (MATCH)* **1980**, *8*, 215–268.
- (216) Balaban, A. T.; Barasch, M.; Marcus, S. Picture grammars in chemistry. Generation of acyclic isoprenoid structures. *Math. Chem. (MATCH)* **1980**, *8*, 193–213.
- (217) Barasch, M.; Marcus, S.; Balaban, A. T. Codification of acyclic isoprenoid structures using context-free grammars and push-down automata. *Math. Chem. (MATCH)* **1981**, *12*, 25–64.
- (218) Balaban, A. T. Prediction of physical properties from chemical structures. In *Recent Advances in Chemical Information*; Collier, H., Ed.; Royal Society of Chemistry, Special Publication No. 120: London, 1993.
- (219) Kvasnicka, V.; Pospichal, J. Graph theory of synthons. *Internat. J. Quantum Chem.* **1990**, *38*, 253–278. Koca, J.; Kratochvil, M.; Kvasnicka, V.; Matyska, L.; Pospichal, J. *Synthon Model of Organic Chemistry and Synthesis Design*; Springer: Berlin, 1989.

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