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The Concept of Protobranching and Its Many Paradigm Shifting Implications for Energy Evaluations

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Dedicated to Professor Rolf Huisgen on the occasion of his 87th birthday

Abstract: Branched alkanes like isobutane and neopentane are more stable than their straight chain isomers, *n*-butane and *n*-pentane (by 2 and 5 kcal mol^{-1}, respectively). Electron correlation is largely responsible. Branched alkanes have a greater number of net attractive 1,3-alkyl–alkyl group interactions, there are three such stabilizing 1,3 "protobranching" dispositions in isobutane, but only two in *n*-butane. Neopentane has six protobranches but *n*-pentane only three. Propane has one protobranch and is stabilized appreciably, by 2.8 kcal mol^{-1}, relative to methane and ethane. This value per protobranch also applies to the *n*-alkanes and cyclohexane. Consequently, energy evaluations employing alkane reference standards, for example, of small ring strain and stabilizations due to conjugation, hyperconjugation, and aromaticity, should be corrected for protobranching, for example, by employing Pople's isodesmic bond separation reaction method. This reduces the ring strain of cyclopropane to 19.2 from the conventional 27.7 kcal mol^{-1}, while the stabilization energies of alkenes and alkynes due to hyperconjugation (5.5 and 7.7 kcal mol^{-1} for propene and propyne) and conjugation (14.8 and 27.1 kcal mol^{-1} for butadiene and butadiyne) are considerably larger than the traditional estimates. Widely diverging literature evaluations of benzene resonance energy all give $\approx$65 kcal mol^{-1} after adjusting for conjugation, hyperconjugation, and protobranching "contaminations." The BLW (block localized wavefunction) method, which localizes π bonds and precludes their interactions, largely confirms these stabilization estimates for hyperconjugation, conjugation, and aromaticity. Protobranching is seriously underestimated by theoretical computations at the HF and most DFT levels, which do not account for electron correlation satisfactorily. Such levels give bond separation energies, which can differ greatly from experimental values.

Keywords: aromaticity · hyperconjugation · protobranching · ring strain

Introduction

The quantitative evaluation of the energies associated with many highly important chemical concepts such as aromaticity (Faraday, 1825;[1] Kekulé, 1866),[2] ring strain (Baeyer, 1885),[3] conjugation (Thiele, 1899),[4] alkane branching (Rossini, 1934;[5] Nenitzescu, 1935)[6] and hyperconjugation (Mulliken, 1939),[7,8] depend upon the use and choice of reference compounds. Most of the quantities associated with these concepts are not directly measurable experimentally, but nevertheless, are very significant for interpreting the behavior of molecules. Consequently, the availability of accurate thermochemical data, in particular from the API project[5] dating from the 1930s, stimulated chemists to devise evaluation methods to estimate energies attributed to these concepts. Necessarily, these methods, as well as the molecules used as references or models, depend on arbitrary choices, however reasonable they may appear to be. The conventional equations most often employed for this purpose are illustrated in Scheme 1. Many other defining equations have been or might be used instead.

Branched hydrocarbons are more stable than their linear isomers. Branched hydrocarbons have more 1,3-alkyl–alkyl

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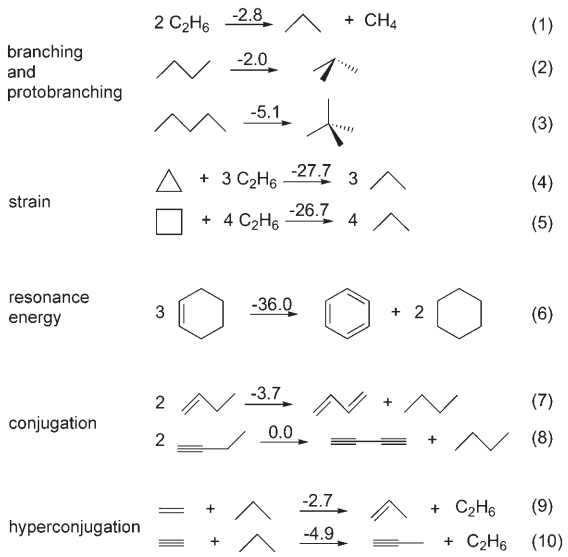

Scheme 1. Conventional equations for the evaluation of protobranching (1), branching (2 and 3), ring strain (4 and 5), aromatic stabilization energy (6), conjugation (7 and 8), and hyperconjugation (9 and 10). Values in kcal mol^{-1} are based on experimental heats of formation at 298 K.[9]

interactions, but these also are present in their linear counterparts. The most direct conclusion is that 1,3-alkyl–alkyl interactions stabilize hydrocarbons, not only the branched, but also the linear isomers. The net attractive character of the most basic 1,3-alkyl–alkyl interaction is demonstrated by the BSE evaluation of the 2.8 kcal mol^{-1} stabilization of propane versus methane and ethane [Equation (1), Scheme 1]. This paper examines the consequences of such 1,3-alkyl–alkyl interactions ("protobranching") on the evaluation of ring strain, conjugation, hyperconjugation, and aromatic resonance energies.

Note that propane, other unbranched alkanes, and cyclohexane are employed as reference compounds in all equations in Scheme 1 [except Equation (1)]. We now argue that such alkanes are biased choices for this purpose since they benefit from stabilizing protobranching interactions, which are absent from the molecules being evaluated.[10,11] Additionally, Equations (6)–(8) suffer from an imbalance of hyperconjugation.[12] Thus, the three reference cyclohexene molecules in Equation (6) are each stabilized by two hyperconjugative interactions. Consequently, the resonance energy of benzene is grossly underestimated by Equation (6).[12] Ideally, the best model reference compounds not only should lack the feature of interest, but also all other perturbing effects.

While chemical knowledge has been refined enormously since the pioneering thermochemical investigations of the 1930s, early equations used to evaluate energies associated with strain, conjugation, hyperconjugation, and aromaticity (Scheme 1) are still commonly cited. However, "perturbing effects," which were not known or considered in the 1930s, contaminate these evaluations.[12,13] The present paper emphasizes a perturbing effect, "protobranching,"[10,11,14,15] the nature of which is the same as the well known branching effect. Propane is stabilized by the net attractive composite of carbon and hydrogen interactions not present in methane and in ethane [Eq. (1)]. Analogous 1,3-methyl–methyl interactions stabilize isobutane by three and neopentane by six such protobranches (Figure 1). The energies of isobutane

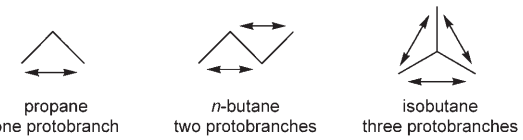

Figure 1. Protobranching interactions in propane (1), *n*-butane (2), and isobutane (3). Similarly, neopentane and cyclohexane have six protobranching interactions each. While branched alkanes have a greater number of protobranches, attractive 1,3-alkyl–alkyl interactions also are present in linear alkanes.

and neopentane are lower than *n*-butane and *n*-pentane, respectively, but the latter also benefit from protobranching. *n*-Butane has two and *n*-pentane three protobranching (1,3-alkyl–alkyl) interactions, respectively. Homologation of any alkane, in either a linear or branched fashion, results in a larger number of stabilizing 1,3-alkyl–alkyl protobranching interactions. We define "protobranching" as the net stabilizing 1,3-alkyl-alkyl interactions existing in normal, branched, and most cycloalkanes, but not in methane and ethane.[10–12,16–18] While the thermochemical effect of what we now call "protobranching", was recognized by Allen fifty years ago,[19–21] its consequences and ramifications have not been appreciated.

The main purpose of this paper is to reexamine and reevaluate all of the energies in Scheme 1 based on a uniform treatment, which avoids what we perceive to be perturbing effects that "contaminate" their assessment. Our reevaluations result in substantial changes from the conventional values given in Scheme 1.

We emphasize that protobranching is directly related to the well known branching effect in alkanes. Branched alkanes were discovered in the 1930s to be more stable then *n*-alkanes through two independent lines of investigation, direct isomerization reactions, for example, the $AlCl_3$-catalyzed conversion of *n*-butane to isobutane,[22,23] and the systematic thermochemical investigations sponsored by the American Petroleum Institute.[5] The heat of formation of isobutane is 2.0 kcal mol^{-1} lower than *n*-butane, and neopentane is favored by 5.1 kcal mol^{-1} over *n*-pentane [Scheme 1, Equations (2) and (3)]. However, because of the stability of protobranching, the branching energies given by Equations (2) and (3) are underestimated since *n*-alkanes contain the same stabilization.

Results and Discussion

Hydrocarbon energy relationships and their interpretation: How does one divide the total energy of a molecule into transferable components? Fajans' 1920 assumption[24] that

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C–C and C–H bond energies were constant was negated in the 1930s when accurate thermochemical data became available.[5] Although having the same number of two-atom CC and CH interactions, branched alkanes are more stable than their normal alkane isomers. Starting with Eyring[25] and continuing today, numerous research groups considered the energetic consequences of three-atom CCC, CCH, HCH interactions.[21] However, the quantities and even the signs associated with such terms varied widely and are still disputed.[16,26,27] Gronert's recent treatment[26–28] assumes that these three-atom (geminal) interactions are all repulsive, but we[16] found that a single attractive term reproduced an extended set of data equally well. The conclusion that differences in C–H and C–C bond energies are due to hyperconjugative stabilization of the resulting radical, and not on geminal repulsion, were further supported by Ingold and DiLabio's EPR measurements.[28,29]

Gronert's[27] comparison of the bond dissociation energies of C–H and C–CH_3 bonds in alkanes requires that a CH_3-C-CH_3 interaction is 2 kcal mol^{-1} more favorable than a CH_3-C-H interaction. The enhanced stability of the CH_3-C-CH_3 structural unit is akin to protobranching: 1,3-alkyl–alkyl interactions. Nevertheless, Gronert argues that these 1,3-alkyl–alkyl interactions are repulsive, calling attention to the widened angle ($\measuredangle$CCC = 112.4°) in propane. However, this angle widening is inconsequential energetically; imposing a 109.5° CCC bond angle in propane increases the energy by only 0.3 kcal mol^{-1} at various levels of theory, when all other parameters are fully optimized. Full optimization at the correlated MP2/6-311+G(d,p) level actually decreases the $\measuredangle$CCC by 0.77° relative to the HF/6-311+G(d,p) geometry, indicating that 1,3-methyl–methyl correlation effect is net attractive. Note that the accurate computation of protobranching and branching energies requires the use of MP2 or other electron correlated levels of theory.[14] Grimme's analysis of stereoelectronic effects in alkane isomers stresses the importance of 1,3-interpair (CC/CC) electron correlation effects which favor the branched isomers.[30]

Ziegler et al.[31] recently analyzed computed deviations in C–H and C–C bond (dissociation) energies using Gronert's geminal repulsion model. However, they did not employ correlated levels of theory and their computed "total bond energies" do not agree with experimental bond dissociation energies. Thus, their 8.6 kcal mol^{-1} C–CH_3 total bond energy difference of ethane versus neopentane is considerably larger than the 3.6 kcal mol^{-1} experimental difference. Hyperconjugative stabilization of alkyl radicals, along with the protobranching of alkanes, accounts for the BDE trends quite well.[16,32]

CH bond energies may be based on one fourth of the atomization energy (AE) of methane. Assuming that the CH bond energies of ethane are the same, the CC bond energy in ethane (78.8 kcal mol^{-1}) can be calculated from its AE. However, this treatment assumes that there are no three-atom contributions arising from HCH interactions in methane and ethane or from HCC as well as HCCH interactions in the latter. There is no satisfactory way to account for the rotational barrier of ethane only on the basis of two- and three-atom interactions if these are assumed to be structure/conformation independent.

Many two-, three-, four-atom, and higher terms are needed for a complete dissection of all the individual interaction energies of a molecule even as simple as propane. Molecular mechanics (MM) is the best approach along such phenomenological lines, but the same reservations apply. Although capable of reproducing energies as well as many other physical properties very accurately, the success of MM depends on the empirical adjustment of many parameters as well as the assumptions of its basic methodology.

Quantum mechanics (QM) also can achieve high accuracy, but has still not solved the "alkane chain branching mystery" fully. Pitzer and Catalano's[33] 1956 analysis of neo- versus *n*-pentane, iso- versus *n*-butane, as well as propane vs. methane and ethane (our "protobranching") attributed the energy differences to zero-point, thermal, and van der Waals attractive (London dispersion[34]) effects. Indeed, HF (which does not explicitly describe electron correlation) and DFT (which describes electron correlation based on the local density) levels, fail in reproducing the butane and pentane isomerization energies, as well as their isodesmic bond separation energies and that of propane.[14] In contrast, MP2, and especially CCSD(T) and other higher level correlation methods, succeed well with all of these tasks.

Nevertheless, Pitzer's "dispersion" explanation does not suffice. HF and DFT methods lack dispersion, but reproduce some non-bonded effects quite well, such as those responsible for the ethane rotational barrier,[18,35] the *n*-butane conformational energy differences,[30] and the greater stability of *trans*- over *cis*-2-butene. Grimme[30] considers "middle range" correlation effects to contribute almost exclusively to energy differences between linear and branched isomers.

We stress that we are *not* concerned here with the detailed analysis of all the effects responsible for protobranching and other intramolecular hydrocarbon interactions. Instead, the primary purpose of this paper is to consider the consequences of the realization that propane and higher *n*-alkanes benefit from the same net stabilizing influences (whatever their detailed nature may be) that are responsible for the "branching effect" exemplified by isobutane and neopentane. Because of "contamination" by this "protobranching" stabilization, we argue that *n*-alkane, cyclohexane, and other hydrocarbons are seriously compromised as reference molecules for the evaluation of energies associated with the basic concepts of ring strain, hyperconjugation, conjugation, and aromaticity. Their conventionally evaluated energies (Scheme 1) can change two-fold in magnitude when protobranching is taken into account. All the experimental energies employed in this paper (unless otherwise noted) are based on the heats of formation at 298 K given in the NIST compilation.[9] Although superior conceptually, 0 K data is much less readily available and has not generally been employed in the prior literature.

"Protobranching" describes the net stabilizing interactions between 1,3-disposed methyl and/or alkyl groups in propane,

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the higher *n*-alkanes, and cyclohexane. Protobranching depicts the total sum of all the individual interactions of the carbons and hydrogens of 1,3-disposed methyl and methylene groups. The equivalence of the various combinations is assumed, since their protobranching values are the same (see Table 1). According to the long-held tenets of conformation analysis, saturated hydrocarbons are considered to be "strain free" if they do not possess abnormal bond lengths or angles, eclipsed conformations, or closely-approaching atoms. However, Pople's isodesmic bond separation energies[36–38] (based on methane and ethane, see latter discussion) reveal that all these "strain free" molecules benefit from protobranching stabilization and, in that sense, have "negative strain."

Table 1. Evaluation of bond separation energies for saturated hydrocarbons (in kcal mol^{-1}). NIST 298 K thermochemical data were employed (see Table 1 in the Supporting Information).

Molecule	Bond separation reaction	Total reaction energy	Number of protobranches	Energy per protobranch
propane	$CH_3CH_2CH_3 + CH_4 \rightarrow 2\ CH_3CH_3$	2.83	1	2.83
n-butane	$CH_3(CH_2)_2CH_3 + 2\ CH_4 \rightarrow 3\ CH_3CH_3$	5.69	2	2.84
n-pentane	$CH_3(CH_2)_3CH_3 + 3\ CH_4 \rightarrow 4\ CH_3CH_3$	8.59	3	2.86
n-hexane	$CH_3(CH_2)_4CH_3 + 4\ CH_4 \rightarrow 5\ CH_3CH_3$	11.32	4	2.83
n-heptane	$CH_3(CH_2)_5CH_3 + 5\ CH_4 \rightarrow 6\ CH_3CH_3$	14.10	5	2.82
cyclohexane	$(CH_2)_6 + 6\ CH_4 \rightarrow 6\ CH_3CH_3$	16.53	6	2.76
isobutane	$CH(CH_3)_3 + 2\ CH_4 \rightarrow 3\ CH_3CH_3$	7.73	3	2.58
isopentane	$(CH_3)_2CHCH_2CH_3 + 3CH_4 \rightarrow 4\ CH_3CH_3$	10.94[a]	4	2.74
neopentane	$C(CH_3)_4 + 3\ CH_4 \rightarrow 4\ CH_3CH_3$	13.65	6	2.28

[a] To compensate for the skew interaction in isopentane, 0.7 kcal mol^{-1} was added.

While the name, "protobranching," and its ramifications (discussed in this paper) are new, antecedents go back to the 1930s. Allen deduced a value of 2.3 ± 0.3 kcal mol^{-1}, which is very similar to our 2.83 kcal mol^{-1} protobranching value based on Pople's BSE concept. George and Trachtman[39–42] have discussed the differences between Pople's isodesmic BSE evaluations and the results of their homodesmotic scheme at length.[43]

Isodesmic and homodesmotic considerations: Bond separation energy (BSE) evaluations employ isodesmic equations that retain the number of bonds of a given formal type, but change their relationship to one another.[36–38] For example, the isodesmic BSE equation for butadiyne has 10 C–H, 1 C–C, and 2 C≡C bonds on each side:

$$HC{\equiv}C{-}C{\equiv}CH + 2\,CH_4 \rightarrow 2\,HC{\equiv}CH + H_3C{-}CH_3$$

(isodesmic BSE)

The major criticism of such BSE evaluations is the imbalance of hybridization, which potentially has significant consequences. CH and CC bond energies depend on the carbon hybridization, but this is not taken into account in the BSE equation above. Thus, there are two more strong C(sp)–H bonds on the right than on the left. The left side has two more weaker C(sp^3)–H bonds than the right. To some extent this imbalance is ameliorated by the stronger C(sp)–C(sp) bond (in butadiyne) on the left, compared to the weaker C(sp^3)–C(sp^3) bond (in ethane) on the right.

To overcome this hybridization problem and to refine isodesmic BSE treatments, George et al.[39–42] developed "homodesmotic" reactions. These were defined originally[39] as having: "1) equal numbers of carbon atoms in their various states of hybridization in reactants and products and 2) equal numbers of carbon atoms with zero, one, two, and three H atoms attached in reactants and products." While George et al.[41] stated that "these conditions imply that there are equal numbers of each type of CC bond (sp^3–sp^3, sp^3–sp^2, etc.) and that the various types of C–H bonds are matched as closely as possible," this statement is not true for general hydrocarbon reactions. Subsequently, George et al. introduced[40] a refined definition of homodesmotic reactions as having "1) equal numbers of each type of carbon–carbon bond (C(sp^3)–C(sp^3), C(sp^2)–C(sp^2), C(sp^2)=C(sp^2), C(sp^3)–C(sp^2), etc.) in reactants and products and 2) equal numbers of each type of carbon atom (sp^3, sp^2, sp) with zero, one, two, and three hydrogens attached in reactants and products." The non-equivalence of these two definitions and the resulting confusion in the literature will be discussed in a forthcoming publication,[41] in which we suggest the use of the term "hypohomodesmotic" to describe reactions satisfying the original definition proposed by George et al.,[39] reserving the term "homodesmotic" for reactions adhering to the refined definition given in reference 36. An example of a hypohomodesmotic equation is given below, which (like the isodesmic BSE reaction above) has been used, in an equivalent way, to evaluate the diyne conjugation energy.[44,45]

$$HC{\equiv}C\text{-}C{\equiv}CH + CH_3CH_2CH_2CH_3 \rightarrow 2HC{\equiv}CCH_2CH_3$$

(hypohomodesmotic)

The number and types of CH bonds are consistent in the hypohomodesmotic equation but none of the C(sp)–C(sp), C(sp)–C(sp^3), and C(sp^3)–C(sp^3) bonds on the left and right side are matched! As we emphasize below, other, even more serious deficiencies, such as hyperconjugation and protobranching, perturb and contaminate hypohomodesmotic treatments but not BSE evaluations.

To summarize, both homodesmotic (as originally defined) and isodesmic BSE equations involve changes in the bond environments. The net hybridization imbalances for the equations above are:

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isodesmic : 2 $C(sp^3)$-H → 2 C(sp)-H

$$C(sp)-C(sp) \rightarrow C(sp^3)-C(sp^3)$$

hypohomodesmotic :

$$C(sp)-C(sp) + C(sp^3)-C(sp^3) \rightarrow 2\ C(sp)-C(sp^3)$$

However, the energetic consequences of these imbalances may not be as serious as commonly assumed, since they tend to cancel. The theoretical bond energies derived by Exner and Schleyer[46] provide a means of assessing energies associated with hybridization changes. Thus, $C(sp^2)$–H and C(sp)–H bond energies are about 2 and 6 kcal mol^{-1} larger, respectively, than $C(sp^3)$–H.[47] These differences are partially offset by the imbalance in C–C hybridization: the single C(sp)–C(sp) bond in butadiyne is stronger than the $C(sp^3)$–$C(sp^3)$ single bond in ethane. Such changes in CC σ bond energies with carbon hybridization may also be substantial. Indeed, Dewar once claimed that the resonance energy of butadiene did not result from π electron delocalization but "can be described quantitatively to the variation in bond energy with hybridization."[48] Unfortunately, Exner and Schleyer could not provide C–C bond energies corresponding to different bond environments, since they could not exclude effects arising from π conjugation.

We conclude that George et al.'s criticism that "isodesmic reactions involve quite profound changes in the nature of the C–H and C–C bonds" may be exaggerated. Instead, we argue below that homodesmotic reactions introduce far more serious imbalances than are present in bond separation energy treatments. Isodesmic BSE reactions have the further advantage of being uniquely defined rather than requiring arbitrary choices of reference molecules. Although neither treatment is perfect, we emphasize the additional advantages of isodesmic BSE over hypohomodesmotic and homodesmotic reactions below.

We now discuss the many ramifications of the protobranching concept. This paper considers the evaluation of energies associated with 1) straight and branched alkanes, 2) ring and cage strain, 3) resonance and aromatic stabilization energy, 4) hyperconjugation in alkenes and alkynes.

Evaluation of protobranching energies of straight and branched alkanes: The isodesmic bond separation energies (BSE) provided in Table 1 make use of NIST 298 K experimental data[9] to evaluate protobranching in a number of "strain-free" linear, branched, and cyclic alkanes. When compared with methane and ethane, propane (as well as higher alkanes) is stabilized appreciably by protobranching. The average value for each protobranch (ca. 2.8 kcal mol^{-1}) is remarkably constant (Table 1, last column) for the higher *n*-alkanes as well as cyclohexane.[49]

The stabilization per protobranch in isobutane and neopentane is somewhat attenuated. Protobranching is a net favorable composite of attractions (larger) and repulsions (smaller). The repulsion contributions increase somewhat in branched hydrocarbons, since the methyl groups are in closer proximity (note the C-C-C bond angle trend 112.7° in propane, 111.0° in isobutane, and 109.5° in neopentane).[50] However, reduction of the CCC bond angle does result in attenuation of the average value of the protobranching interaction in branched hydrocarbons, to 2.58 and 2.28 kcal mol^{-1} in isobutane and neopentane, respectively (Table 1). The CCC angle widening argument, considered by Gronert[26,27] to be the "gold standard" indicating that the geminal methyl group interaction is repulsive has been addressed above. Grimme[30] has stressed the importance of medium range interpair correlation effects, which are not computed at the commonly used DFT levels. The CCC angle widening in propane may be due to the greater net attraction at such angles, rather than Gronert's "C-C-C repulsion".[26,27]

Computational Models

In historical terms, the origin of the branching stabilization, and thus the origin of protobranching as well, has been thought to arise from net attractive intramolecular van der Waals interactions (dispersion).[33] The intramolecular van der Waals stabilization of methane and ethane are small, but it increases with alkane homologation. The use of ab initio methods allows us to gauge the degree to which these systems are stabilized by van der Waals and other long-range interactions. Post Hartree-Fock ab initio methods, such as MP2, explicitly account for electron correlation, in contrast to Hartree-Fock (HF). Thus, one can gain insight into the role of dispersion, as well as other effects of electron correlation, in branching stabilization by examining the differences between these two theoretical levels. Density functional theory (DFT) provides insight as well. Various functionals include different degrees of correlation. In general, these functionals perform poorly for long-range correlation and thus van der Waals complexes. While overcoming the van der Waals/non-covalent interaction problem is the topic of much current research in the field,[51–59] satisfactory density functionals are not in common use. Grimme's[30] recent analysis of failures in computing alkane isomer energy differences is due to the neglect of "medium-range" electron correlation effects rather than dispersion, in DFT.

Other problems in describing hydrocarbon properties have also been emphasized in the literature.[14,17,30,60–74] Check and Gilbert's analysis of homolytic C–C bond breaking energies of methyl-substituted ethane show B3LYP to have increasing errors as the number of methyl group substitutions is increased.[60] We have recently tested a large number of density functionals by computing the Pople bond separation reaction energies of *n*-alkanes (propane through decane) and found that all functionals systematically underestimate the energy of these reactions.[14] Schreiner et al.[63] found that DFT incorrectly assigns the lowest energy isomers for a number of large hydrocarbon compounds, generally underestimating the energy of structures containing only single bonds and small rings. Cage systems, like those studied by Schreiner, as well as *n*-alkanes all possess stabili-

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zation from protobranching. Our studies[17] on these same compounds showed that Truhlar's highly parameterized M05-2X functional[56] outperformed other older functionals. Most current density functionals are unable to describe hydrocarbon branching stabilization accurately.

Despite shortcomings, computational data can provide insight into the preference of protobranching in small molecules. Therefore, we have used Gaussian 98[75] and 03[76] at HF, DFT, MP2, and CCSD(T) levels with the 6-311++G-(d,p) basis set to complement experimental data. Computed energies include zero-point vibrational energies (ZPE) and thermal corrections to 298 K, unless otherwise stated.

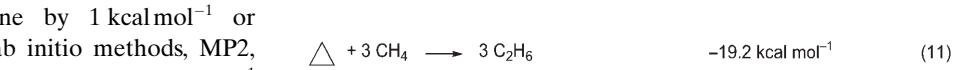
Quantum mechanical assessments of the branching effect (Table 2) include HF, DFT, and correlated ab initio methods. The HF energy of isobutane versus *n*-butane is only 0.40 kcal mol^{-1}. Inclusion of ZPE and thermal corrections to 298 K adds an additional stabilization of 0.33 kcal mol^{-1}, but the sum, 0.73 kcal mol^{-1}, is much less than the experimental value, 2.04 kcal mol^{-1}. DFT methods describe electron correlation based only on the local density: nonlocal effects are only partially incorporated into DFT calculations when the electron density gradient is considered.[77] Like HF, DFT systematically underestimates the branching stabilization. B3LYP, as well as other widely used functionals, underestimates the stabilization of propane by 1 kcal mol^{-1} or more![14] In contrast, the post-HF ab initio methods, MP2, SCS-MP2[78] and CCSD(T),[79] agree to within 0.40 kcal mol^{-1} for propane.

Table 2. Performance of various theoretical levels in evaluating branching stabilization. The 6-311++G(d,p) basis set was used throughout. E_0 is the quantity given by the electronic energies. ZPE/thermal is the contribution to branching stabilization from scaled zero-point vibrational and thermal corrections to 298 K (data in kcal mol^{-1} were derived from data in Table 2 in the Supporting Information).

	propane + methane → 2 ethane			isobutane → *n*-butane		
Method	E_0	ZPE/ thermal	E_0 + ZPE/ thermal	E_0	ZPE/ thermal	E_0 + ZPE/ thermal
HF	0.95	0.44	1.39	0.40	0.33	0.73
B3LYP	1.22	0.43	1.65	0.59	0.30	0.89
MP2	2.34	0.50	2.84	1.95	0.38	2.33
SCS-MP2	1.96	0.50	2.46	1.58	0.38	1.96
CCSD(T)	2.09	0.50	2.59	1.66	0.38	2.04
experiment			2.83			2.04

Protobranching and ring/cage strain energies: Strain is a virtual quantity; its evaluation depends on comparisons with models assumed to be "strain-free." As originally conceived by Baeyer in 1885,[3] ring strain was based on CCC bond angle deviations from tetrahedral in cyclic alkanes, which he assumed to be planar. All cycloalkane rings (except cyclopropane) are now known to favor non-planar conformations, which, for cyclohexane and the larger rings minimize angle strain. The non-planar preference of cyclopentane (which would have nearly perfect 108° CCC angles in D_{5h} symmetry) was rationalized by Pitzer's concept of torsional strain.[80,81] All C–H bonds are eclipsed in the planar geometries of cycloalkanes; hence, both cyclopentane and even cyclobutane pucker as a consequence. Eclipsing also is responsible for some of the strain of cyclopropane.

Conventional evaluations of strain energy employ propane or other *n*-alkanes as "strain-free" models; such alkanes prefer staggered conformations energetically and are assumed not to possess other perturbing effects. For example, the conventional homodesmotic evaluation of the strain in cyclopropane [Eq. (4), Scheme 1] is based on these assumptions. However, we have shown above that (unlike cyclopropane) propane and higher alkanes are stabilized by protobranching; in that sense these commonly used reference molecules have "negative strain." The conventional ring strain definition is flawed when the same structural features are not present in the rings as in the *n*-alkanes. Cyclopropane is a case in point; no protobranching 1,3-alkyl–alkyl interactions are present since all carbon atoms are directly bonded to one another. Hence, the traditional homodesmotic evaluation [27.7 kcal mol^{-1} using experimental data, Eq. (4)] overestimates the ring strain. Each of the three propanes on the left side is stabilized by a protobranch and this substantial (8.5 kcal mol^{-1}) perturbation is not balanced on the right side. Pople's isodesmic BSE [Eq. (11)] does not



(11)

suffer from this imbalance and provides a much smaller estimate of the strain energy in cyclopropane (19.2 kcal mol^{-1}). We argue that the strain energy of cyclopropane is really 8.5 kcal mol^{-1} less than the conventional value [27.7 kcal mol^{-1}, Eq. (4)].

Furthermore, cyclopropane is the only cycloalkane with fully eclipsed C–H bonds. Based on the 2.9 kcal mol^{-1} ethane rotation barrier,[82] each pair of eclipsed vicinal C–H bonds can be assigned a torsional strain of about 1 kcal mol^{-1}. Consequently, the eclipsing strain in cyclopropane could be as large as 6 kcal mol^{-1} (the bending of the H atoms away from one another may reduce this amount). Hence, the angle strain of the carbon skeleton of cyclopropane may actually be as low as 13 kcal mol^{-1}! This is less than half of the conventionally accepted (total) strain energy of cyclopropane.

Exner and Schleyer analyzed the energy contributions of cyclopropane most recently.[46] The large reduction of the strain energy from expectations based on the 60° CCC angles (to 13, 19, or even to the conventional 27.7 kcal mol^{-1}) is due to the σ-aromatic stabilization, which is now firmly established in cyclopropane.[83] Comparing the Baeyer angle strain of planar silicon and planar carbon rings (Figures 2 and 3, respectively) shows the unusual nature of cyclopropane. As Baeyer strain is only concerned with deviations from the idealized sp^3-hybridized bond angle, one expects "V-shaped" or parabolic curves when strain energies are plotted against the size of *planar* rings. The behavior of the planar Si_nH_{2n} rings (Figure 2) is just as Baeyer predicted.

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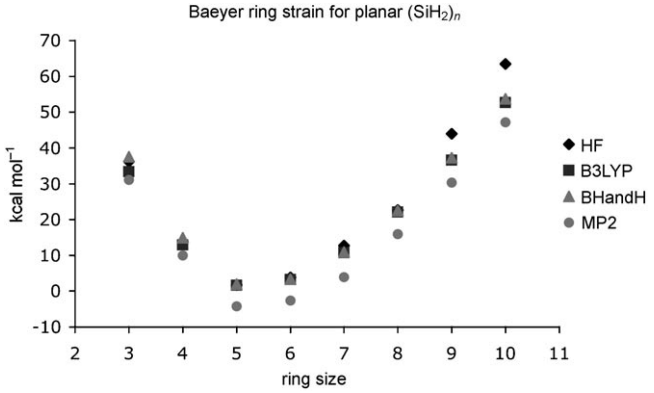


Figure 2. Baeyer (angle) ring strain for planar $(SiH_2)_n$ rings as computed by the BSE equation $nSi_2H_6 \rightarrow nSiH_4 + (SiH_2)_n$ (see Table 3 in the Supporting Information). Si–H bonds are partially ionic and silicon does not rehybridize when the ring bond angles are deformed. Hence, the strain of small silicon rings follows Baeyer's expectation.

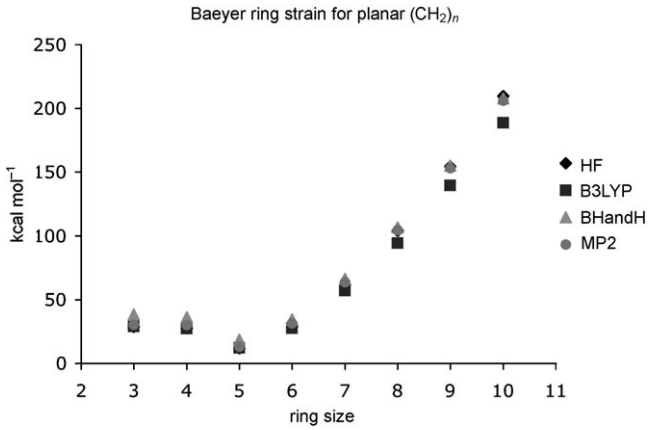


Figure 3. Baeyer ring strain for planar $(CH_2)_n$ rings, as computed by the BSE equation, $n\ C_2H_6 \rightarrow n\ CH_4 + (CH_2)_n$ (see Table 3 in the Supporting Information). Note the marked deviation of cyclopropane from Baeyer's expectations and from the behavior of trisilacyclopropane (Figure 2).

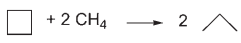
However, the left side of the corresponding graph (Figure 3) for planar carbon rings is quite different, as the strain energy of cyclopropane is much less than expected on the basis of its 60° CCC angles and eclipsed vicinal C–H interactions. Stabilization by σ-aromaticity is responsible for the abnormal behavior of cyclopropane.[76,83,89,90]

HF, B3LYP, and MP2 computations with the 6-311++G(d,p) basis set show all three methods perform well for cyclopropane (Table 3). The nearly equal energy computed by these three methods leads us to conclude that protobranching in cyclopropane is small or nonexistent.

The evaluation of the cyclobutane strain energy and its protobranching are problematic. While there are four CH_2 groups, only two unique 1,3-alkyl–alkyl cross-ring (protobranching) interactions are present.[84–86] The conventional homodesmotic evaluation, Equation (5) (Scheme 1), overestimates the strain since there are four propanes (each stabilized by one protobranch) on the left side; the 5.66 kcal mol^{-1} correction applied to Equation (12), which balances the two cross ring 1,3-interactions in cyclobutane with two propane molecules, results in a cyclobutane strain energy of 21.0 kcal mol^{-1}. The BSE Equation (13) gives 15.4 kcal mol^{-1} using experimental data, but underestimates the strain due to the presence of the stabilizing protobranching in cyclobutane.

Table 3. Strain energies of cyclopropane based on the BSE Equation (11). E_0 (the electronic) and ZPE/Thermal energies (the scaled zero-point and thermal corrections to 298 K) are in kcal mol^{-1}. The 6-311++G(d,p) basis set was employed uniformly.

Level	E_0	ZPE/thermal	E_0 + ZPE/thermal
HF	−24.65	4.28	−20.37
B3LYP	−23.15	4.16	−18.99
MP2	−23.43	4.15	−19.28
experiment			−19.19



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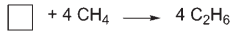


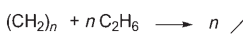
(13)

The data in Table 4 analyze protobranching in cyclobutane by computing the BSE at HF, B3LYP, and MP2 theoretical levels. In contrast to the BSE of cyclopropane, not all methods perform the same for cyclobutane, the behavior is similar to that of other linear and branched alkanes (see Table 2). We therefore conclude that cyclobutane is stabilized by protobranching interactions.

Table 4. Cyclobutane BSE evaluations of Equation (13) (in kcal mol^{-1}). E_0 is the electronic energy. ZPE/thermal is the scaled zero-point vibrational and thermal corrections to 298 K.

	E_0	ZPE/thermal	E_0 + ZPE/thermal
HF/6-311++G(d,p)	−22.53	4.46	−18.06
B3LYP/6-311++G(d,p)	−20.86	4.32	−16.54
MP2/6-311++G(d,p)	−19.25	4.55	−14.70
experiment			−15.38

The conventional (homodesmotic) strain energies of the cycloalkanes are evaluated in Equation (14). With the exception of cyclopropane and cyclobutane (discussed above), this assessment balances protobranching on the left and right sides of the equation. Thus, the six protobranches of cyclohexane are mirrored by the six protobranches in the six propane molecules. The isodesmic BSE, Equation (15), is not protobranching balanced and gives the total stabilization or destabilization inherently present within the molecule being evaluated. Thus, on the basis of methane and ethane [Eq. (15)], cyclohexane (BSE −16.53 kcal mol^{-1}) is highly



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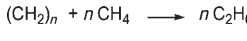

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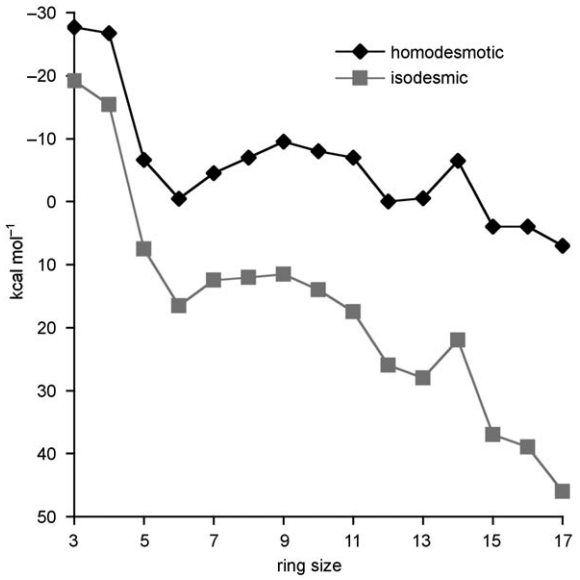
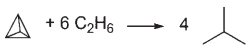


Figure 4. Comparison plots (derived from George et al.),[41] based on experimental data) of the energies (in kcal mol^{-1}) given by the homodesmotic [Equation (14), ◆) and isodesmic reactions [Equation (15), ■], as a function of cycloalkane ring size.

stabilized. The differences in these definitions have been discussed in detail by George et al.,[41] and are clearly shown in Figure 4.

Tetrahedrane, cubane, dodecahedrane, norbornane, adamantane, and tetramethyladamantane also illustrate the importance of protobranching on the strain evaluation. Despite the very large conventionally estimated strain energy of 136.3 kcal mol^{-1} [Eq. (16)],[87,88] large diatropic NICS values in the center indicate that tetrahedrane is α-aromatic.[89,90] Like cyclopropane, tetrahedrane is devoid of protobranching. Hence, the strain energy, based on the conventional CH group increment [Eq. (16)], is overestimated by 30.9 kcal mol^{-1}. While the BSE tetrahedrane strain energy, 105.4 kcal mol^{-1} [Eq. (17)], is still large, it is far less than that expected on the basis of the extreme bond angle deformations.



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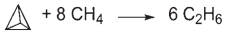
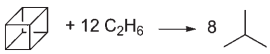


(17)

Cubane has 12 1,3-alkyl–alkyl interactions, counting two for each face. This is half the number present in eight isobutane molecules. Thus, the homodesmotic strain evaluation of 164.8 kcal mol^{-1}, given by Equation (18) is overestimated by ca. 30 kcal mol^{-1}.[91] On this basis, Equation (19) uses twelve protobranches in isobutane to balance the protobranching in cubane, and the strain is reduced to 133.9 kcal mol^{-1}. However, the isodesmic BSE [Eq. (20)] finds the total destabilization of cubane to be only 102.9 kcal mol^{-1}.



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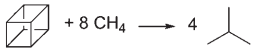

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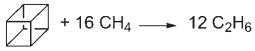
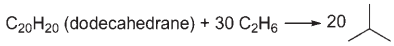


(20)

Dodecahedrane has 60 1,3-alkyl–alkyl interactions, five for each of the 12 faces (or three for each of the 20 vertexes). The homodesmotic strain estimate, 58.4 kcal mol^{-1} [Eq. (21)], is based on 20 isobutane reference molecules, but each of these is stabilized substantially (7.73 kcal mol^{-1}, Table 1) by protobranching. Since about 30 kcal mol^{-1} of the conventional strain energy can be ascribed to the 30 eclipsed vicinal C–H interactions, the "neglect of protobranching" error can easily account for the remainder. Indeed, the isodesmic BSE, Equation (22), shows dodecahedrane to be stabilized by 96.2 kcal mol^{-1}, relative to methane and ethane! This value is similar to the sum of the stabilization energies of 12 cyclopentanes computed by BSE (cf. Figure 4).



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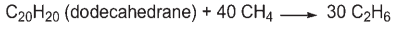
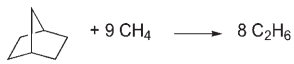


(22)

Similarly, the strain energy of norbornane can be evaluated by the homodesmotic Equation (23), which matches each of the six isobutane-like and the five propane-like protobranching interactions, a strain of 15.8 kcal mol^{-1} results. However, if one considers the isodesmic Equation (24), norbornane is stabilized by 13.8 kcal mol^{-1} as a result of protobranching interactions.

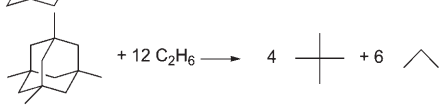
(23)



(24)

Equations (25) and (26) show the conventional homodesmotic analysis of strain in adamantane and tetramethyladamantane. However, the reference propane, isobutane, and neopentane are greatly stabilized by protobranching. Thus, the isodesmic BSE value [Eqs. (27) and (28)] show both cages to be strongly stabilized. BSE evaluations at HF, B3LYP, and MP2 levels show the underestimation of the branching stability by DFT in adamantane and tetramethyladamantane (Table 5).

(25)



(26)

(27)

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Table 5. BSE evaluations of Equations (17), (20), (22), (24), (27) and (28) (in kcal mol^{-1}). E_0 is the electronic energy. ZPE/Thermal is the scaled zero-point vibrational and thermal corrections to 298 K.

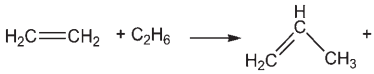
	E_0	ZPE/thermal	E_0 + ZPE/thermal
tetrahedrane [based on Equation (17)]			
HF/6-311++G(d,p)	−126.97	14.70	−112.27
B3LYP/6-311++G(d,p)	−117.07	14.68	−102.39
MP2/6-311++G(d,p)	−123.45	15.73	−107.72
cubane [based on Equation (20)]			
HF/6-311++G(d,p)	−137.93	22.59	−115.34
B3LYP/6-311++G(d,p)	−127.20	22.71	−104.49
MP2/6-311++G(d,p)	−126.18	24.60	−101.58
experiment			−102.9
dodecahedrane [based on Equation (22)]			
HF/6-311++G(d,p)	2.80	43.80	46.60
B3LYP/6-311++G(d,p)	13.40	43.33	56.73
MP2/6-31G(d)	–	–	–
experiment			96.2
norbornane [based on Equation (24)]			
HF/6-311++G(d,p)	−6.04	8.36	2.32
B3LYP/6-311++G(d,p)	−4.07	8.31	4.24
MP2/6-311++G(d,p)	7.31	9.09	16.40
experiment			13.82
adamantane [based on Equation (27)]			
HF/6-311++G(d,p)	11.04	12.35	23.39
B3LYP/6-311++G(d,p)	13.29	11.80	25.09
MP2/6-311++G(d,p)	33.52	13.50	47.02
experiment			42.10
tetramethyladamantane [based on Equation (28)]			
HF/6-311++G(d,p)	19.44	16.44	35.88
B3LYP/6-311++G(d,p)	24.36	15.16	39.52
MP2/6-31G(d)	61.63	17.27	78.99
experiment			69.38

We have recently analyzed hyperconjugation using isodesmic (non-BSE) equations and by describing the virtual states where the hyperconjugative interactions in 1-butene and 1-butyne were absent.[13] However, the equations employed did not compensate for protobranching. To illustrate, Equation (9) can be derived conceptually in a different way by adding Equation (1) and (31).

Equation (31) gives the revised isodesmic BSE value for alkene hyperconjugation directly. Similarly, Equation (32) applies to alkyne hyperconjugation. Both these BSE-based values assume that no protobranching corrections are needed for propyne (readily understood in view of the 180° bond angle and the C(1)–C(3) distance) and for propene (which is more problematic).

Does propene (or other olefins) have stabilizing protobranching type 1,3-interactions? The bond separation energies (BSE) at HF, B3LYP, and MP2 with the 6-311++G(d,p) basis set are given for propene in Table 6, for propane in Table 2, and for cyclopropane in Table 3. Note that the B3LYP versus MP2 BSE difference of propene (0.19 kcal mol^{-1}) is nearly the same as the 0.29 kcal mol^{-1} of cyclopropane (which has no protobranching) rather than the 1.19 kcal mol^{-1} BSE difference in propane (which has protobranching. Hence, we do not employ a protobranching correction for 1,3 CH_n–C=C. Instead, we assume that the hyperconjugation energies, which benefit from $\pi \rightarrow \sigma^*_{CH_3}$ as

+ 18 CH_4 ⟶ 16 C_2H_6 69.4 kcal mol^{-1} (28)



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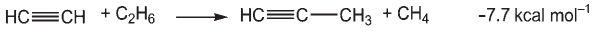
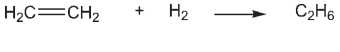


(32)

The effect of protobranching on hyperconjugation and conjugation energy estimation: Mulliken's concept of hyperconjugation[7,8] is described as the stabilization resulting from the interaction of the low lying π* orbital of an olefin with an occupied orbital of an alkyl substituent having correct symmetry. The conventional evaluations of the energies of hyperconjugation (Scheme 1) are based on comparisons of the differences in heats of hydrogenation of alkenes with ethene and alkynes with ethyne.[92] Thus the sum of Equation (29) and (30) (given directly by Equation (9), −2.7 kcal mol^{-1}) is the commonly quoted value for the hyperconjugation stabilization by a methyl (or other alkyl group) on a CC double bond. A similar procedure gives Equation (10) for alkynes. We now argue that the values derived from Equations (9) and (10) are too low since the reference compound in both these equations, propane, is stabilized by protobranching.



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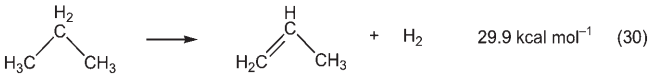

(30)

Table 6. BSE analysis of propene. The E_0 (electronic) and the ZPE/thermal (scaled zero-point vibrational and thermal corrections to 298 K) are in kcal mol^{-1}. All computations used the 6-311++G(d,p) basis set.

	propene + methane → ethene + ethane		
Level	E_0	ZPE/thermal	E_0 + ZPE/thermal
HF	3.74	0.54	4.28
B3LYP	4.70	0.50	5.20
MP2	4.99	0.40	5.39
experiment			5.53

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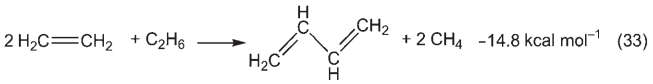
well as Mulliken's $\pi^* \leftarrow \sigma_{CH_3}$ stabilization, includes nearly all 1,3 contributions. Consequently, we do not apply explicit protobranching corrections to the C=C−C moieties of olefins. As an illustration, we assume cyclohexene to have two hyperconjugation and four protobranching interactions.

The homodesmotic Equations (7) and (8) (Scheme 1) have been used, in effect, to evaluate the conjugation stabilization in 1,3-butadiene[93] and 1,3-butadiyne.[45] In our view, such equations are inappropriate to evaluate conjugative stabilization,[13] as hyperconjugation is present in the reference olefins (and acetylenes) on the left side but is not compensated on the right. Furthermore, both 1-butene and 1-butyne (used in Equations (7) and (8) as reference molecules) also contain a single protobranching interaction. Despite suffering from problems associated with changes in hybridization (see above), isodesmic BSE Equations (33) and (34) provide unbiased evaluations of the conjugation energies of 1,3-butadiene (14.8 kcal mol^{-1}) and 1,3-butadiyne (15.1 kcal mol^{-1}). However, as a result of the large bond energy differences between C(sp)–C(sp) and C(sp^3)–C(sp^3) bonds ($\approx$6 kcal mol^{-1}),[46] we have augmented this value by an additional 12 kcal mol^{-1}. Thus the conjugation of 1,3-butadiyne (27.1 kcal mol^{-1}) is roughly twice the conjugation energy of 1,3-butadiene (14.8 kcal mol^{-1}).



Block-localized wave function: The block-localized wave function (BLW) method of Mo et al.[94,95] is an entirely different approach to quantify the effect of electron delocalization in unsaturated systems. BLW is closely associated with valence bond (VB) theory and can be employed at practicable DFT levels. The wave function of the major contributor to a resonance hybrid, for example, a localized, non-conjugating cyclohexatriene, can be optimized self-consistently. In effect, BLW "turns off" the π conjugation in butadiene, the hyperconjugation in propene, and the aromaticity in benzene, but allows the σ framework to relax optimally. BLW thus affords a considerable conceptual advantage over conventional delocalization energy assessments using thermochemical data and isodesmic or homodesmotic reactions. Such reactions attempt to approximate a virtual Lewis structure (the most stable resonance structure), in which the effects of electron delocalization are absent, as a composite of non-delocalized model reference compounds. As an illustration, the BSE Equation (31) is not balanced with regard to the number of C(sp^2)−X and C(sp^3)−X bonds (X = H or C), but the BLW method applied to propene does not have this fault. The difference between the BLW and Kohn–Sham (KS) wave functions of the same compound gives the resonance energy (following the Pauling–Wheland definition) directly. The BLW method already has been applied to many molecules,[12,18,32,95–101] including the evaluation of the hyperconjugation of propene and the aromaticity of benzene.

The validity of our revised hyperconjugation energy of propene, and other molecules, is substantiated by the BLW method. For propene, the delocalized (KS) and localized (BLW) wave functions can be expressed as

$$\Psi(\mathrm{del}) = \hat{A}(\sigma 1a''^2 2a''^2)$$

and

$$\Psi(\mathrm{loc}) = \hat{A}(\sigma' \pi^2_{C=C} \pi^2_{CH_3})$$

where $\pi_{C=C}$ and π_{CH_3} are group orbitals expanded in CH_2=CH and CH_3 groups, and are nonorthogonal. In contrast, canonical MOs 1a″ and 2a″ are delocalized for the whole system and orthogonal. The energy difference between these two wave functions, which are independently optimized self-consistently, represents the vicinal interaction between the π double bond and the adjacent methyl group, or more simply the hyperconjugation of the methyl group. Using the Gamess pVTZ basis set[102–104] the adiabatic hyperconjugation energy of propene is estimated to be −6.3 kcal mol^{-1} at the B3LYP level, agreeing well with the −5.5 kcal mol^{-1} obtained in Equation (32). BLW gives values of −12.4 kcal mol^{-1} for propyne, agreeing well with the Pople isodesmic BSE energy after correction for hybridization imbalance (−13.7 kcal mol^{-1}). Furthermore, the BLW values for 1,3-butadiene (−12.7 kcal mol^{-1}) and 1,3-butadiyne (−27.8 kcal mol^{-1}) also closely match our corrected BSE values, −14.8 and −27.1 kcal mol^{-1}, respectively. The pronounced differences between the uncorrected BSE (−15.1 kcal mol^{-1}) and BLW (−27.8 kcal mol^{-1}) diyne estimates (see summary Table 7 in the Conclusions) likely arises from carbon hybridization differences when employing isodesmic bond separation reactions. We argue that BLW treatments offer the most accurate unbiased energy assessment.

Protobranching and aromatic resonance (RE) and stabilization energies (ASE): Kistiakowsky's seminal evaluation of the resonance energy of benzene [Eq. (37, Scheme 2][93] has been criticized,[12] and now has only well deserved historical importance. His 36 kcal mol^{-1} value,[93] based on the heats of hydrogenation of benzene and cyclohexene, is badly flawed, since the three reference cyclohexenes on the right side are stabilized considerably by hyperconjugation (a concept unknown at that time), for which there is no compensation on the left side. Consequently, the RE of benzene must be nearly twice as large as Kistiakowsky's 36 kcal mol^{-1} value[12] (note the corrected −69.0 kcal mol^{-1} RE$_c$ in Scheme 2).

Many model reactions (isodesmic, homodesmotic, etc.) have been used to estimate the total resonance energy (RE) as well as the ASE, "aromatic" stabilization energy (greater than the stabilization solely due to conjugation) of benzene.[12,105,106] According to Pauling and Wheland, resonance energy is defined as the difference between the actual

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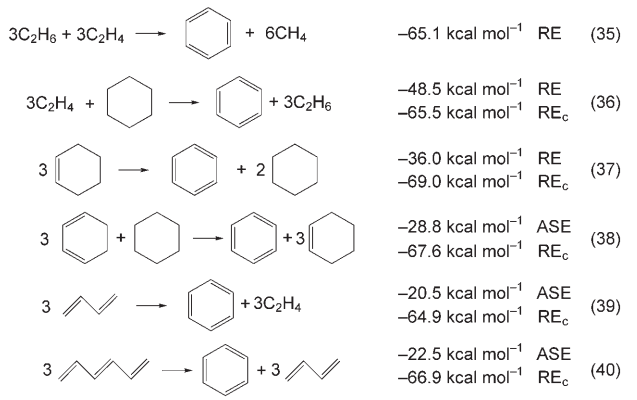

Scheme 2. Equations that have been employed in the literature to evaluate the resonance (RE) and aromatic stabilization energies (ASE) of benzene using experimental data.[106] The RE_c values have been corrected for the perturbing effects of protobranching, hyperconjugation, and conjugation (see text). Note that all the RE_c values are nearly the same.

energy of a molecule and the virtual energy of the most stable resonance contributor.[107–111] Since the real reference molecules chosen to approximate the virtual energy of a non-resonating cyclohexatriene are never free from other stabilizing or destabilizing interactions, these perturbing features ("contaminations") should be balanced in the defining equations as completely as possible. Unfortunately, the RE values from Equations (36–40) in Scheme 2 do not correct for the stabilization from conjugation, hyperconjugation, and protobranching interactions. The corresponding RE_c values include these corrections.

The set of ASE evaluations [Equations (38–40), Scheme 2], were devised to evaluate the extra benzene RE relative to conjugated but non-aromatic reference molecules.[106] Suitable corrected, these equations may also serve to evaluate the total resonance energy (RE_c) of benzene. Remarkably, when the hyperconjugation, protobranching, and conjugation present in the reference molecules (see Scheme 2 and Figure 5) are considered, the various aromaticity evaluations [Eqs. (35–40)] yield surprisingly consistent resonance energies! Unlike the 51 kcal mol^{-1} uncorrected range discussed by Cyranski,[106] the RE_c values in Scheme 2 range by only 4.1 kcal mol^{-1}, from 64.9 to 69.0 kcal mol^{-1}!

The isodesmic BSE [Eq. (35) of Scheme 2, RE = −65.1 kcal mol^{-1}] falls within this range, suggesting that no hybridization correction (see above) is necessary. Six protobranching corrections have been used to correct Equation (36) to the −65.5 kcal mol^{-1} RE_c value, but protobranching is balanced or not present in the other equations. Hyperconjugation is balanced in Equation (38) but six corrections are applied to Kistiakowsky's original Equation (37)[93] to give the −69.0 kcal mol^{-1} RE_c of benzene. Equations (38–40) were devised to estimate the ASE of benzene, but also can be used, after correction for the conjugation in the reference compounds (see Table 6 and the Supporting Information), to assess the corresponding RE_c values in Scheme 2.

Clearly contributions from conjugation, hyperconjugation, and protobranching should be considered when evaluating resonance energies. After correcting for these effects, the inconsistencies in RE's given by Equations (35–40) and those discussed by Cyranski[106] largely vanish (Figure 5 and the RE_c values in Scheme 2).

Dewar's original definition of the benzene aromatic stabilization energy (ASE), Equation (39) in Scheme 2, is intended to estimate the extra resonance energy due to the cyclic electron delocalization.[48] However, benzene only has *syn* conformations, which, for 1,3-butadiene, are 3.0 kcal mol^{-1} higher in energy than the *anti* conformations. Equation (38), employing 1,3-cyclohexadiene as the reference, removes the *syn*/*anti* discrepancy (as well as balances all protobranching and hyperconjugation interactions) and results in our recommended ASE value of −28.8 kcal mol^{-1}. This value may be compared with the recent mathematical derivation of Dewar resonance energy, 32.7 kcal mol^{-1}, obtained by Fishtik and Datta.[112]

Conclusion

Protobranching is a simple concept with remarkably broad, paradigm-shifting implications for energy evaluations in organic chemistry. Protobranching extends the well-established concept of branching stabilization (e.g. in isobutane and neopentane) to *n*-alkanes and to cycloalkanes. The consequences for energetic analysis are fundamental: *n*-alkanes larger than ethane (as well as cyclohexane) no longer can be considered to be ideal "strain-free" unbiased reference molecules. They benefit from considerable stabilization not pres-

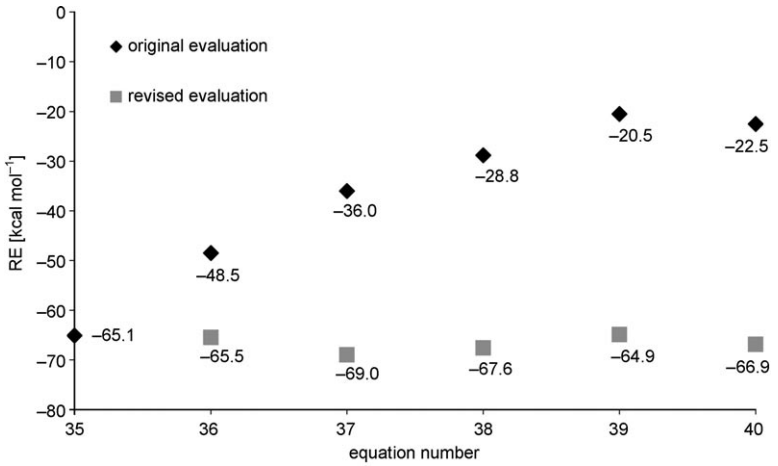

Figure 5. Original RE and ASE values compared with the corrected RE_c values for Equations (35–40) in Scheme 2.

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ent in methane and ethane. All "perturbing" interactions, other than the one of interest, should be balanced in reference molecules, but this is not realized in larger systems. Unblemished energetic analysis requires the elimination of all contaminants, either stabilizing or destabilizing, in reference molecules.[113] Despite suffering from some hybridization differences, this is achieved better by isodesmic BSE treatments (rather than by homodesmotic equations), which employ simple molecules as references (methane, ethane, ethene, etc.). These reference molecules lack perturbing effects (e.g., conjugation, hyperconjugation, and strain, as well as protobranching) and provide an unbiased and uniquely defined standard by which to judge energies. When protobranching is not considered, incomplete and potentially misleading energetic analyses result.

The use of isodesmic equations reduces the conventional (homodesmotic) strain energy of cyclopropane from 27.7 to 19.2 kcal mol^{-1}, and also reduces the conventional ring strain estimates of cyclobutane, tetrahedrane, cubane, dodecahedrane, norbornane, adamantane, and tetramethyladamantane considerably.

Protobranching also helps reconcile the seemingly inconsistent values, ranging from 18.4 to 66.9 kcal mol^{-1},[106] for the benzene stabilization energy given by many literature schemes.[106] Agreement is achieved when conjugation, hyperconjugation, and protobranching corrections are applied. Kistiakowsky's classical resonance energy,[93] 36.0 kcal mol^{-1}, is underestimated due to the neglect of hyperconjugation. For benzene, we recommend the RE = −65.1 kcal mol^{-1} based on the bond separation energy [Eq. (35)] and the ASE = 28.8 kcal mol^{-1} based on Equation (38). The block-localized wave function (BLW) method,[12] which compares the energy of a real molecule with that of its most stable localized resonance hybrid, provides alternative estimates (Table 7). For benzene, [65.4 (RE) and 25.7 (ASE) kcal mol^{-1}] these are nearly identical with our recommendations above.

When protobranching is taken into account, the conventional hyperconjugative stabilization of an alkene by an alkyl group more than doubles, from 2.5 to 5.5 kcal mol^{-1}. The BLW value is 6.3 kcal mol^{-1}. The alkyne alkyl group hyperconjugation increases from 5.0 to 7.7 kcal mol^{-1}, based on BSE; the BLW value is even larger (12.4 kcal mol^{-1}). Consideration of protobranching increases diene conjugation energy from 3.7 to 14.8 kcal mol^{-1} (BLW 12.7 kcal mol^{-1}) and that for diynes from 0.2 to 15.1 kcal mol^{-1} (27.1 kcal mol^{-1} after correction for C–H hybridization imbalance, see above). BLW gives 27.8 kcal mol^{-1}. Table 7 summarizes our major thermochemical and BLW evaluations with the conventional values.

Table 7. Summary of conventional, revised, and BLW-B3LYP/pVTZ energy evaluations of strain, hyperconjugation, conjugation, and benzene aromaticity (kcal mol^{-1}).

Property	Conventional evaluation	Revised evaluation (based on BSE)	BLW evaluation
ring/cage strain			
cyclopropane	27.7	19.2	–
cyclobutane	26.7	21.0[a]	–
tetrahedrane	136.3	105.4	–
cubane	164.8	102.9[a]	–
hyperconjugation			
propene	2.7	5.5	6.3
propyne	4.9	7.7 (13.7)[b]	12.4
conjugation			
butadiene	3.7	14.8	12.7
butadiyne	0.0	15.1 (27.1)[b]	27.8
aromaticity of benzene			
ASE	20.5	28.8	25.7[12]
RE	36.0	65.1	65.4

[a] Corrected for protobranching; see text. [b] Corrected for C(sp) to C-(sp^3)–H hybridization imbalance.

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