(*ipso*-C), 127.73 (J_{CCCCF} = 1.7 Hz, 2 *o*-C), 128.53 (2 *m*-C), 130.95 (*p*-C), and for the tolyl group 21.71 (Me), 127.90 (*m*-C), 129.90 (*o*-C), 134.38 (*p*-C), 145.88 (*ipso*-C); mass spectrum, *m/e* (relative intensity) 398 (14, M^+), 243 (6, M^+ – Ts) 227 (7, M^+ – TsO); high-resolution mass spectrum 398.0429, calcd for $C_{16}H_{12}F_6O_3S$ 398.0411. Anal. Calcd: C, 48.25; H, 3.04. Found: C, 48.32; H, 3.20.

1-Phenyl-1-methyl-2,2,2-trifluoroethyl tosylate (2):[1a] ^{13}C NMR ($CDCl_3$) δ 18.77 (q, J_{CCCF} = 1.3 Hz, CH_3CCF_3), 87.45 (q, J_{CCF} = 30.5 Hz, CO), 123.36 (q, J_{CF} = 284.4 Hz, CF_3), 127.12 (J_{CCCCF} = 1.1 Hz, 2 *o*-C), 128.34 (2 *m*-C), 129.68 (*p*-C), 135.58 (*ipso*-C) and for the tolyl group 21.62 (Me), 127.46 (*m*-C), 129.82 (*o*-C), 134.69 (*p*-C), 145.01 (*ipso*-C).

1-Phenyl-2,2,2-trifluoroethyl tosylate (1):[1b] ^{13}C NMR ($CDCl_3$) δ 78.13 (q, J_{CCF} = 34.3 Hz, CO), 122.30 (q, J_{CF} = 281.1 Hz, CF_3), 127.92 (2 *o*-C), 128.10 (2 *m*-C), 129.65 (*ipso*-C), 130.24 (*p*-C), and for the tolyl group 21.56 (Me), 128.63 (*m*-C), 129.79 (*o*-C), 132.98 (*p*-C), 145.44 (*ipso*-C).

1-Phenyl-1-(trifluoromethyl)-2,2,2-trifluoroethanol (13): ^{13}C NMR ($CDCl_3$) δ 77.08 (sep, J_{CCF} = 30.0 Hz, CO), 123.02 (q, J_{CF} = 287.0 Hz, CF_3), 126.72 (J_{CCCCF} = 1.5 Hz, 2 *o*-C), 128.80 (2 *m*-C), 129.63 (ipso-C), 130.42 (*p*-C). This spectrum has been reported [19b] and while the spectral data are in agreement our assignments of the ring carbons, which are based on the observed ^{13}C–^1H couplings, are different.

Crystals of the compounds **1**–**4**[1c] were sealed in 0.2–0.3 mm Lindemann capillaries. Precession photographs were used to obtain preliminary cell and symmetry information. Further work on each crystal on an Enraf-Nonuis CAD-4 diffractometer with graphite monochromatized Mo Kᾱ radiation (λ 0.71069 Å) gave the crystal data summarized in Table II. Cell constants were obtained by least-squares refinement of the setting angles of 25 reflections within the θ ranges specified. Conditions used for each data collection are also summarized in Table II. For each reflection backgrounds were measured by extending the scan by 25% on either side of the peak and were measured for half the time taken to collect the peak. During each data collection several standard reflections were periodically checked for crystal and instrument stability. No significant fluctuations were observed.

For each data set, Lorentz and polarization corrections were applied. Averaging symmetry equivalent data and excluding reflections which were either systematically absent or had F_{obsd} = 0.0 gave the final totals of independent reflections shown in Table II.

Each structure was routinely solved by the use of the program MULTAN 11 on a PDP 11/23 computer followed by cycles of least-squares and Fourier calculations to locate any missing atoms in the trial structures. Hydrogen atoms were located in difference Fourier maps or were placed in calculated positions. For each structure, full-matrix least-squares calculations minimizing $\sum w[|F_o| - |F_c|]^2$ have converged to the residuals in Table II. In these final cycles of refinement weights were given by expressions of the form $w = 4F^2[\sigma(I)^2 + (pF^2)^2]^{-1}$ with values for *p* indicated in Table II. Final difference Fourier maps for each structure were featureless. A PDP 11/23 computer and programs in the Enraf-Nonius SDP package were used throughout the refinements. Final positional parameters for all atoms (Table IX), tables of thermal parameters (Table X), and final structure factor amplitudes (Table XI) are deposited as supplementary material.

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Registry No. 1, 13652-13-6; 2, 73572-26-6; 3, 86669-62-7; 4, 86669-60-5; 12, 93923-55-8; 13, 718-64-9; $PhCOCF_3$, 434-45-7; $NaHSO_3$, 7631-90-5; KCN, 151-50-8.

Supplementary Material Available: Complete bond length and bond angle information for 1–4 (Tables III and IV), reported structures of secondary tosylates (Table VI), selected torsion angles and contact distances (Tables VII, VIII), atomic coordinates for 1–4 (Table IX), and thermal parameters (Table X) (20 pages). Structure factor tables available from authors. Ordering information is given on any current masthead.

Specification of Relative Stereochemistry in Bridged Bicyclic and Spirobicyclic Systems

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A system is proposed for the specification of relative stereochemical relationships within bridged, bicyclic systems with three equal length bridges, most notably bicyclo[2.2.2]octanes, in bicyclic arrays with two identical bridges when the third is larger, such as bicyclo[3.2.2]nonanes, and in spirobicyclic compounds. For any bridged, bicyclic array with two equal and one larger or three equal bridges, a numbering scheme is assigned on the basis of an appropriate and convenient nomenclature system. A sense of rotation is then defined for the axis passing through both bridgehead atoms on the basis of the relative numbering of the three bridging atoms attached to bridgehead atom number 1. Then, substituents that are oriented with this sense of rotation are tagged *M* (mit) and those with the opposite orientation are referred to as *G* (gegen). For any spirobicyclic system, the framework atoms are numbered according to classical nomenclature rules (e.g., the smallest bridge is numbered first). The stereochemical positioning of substituents on each ring is then specified to be *M* if they are on the same face of that ring as the lower numbered atom of the other ring while *G* is used for the opposite relationship.

The specification of relative stereochemical relationships within bicyclic systems of both the bridged and spiro kind has represented a significant nomenclature problem that has not as yet been adequately addressed. Difficulties are found with all spirobicyclic systems, while problems are most apparent in bridged bicyclic arrays that have two identical length bridges and where the third is at least the same size or larger (e.g., bicyclo[2.2.2]octanes and bicyclo[3.2.2]nonanes). In response to these needs we have developed a scheme that simplifies such nomenclature problems to the greatest extent possible. We propose its adoption by the organic chemical community at large.

Bridged Bicyclics

While several different systems have evolved independently for the specification of relative stereochemistry

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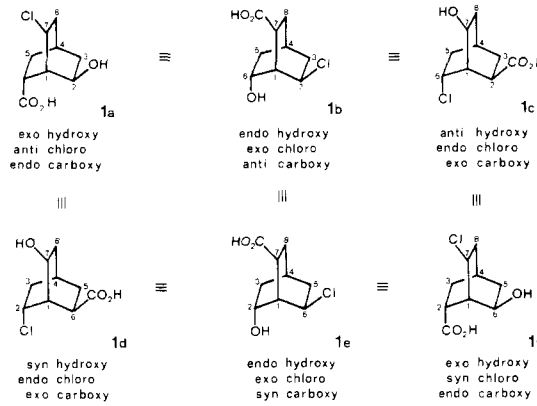

Figure 1.

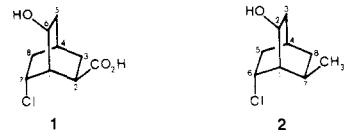

Figure 2.

in bridged systems, all depended on the identification of bridges of lowest and highest priority and specification of stereochemistry as endo/exo and syn/anti, as appropriate. Such systems have a number of disadvantages, not the least of which is that the specification of stereochemical relationships should be definable without regard to substitution patterns on the basis of arbitary assignments of substituent hierarchy. We became keenly aware of these problems during the course of compiling a data bank of ^{13}C NMR spectral data for common bicyclic systems. The problem is most serious with bicyclo[2.2.2]octanes, and we have chosen to illustrate these difficulties with a worst-case example, the chloro hydroxy acid shown in Figure 1. Depending on the assignment of the order of priority of bridges, there are six unique permutations (3*2*1), **1a–1f**.

It is clear that a single, unambiguous name can be assigned from bridge priorities derived from substituent priorities (e.g., $HO_2C > HO > Cl$), and the above ranking of substituents would lead to the name *endo*-6-chloro-*anti*-7-hydroxybicyclo[2.2.2]octane-*endo*-2-carboxylic acid. However, such rankings are notoriously fickle upon substituent transformations and synthetically minor modifications of substituents can lead to reordered rankings that make ready comparisons between starting material and product stereochemistries all but impossible. Thus, reduction of the carboxylic acid function to a methyl group (Figure 2) would result in the ordering $HO > Cl > CH_3$ and the name *exo*-6-chloro-*syn*-7-methylbicyclo[2.2.2]octan-*endo*-2-ol for the resulting compound. Clearly, any comparison of *relative* stereochemical relationships between **1** as endo-2,endo-6,anti-7 and **2** as endo-2,exo-6,syn-7 would be difficult at best.

The problems outlined above result from two factors: (1) modification of the substituents can result in reordering of priorities and (2) there are two, distinct specifiers of stereochemistry (endo/exo and syn/anti). The first is a general consequence of the process of chemical transformation and thus will be an inevitable part of any nomenclature system. However, the second adds unnecessary confusion and the system which we propose below eliminates this factor.

The System

For any bridged, bicyclic array with two equal and one larger or three equal bridges, a numbering scheme is assigned based on an appropriate and convenient nomenclature system. A sense of rotation is then defined for the axis passing through both bridgehead atoms on the basis of the relative numbering of the three bridging atoms attached to bridgehead atom number 1. Then, and quite simply, substituents that are oriented with this sense of rotation are tagged *M* (mit) and those with the opposite orientation are referred to as *G* (gegen). Before proceeding with specific examples, it is important to note that this system reduces the possible names from the six permutations outlined above to just two, since, regardless of the scheme used to assign numbering, there can be but two senses of rotation about the axis passing through the bridgehead atoms. Thus the six alternate names outlined for **1** above reduce to

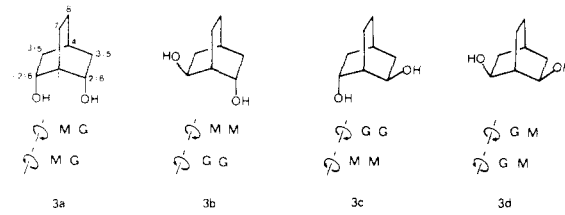

Figure 3.

1a, **1b**, and **1c**: *G*-2/*G*-6/*G*-7

1d, **1e**, and **1f**: *M*-2/*M*-6/*M*-7

The most important point is that *either* name *G*/*G*/*G* or *M*/*M*/*M* imparts the same stereochemical message: all substituents with the same stereochemical specifier are oriented in the same direction relative to the axis sense. Thus, the absolute sense of rotation assigned becomes unimportant so long as the stereochemical tags are listed in order of carbon number. Thus, while the *G*/*G*/*G* relationship in **1a** becomes *M*/*M*/*M* in the reduction product **2**, the fact that the stereochemical relationships in both are the same is readily apparent. Complete names for **1** and **2** would be *M*6-hydroxy-*M*7-chlorobicyclo[2.2.2]octane-*M*2-carboxylic acid and *M*6-chloro-*M*7-methylbicyclo[2.2.2]octan-*M*2-ol.

When the specifiers are of opposite sense there are two unique situations, *M*/*G* and *G*/*M*. This situation is illustrated with the stereoisomeric diols **3**, in Figure 3.

These compounds have two identical substituents (aside from stereochemical orientation) and thus there are, a priori, two senses of rotation to be considered for each. Note that for both meso diols **3a** and **3d**, where the substituents are oriented oppositely, the stereochemical specification is the same with either rotational sense. Conversely, the enantiomers **3b** and **3c** switch between *M*/*M* and *G*/*G* depending on the sense chosen and we propose that in such arbitary cases *M* be given priority over *G*.

We feel that his system of stereochemical specification has decided advantages over those currently in use and we propose that it be adopted as a standard for nomenclature. It would indeed be possible to apply the *M*/*G* systems to *all* bridged bicyclic systems for the sake of consistency. However, the use of exo/endo and syn/anti terms in, for instance, bicyclo[2.2.1]heptanes is only slightly more cumbersome than the *M*/*G* system and we are opposed to the introduction of new terminology where significant difficulties do not currently exist.

Spiro Systems

Similar, though more serious, problems exist with spiro systems and we would like to propose an extension with

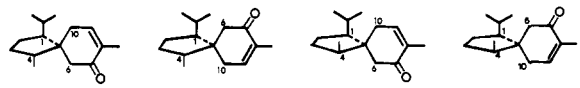

Figure 4.

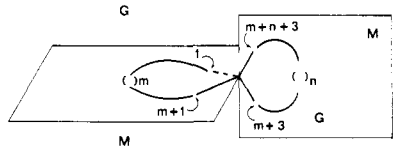

Figure 5.

modification of the *M*/*G* system to cover this class as well.

Existing systems for the specification of relative stereochemical relationships in spiro fused compounds are all either cumbersome or confusing, or both. Numerous investigators have resorted to the Cahn–Ingold–Prelog *R*/*S* notation, but this system requires considerable attention to detail and adds confusion when priorities change through chemical transformations. Others have used cis/trans terminology (Figure 4), either without a clear definition of reference points for these relationships[1] or with a reference system that so complicates the situation that conversational use is not possible.[2]

Chemical Abstracts employs α,β terminology that is adequate when only one ring has chiral centers but becomes difficult to use when it is necessary to specify stereochemical information concerning both rings. The system described below has none of the problems mentioned above for existing schemes and can be used in a conversational sense while also providing a unique and unambiguous method for the specification of stereochemistry.

The *M*/*G* System

For any spirobicyclic system, the framework atoms are numbered according to classical nomenclature rules (e.g., the smallest bridge is numbered first). The stereochemical positioning of substituents on each ring is then specified to be *M* if they are on the same face of that ring as the lower numbered atom of the other ring while *G* is used for the opposite relationship (Figure 5). This system has the advantages that relative relationships both within each ring and between the rings are easily preceived. In addition, the *relative* relationships within each ring are invarient with substituent changes in the other ring. Application of these rules to the four, isomeric spirobicyclo[4.5]decanes **5**–**8** in Figure 4 results in specification as

5: 1-*G*,4-*M* **6**: 1-*M*,4-*G*

7: 1-*G*,4-*G* **8**: 1-*M*,4-*M*

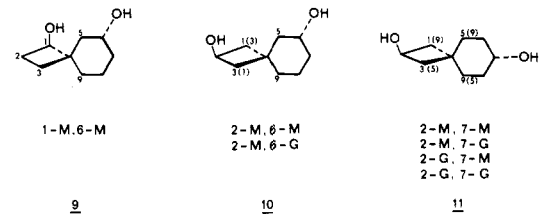

Figure 6.

In most cases the numbering of the framework atoms is straightforward and follows directly from the position of substituents. However, take for example, the three isomeric diols **9**–**11** shown in Figure 6. For **9** there is no ambiguity in the numbering of either ring as only one scheme is available that places the hydroxyl groups on the lowest numbered atoms and the unique name shown is easily derived as well as interpreted. However, because of pseudo symmetry elements there are two unique schemes for **10** and four for **11**.

We propose that in this and similar cases *M* take precedence over *G* to ensure that one and only one unique name can be derived for any substance. Thus an *M*,*G* is preferred over a *G*,*M* and an *M*,*M* over either of these. Thus, **11** would be named *M*2,*M*7-spirobicyclo[4.5]nonanediol. Nonetheless, it is important to note that regardless of the numbering scheme chosen, all derived names will clearly imply a unique relationship for the substituents on each ring. We have used this sytem for specifying stereochemistry in over 100 complex, spiro-fused bicyclics of the [3.4], [3.5], [4.4], [4.5], and [5.5] classes and have found it without exception to be easy to apply and that the stereochemical relationships are easily interpreted from the names.

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