1-Methoxy-5-(trimethylsilyl)-1,4-pentadiyne (3f). To a stirred solution of 3.25 g of (trimethylsilyl)acetylene (33.0 mmol) in 90 mL of dry THF were successively added, at -40 °C, 19.3 mL of *n*-butyllithium in *n*-hexane (1.55 M), 5.37 g of HMPT (30.0 mmol), and 4.30 g of copper(I) bromide (30.0 mmol). The temperature of the reaction mixture was allowed to rise to -5 °C, at which temperature stirring was continued for 15 min. To the resulting clear solution was added 5.88 g of **1** (30.0 mmol), followed by stirring for 3.5 h at +25 °C. The product was isolated as described for compounds **3a–e**. Distillation of the crude product gave 3.74 g of pure material: bp 90–91 °C (19 mmHg); $n^{20}{}_{D}$ 1.4630; IR 950, 1250, 2180, 2290 cm^{-1}; NMR (CCl_4) δ 0.15 (s, 9 H), 3.08 (s, 2 H), 3.92 (s, 3 H); mass spectrum, *m/e* 166 ($M^{+}\cdot$).

1-Methoxy-6-methyl-6-heptene-1,4-diyne (3g). To a stirred solution of 2.18 g of isopropenylacetylene (33.0 mol) in 100 mL of dry Me_2SO were successively added, at +20 °C, 3.48 g of TMED (30.0 mmol), 19.3 mL of *n*-butyllithium in *n*-hexane (1.55 M), and 4.30 g of copper(I) bromide (30.0 mmol). After the solution was stirred for 15 min at +20 °C, 5.88 g of **1** (30.0 mmol) was added; this was followed by stirring for 1.0 h at +20 °C. The crude product was isolated as described for compounds **2a–e**. Distillation gave 3.42 g of pure material: bp 44–45 °C (0.5 mmHg); $n^{20}{}_{D}$ 1.4920; IR 955, 1248, 1615, 2280 cm^{-1}; NMR (CCl_4) δ 1.82 (d, 3 H), 3.12 (s, 2 H), 3.85 (s, 3 H), 5.05–5.27 (m, 2 H); mass spectrum, *m/e* 134 ($M^{+}\cdot$).

1-Methoxy-1,4-nonadiyne (3h). To a stirred solution of 2.70 g of 1-hexyne (33.0 mmol) in 100 mL of dry Me_2SO were successively added, at +20 °C, 3.48 g of TMED (30.0 mmol), 1.93 mL of *n*-butyllithium in *n*-hexane (1.55 M), and 2.15 g of copper(I) bromide (15.0 mmol). After the reaction mixture was stirred for 15 min at +20 °C, 5.88 g of **1** (30.0 mmol) was added. The resulting reaction mixture was stirred for 3.0 h at +25 °C. The product was isolated following the procedure given for **3a–e**. Distillation gave 3.20 g of pure material: bp 57–58 °C (0.5 mmHg); $n^{20}{}_{D}$ 1.4660; IR 955, 1245, 2270 cm^{-1}; NMR (CCl_4) δ 0.91 (t, 3 H), 1.18–1.65 (m, 4 H), 2.09 (tt, 2 H), 2.91 (t, 2 H), 3.80 (s, 3 H); mass spectrum, *m/e* 150 ($M^{+}\cdot$).

Registry No. 1, 72610-28-7; **2a**, 60101-72-6; **2b**, 60101-89-5; **2c**, 60101-70-4; **2d**, 72610-03-8; **2e**, 72610-01-6; **2f**, 72610-00-5; **2g**, 72609-99-5; **2h**, 72609-98-4; **3a**, 72610-29-8; **3b**, 72610-30-1; **3c**, 72610-31-2; **3d**, 72610-32-3; **3e**, 72610-33-4; **3f**, 72610-34-5; **3g**, 72610-35-6; **3h**, 72610-36-7; **4a**, 72610-37-8; **4b**, 72610-38-9; **5a**, 72610-39-0; **5b**, 72610-40-3; methoxypropadiene, 13169-00-1; (trimethylsilyl)acetylene, 1066-54-2; isopropenylacetylene, 78-80-8; 1-hexyne, 693-02-7.

Empirical Force-Field-Extended Hückel Molecular Orbital Conformational Analysis of 1-Phenyl-3,3-dimethylbutane

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One of the principal goals of empirical force-field (EFF) calculations is the computation of both reliable molecular geometries and relative conformational energies. By use of numerous currently available force fields, the former goal can, in general, be readily accomplished while the latter goal is not as often attainable.[1,2] The recent combination of empirical force-field (EFF) and extended Hückel molecular orbital (EHMO) calculations, generating a hybrid (EFF–EHMO) method, has been successfully utilized for the calculation of relative orders of conformational energies.[1,2]

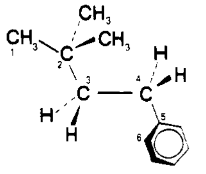

Figure 1. Numbering scheme for 3.

We had previously calculated the geometries and conformational energies of bibenzyl (**1**) and of 1,2-diphenylpropane (**2**), employing the EFF program BIGSTRN.[3] Both **1** and **2** are known, experimentally, to exist predominantly in the phenyl–phenyl anti conformation,[4,5] yet the EFF calculations indicate that both molecules prefer a phenyl–phenyl gauche conformation.[3] The hybrid method (EFF–EHMO)[6] reverses the EFF conclusions and, further, provides conformational energies in qualitative agreement with the experimental results.[1,3,5]

1-Phenyl-3,3-dimethylbutane (**3**), a compound whose conformational analysis was originally reported by Whitesides and co-workers,[7] was the key compound in the exposition of the stereochemistry of the hydroboration–protonation reaction sequence.[8] This reaction was demonstrated to proceed in a predominantly overall cis fashion, i.e., (*E*)-1-phenyl-3,3-dimethyl-1-butene [(*E*)-**4**], upon reaction with BD_3 and acetic acid-d_4, yielded *threo*-1-phenyl-3,3-dimethylbutane-*1,2*-d_2 (*threo*-**3**-d_2); the corresponding *Z* diastereomer [(*Z*)-**4**] yielded the erythro diastereomer (*erythro*-**3**-d_2). The deuterium-decoupled proton spectra of *threo*-**3**-d_2 and *erythro*-**3**-d_2 exhibit vicinal proton–proton coupling constants ($^3J_{HH}$) of 12.5 and 5.0 Hz, respectively, at 30 °C in neat solution.[9] From the temperature dependence of the vicinal coupling constants of **3** the energy difference between the anti and gauche conformers was determined to be 1.70 ± 0.09 kcal/mol in CCl_4 solution, the anti conformer being favored.[7]

Thus, **3** appears to be an excellent candidate to further test the hybrid conformational energy approach (EFF–EHMO). The starting geometries for EFF energy minimization are presented in Table I, as are the final geometries and relative conformational energies. The following dihedral angles are required to define a single conformation of **3**: the 1234 angle, the 2345 angle, and the 3456 angle (Figure 1). A complete description of any of these conformers would require description of the dihedral angle made by the protons of the *tert*-butyl methyl groups with respect to the contiguous carbon atom and atoms 2 and

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(1) D. A. Dougherty and K. Mislow, *J. Am. Chem. Soc.*, **101**, 1401 (1979).

(2) (a) D. A. Dougherty, K. Mislow, J. W. Huffman, and J. Jacobus, *J. Org. Chem.*, **44**, 1585 (1979); (b) S. G. Baxter, H. Fritz, G. Hellman, B. Kitschke, H. J. Linder, K. Mislow, C. Ruchardt, and S. Weinter, *J. Am. Chem. Soc.*, **101**, 4493 (1979).

(3) (a) J. Jacobus, *Tetrahedron Lett.*, 2927 (1976). (b) The program BIGSTRN is available from the Quantum Chemistry Program Exchange, Department of Chemisty, Indiana University, Bloomington, IN 47401.

(4) For bibenzyl, see: K. K. Chiu, H. H. Huang, and L. H. L. Chia, *J. Chem. Soc., Perkin Trans. 2*, 286 (1972); A. M. North, R. A. Pethrick, and A. D. Wilson, *Spectrochim. Acta, Part A*, **30**, 1317 (1974).

(5) For 1,2-diphenylpropane, see: S. L. Spassov, A. S. Orahovats, S. M. Mishev, and J. Schraml, *Tetrahedron*, **30**, 365 (1974); ref 3a.

(6) The extended Hückel program [R. Hoffmann, *J. Chem. Phys.*, **39**, 1397 (1963)] employed was EXTHUC, available from the Quantum Chemistry Program Exchange, Department of Chemistry, Indiana University, Bloomington, IN 47401.

(7) G. M. Whitesides, J. P. Sevenair, and R. W. Goetz, *J. Am. Chem. Soc.*, **89**, 1135 (1967).

(8) G. W. Kabalka, R. J. Newton, Jr., and J. Jacobus, *J. Org. Chem.* **44**, 4185 (1979).

(9) For **3** in CCl_4 solution Whitesides and co-workers[7] report $^3J_{HH}$'s of 13.7 and 4.2 Hz. These data were obtained by iterative calculations on the AA′XX′ spin system exhibited by **3**. The dependence of these coupling constants on solvent is expected to be small;[7] the coupling constants reported herein were obtained directly.[8]

Table I. Geometries and Energies for 3

	dihedral angles, deg						rel energies, kcal/mol	
	starting			final				
	1234	2345	3456	1234	2345	3456	EFF	EFF-EHMO
anti-A	180	180	90	179.7	179.6	−89.6	0.00	0.00
anti-B	180	180	0	179.7	179.9	0.0	0.94	1.59
anti-C	0	180	90	0.6	−179.9	−90.8	3.79	4.11
anti-D	0	180	0	−0.1	180.0	0.0	4.74	5.97
gauche-A	180	60	90	−168.6	−66.2	−65.8	0.35	2.58
gauche-B	180	60	0	−172.4	−66.2	−51.2	0.43	2.52
gauche-C	0	60	90	−164.1	−62.7	−57.9	0.40	2.72
gauche-D	0	60	0	−163.7	−62.7	−57.6	0.42	2.91

3 as well as all of the bond angles and bond lengths of the molecule.

Although all four initial geometries for the anti conformers of 3 lead to unique conformational species, all four initial geometries for the gauche conformers converge, in essence, to a single conformer. The minimum-energy anti conformer is represented in Figure 1; it is that conformer with one of the methyl groups of the *tert*-butyl group anti to C(4) and with the plane of the benzene ring perpendicular to the C(3)–C(4) bond.

The EFF calculations indicate that any of the gauche conformers is more stable than any anti conformer other than anti-A (Table I), the energy difference between anti-A and any gauche conformer being ≤0.43 kcal/mol. If the conformational strain energies are equated to conformational enthalpies and if it is recognized that the gauche conformer is favored with respect to entropy by $R \ln 2$ [there are two equivalent (enantiomeric) gauche conformers for each anti conformer],[10] at the experimental temperature (30 °C) $\Delta G \approx -0.43 - (-RT \ln 2) \approx 0$, implying equal populations of the gauche and anti conformers. Were these conformational energies correct, i.e., were the gauche and anti conformer populations equal, the vicinal coupling constant ($^3J_{HH}$) for the threo d_2 diastereomer would be as shown in eq 1, while that for the erythro d_2

$$^3J_{\text{threo}} = 12.5 \text{ Hz} = (n_1 + n_3)J_g + n_2J_T \quad (1)$$

diastereomer would be as shown in eq 2, where n_1, n_2, and

$$^3J_{\text{erythro}} = 5.0 \text{ Hz} = n_1J_t + (n_2 + n_3)J_g \quad (2)$$

n_3 represent the mole fractions of the phenyl/*tert*-butyl anti, phenyl/*tert*-butyl gauche, and phenyl/*tert*-butyl gauche (enantiomeric) conformers, respectively. Since $\Delta G \approx 0$ and $n_1 \approx 2n_2$ and since $n_2 = n_3$, eq 3 and 4 can be written, where J_t and J_g are the "theoretical" trans and

$$12.5 = 0.75J_g + 0.25J_t \quad (3)$$

$$5.0 = 0.50J_t + 0.50J_g \quad (4)$$

gauche vicinal coupling constants, respectively. The values of J_t and J_g calculated from eq 3 and 4 are 51.8 and −0.6 Hz, respectively; both values are clearly absurd, indicating that the EFF calculations are in error, the conformational energy difference being badly underestimated.

Since, in general, the EFF method provides reliable geometries, the energy-minimized EFF geometries were employed in an extended Hückel molecular orbital calculation with the results presented in Table I. The lowest energy anti conformer from the EFF calculation is also the least energetic by the EHMO calculation. The lowest energy gauche conformer by the EFF method is not the same as that obtained by the EHMO calculation. The energy difference between the least energetic anti and gauche conformers is computed as 2.52 kcal/mol. Correction for the entropy of mixing leads to a conformational free-energy difference of ca. 2.10 kcal/mol, in favor of the anti conformer, at room temperature, a value in reasonable agreement with the experimental value of 1.70 ± 0.09 kcal/mol.

One feature of the EFF–EHMO calculations is noteworthy; two anti conformers of 3 (anti-A and anti-B) are lower in energy than any gauche conformer, in contrast to the EFF calculation in which only anti-A was lower than any gauche conformer. Unfortunately, there is no simple manner to ascertain the validity of this computational prediction.

Calculation of the theoretical values J_t and J_g employing the EFF–EHMO conformer populations and the experimentally determined values of $^3J_{\text{threo}}$ and $^3J_{\text{erythro}}$ yields values of 12.74 and 4.88 Hz, respectively. Employing the temperature-dependent data of Whitesides and co-workers,[7] one finds that the corresponding values are 12.99 and 4.75 Hz, respectively.

The calculated geometries of the minimum-energy anti and gauche conformers indicate relatively minor deformations of the bond angles in proceeding from the anti to the gauche conformation. A priori, it might be expected that angles 234 and 345 would be increased in the gauche conformation relative to the anti conformation. Angle 234 increases from 117.6 to 119.4° while angle 345 increases from 113.5 to 117.8° in the anti to gauche conversion; i.e., the proximity of the *tert*-butyl group to the aromatic ring does distort the molecule. Although more severe distortion might have been anticipated, the increased 2345 dihedral angle (66.2°) is probably responsible for partially alleviating the anticipated nonbonding interactions.

Although the conformational energy difference between the anti and gauche conformers of 3 may be slightly overestimated by the EFF–EHMO method, the net effect on the conformer populations is negligible. The results reported here may be fortuitously accurate; however, we believe that the hybrid method reported here and elsewhere[1,2] provides a useful approach for the computation of relative conformational energies.[11]

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Registry No. 3, 17314-92-0.

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(10) E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis", Interscience, New York, 1966, p 13.

(11) A referee has suggested the need for an explanation of why the EFF gives incorrect results, i.e., the discrepancy in nonbonded, angle bending, etc., terms, and why the EHMO gives a different result, in hopes of modifying the EFF parameters to give "correct" results; we[2a] and others[1] have refrained from presenting such an analysis because of reasons previously cited.[1,2a]