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Synthesis and Characterization of Norbornanediol Isomers and Their Fluorinated Analogues

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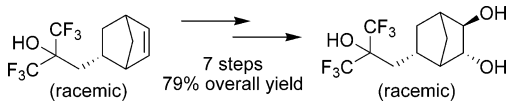
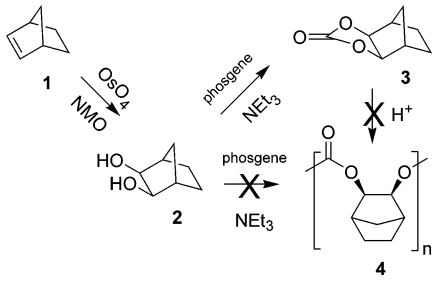


Fluorinated norbornene monomers exhibit the requisite properties for inclusion in 157 nm photoresists, but traditional addition and radical polymerizations with these monomers have failed. Norbornanediols provide an alternate route to these materials via condensation polymerization, and methods have been developed for the efficient synthesis of the *exo*-2-*syn*-7- and *endo*-2-*exo*-3-dihydroxynorbornanes. Synthesis of the fluorinated analogues is complicated by steric and electronic effects; however, a high-yielding synthesis of *endo*-2-*exo*-3-dihydroxynorbornane bearing a 5-*endo*-[2,2-bis(trifluoromethyl)hydroxyethyl] substituent is reported.

The continued drive to miniaturize microelectronic devices has been accomplished by printing the circuit elements with ever-decreasing wavelengths of light.[1] Leading edge manufacturing is now done with 193 nm light, and many are pursuing exposure at 157 nm. Polynorbornenes are of particular interest as the basis for the design of photoresists due to their unique set of desirable properties, including high glass transition temperatures, high resistance to reactive ion etching, low UV absorbance, and relative ease of synthesis.[2] However, at 157 nm, even aliphatic hydrocarbons such as polynorbornene absorbs strongly.[3] Fortunately, introduction of fluorinated substituents into the norbornane skeleton provides materials with sufficient transparency to be used at this wavelength,[4] but the most transparent of the fluorine-substituted norbornene monomers resists addition polymerization initiated by classical catalysts.[2] Therefore, an alternate route to fluorinated norbornene polymers by condensation polymerization was sought. Norbornanediols offer a number of attractive opportunities for the preparation of such polymers, for example, via condensation with phosgene to yield polycarbonates.

SCHEME 1. Synthesis and Phosgene Condensation of 2-*exo*-3-*exo*-Norbornanediol



Although synthetic routes from norbornene to the 2,3-dihydroxy-[5] and 2,7-dihydroxy[6,7] norbornane have been reported, much of this chemistry is not viable for fluorine-substituted norbornane systems as the synthetic methods do not provide sufficient yields or purity of the monomers. The preparation of fluorinated norbornane compounds most easily proceeds through the Diels−Alder reaction of cyclopentadiene with a fluorinated alkene, which have been previously investigated.[4] In this study norbornene was used as a model to develop routes to the corresponding diols. After the synthesis was optimized for norbornene, these routes were investigated with the incorporation of fluorinated substituents. It was soon discovered that, in most cases, the hydrocarbon norbornene was not an appropriate model for the fluorinated monomers.

The most straightforward route from norbornene, **1**, to a norbornane diol is oxidative dihydroxylation. The *cis*-diol can be obtained by oxidation with either permagnate[6] or osmium tetraoxide. As reported for a range of reactions with the alkene functionality of norbornene,[8] the higher steric hindrance on the *endo* face leads to a strong preference for the *exo*-diol isomer **2**. While the synthetic route to the monomer is a single step, all attempts to prepare a polycarbonate by condensation with phosgene yielded exclusively the cyclic carbonate **3**. Attempts to carry out the ring-opening polymerization of **3** using either acid or $Sn(Oct)_2$ catalysts also failed;[9] therefore, efforts shifted toward the synthesis of a norbornenediol with regiochemistry that precluded the formation of the cyclic carbonates, specifically, the *trans*-2,3-norbornanediol (Scheme 1).

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(2) Saunders: D. P.; Connor, E. F.; Grubbs, R. H.; Hung, R. J.; Osborn, B. P.; Chiba, T.; MacDonald, S. A.; Willson, C. G.; Conley, W. *Macromolecules* **2003**, *36*, 1534. Barnes, D. A.; Benedikt, G. M.; Goodall, B. L.; Huang, S. S.; Kalamarides, H. A.; Lenhard, S.; McIntosh, L. H.; Selvy, K. T.; Shick, R. A.; Rhodes, L. F. *Macromolecules* **2003**, *36*, 2623. Benedikt, G. M.; Elce, E.; Goodall, B. L.; Kalamarides, H. A.; McIntosh, L. H.; Rhodes, L. F.; Selvy, K. T.; Andes, C.; Oyler, K.; Sen, A. *Macromolecules* **2002**, *35*, 8978. Lipian, J.; Mimna, R. A.; Fondran, J. C.; Yandulov, D.; Shick, R. A.; Goodall, B. L.; Rhodes, L. F.; Huffman, J. C. *Macromolecules* **2002**, *35*, 8969. Mathew, J. P.; Reinmuth, A.; Melia, J.; Swords, N.; Risse, W. *Macromolecules* **1996**, *29*, 2755.

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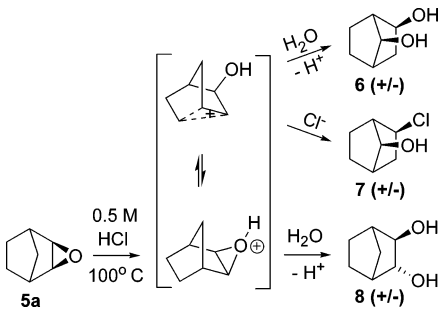
SCHEME 2. Acid-Catalyzed 2-*exo*-3-*exo*-Epoxynorbornane Ring-Opening Products



Previously reported techniques for the synthesis of *trans*-2,3-dihydroxynorbornane are limited to the Raney nickel isomerization of the *cis*-2,3-dihydroxynorbornanes (**2**).[5] Our attempts to repeat this work invariably gave mixtures regardless of the source of the catalyst, and the isomerization failed on the fluorinated norbornanes, so an alternative procedure was sought.

exo-2-*exo*-3-Epoxynorbornane is readily accessible by oxidation of norbornene, but attempts to ring-open the unsubstituted epoxynorbornane **5a** under acidic aqueous conditions yielded a mixture of products due to norbornyl cation rearrangements (Scheme 2).[7] The epoxide ring opening was monitored by GC−MS to determine the time-dependent product distribution and was found initially to yield a complex mixture of dihydroxy- and chlorohydroxynorbornanes[10] (see Figure 1), the chief constituents being the *exo*-2-*syn*-7-dihydroxynorbornane (**6**) and *exo*-2-chloro-*syn*-7-hydroxynorbornane (**7**), as well as the desired *trans*-2,3-diol (**8**). Each of these products was isolated by column chromatography, and the structures were proved by X-ray crystallography. Separation of the isomers required difficult, tedious chromatography, but increasing the reaction time to 1 day led to isomerization to the thermodynamically favored *exo*-2-*syn*-7-dihydroxynorbornane (**6**). Because the primary impurities after 1 day were norbornyl ether oligomers, the product (**6**) could be purified easily by sublimation. Confirmation of the regiochemistry of **6** was verified by reaction with phosgene, which yielded the cyclic carbonate at temperatures above 0 °C. Although this diol was successfully condensed with phosgene at low temperatures to yield a polycarbonate polymer, attempts to ring-open fluorinated epoxynorbornanes under these and other acidic conditions led to a complex mixture of inseparable isomers.

The ring opening of 2-*exo*-3-*exo*-epoxynorbornanes under basic conditions should preclude carbocation rearrangements, but this reaction is complicated instead by steric hindrance inhibiting nucleophilic attack from the *endo*-face. A range of basic aqueous conditions were investigated using hydroxide ion as the nucleophile, but these reactions yielded only starting material. Nucleophilic attack of the unsubstituted epoxide, **5a**, could only be achieved using potassium benzyloxide, which afforded a 30% yield of **9** after 10 days at 150 °C. Reaction with potassium benzyloxide at temperatures below 130 °C yielded only starting material, while temperatures above 160° led to degradation of the material. The benzyl group of **9** was readily removed by palladium catalyzed hydrogenolysis to afford

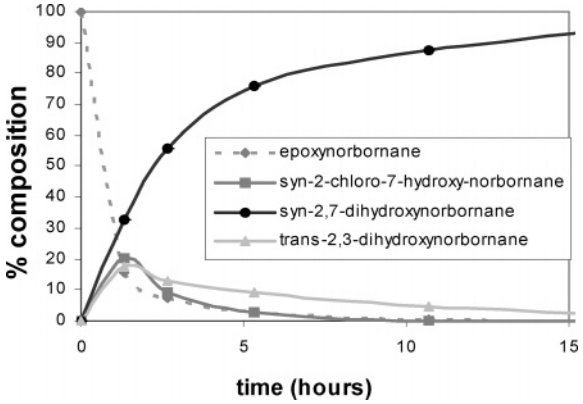
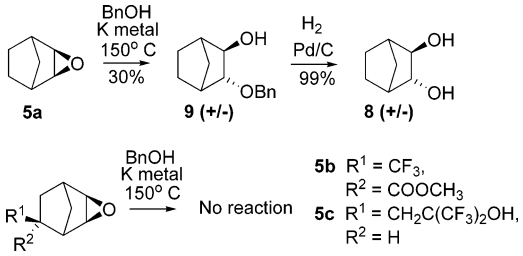


FIGURE 1. Product distribution of acid-catalyzed epoxynorbornane ring opening

SCHEME 3. Base Catalyzed 2-*exo*-3-*exo*-Epoxynorbornane Ring-Opening Products



a racemic mixture of the *trans*-2,3-norbornanediol, **8**. The crystal structure of the di(phenyl carbamate) after reaction of the diol with phenylisocyanate. Condensation with phosgene yielded the corresponding polycarbonate without formation of the cyclic carbonate, making the *trans*-diol the most attractive route to production of fluorinated norbornane condensation polymers. The details of the polymerizations will be reported elsewhere.

Unfortunately, attempts to open the fluorinated norbornene epoxides **5b** and **5c** with potassium benzyloxide at 150 °C failed, and increasing the temperature led to decomposition of the starting material (Scheme 3).

A revised synthetic approach was developed, taking into consideration the sensitivity of norbornanes to strongly acidic conditions and the steric blockage of the *endo* face. The 2-*exo*-3-*exo*-norbornanediol was readily accessible in high yields through osmium tetraoxide dihydroxylation so a synthetic route was devised by which one of the hydroxyls would be protected while the stereochemistry of the other was inverted. This was achieved by protecting the *cis*-*endo*-diol via a *p*-toluenesulfonic acid-catalyzed condensation with benzaldehyde dimethyl acetal. When this reaction was carried out in an ice bath under reduced pressure, the *exo*-isomer **10** was formed exclusively. A single hydroxyl group was deprotected by reaction with DIBAL,[11] and oxidation of the product **11** with PCC afforded 2-*exo*-benzyloxynorbornan-3-one, **12**. Reduction of *exo*-benzyloxynorbornanone with sodium borohydride afforded 61% of the *trans* isomer **13** but regenerated 39% of the *cis* isomer **11**. The stereoselectivity for this reaction is reduced significantly when compared to the reduction of unsubstituted norbornanone, as a result of the bulky benzyl ether on the *exo* face; however,

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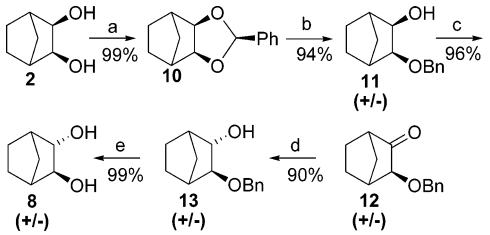
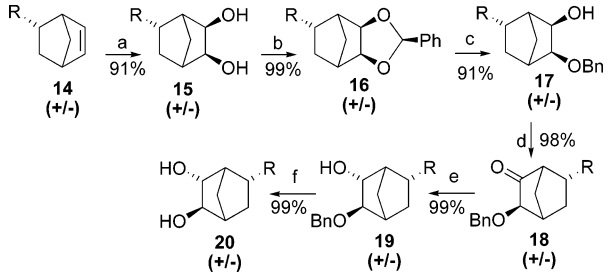
SCHEME 4. Alternative Synthesis of 2,3-*trans*-Norbornanediol[a]



[a] Key: (a) $PhCH(OCH_3)_2$, $PhCH_3$, 0 °C, 10 Torr; (b) DIBAL, $PhCH_3$; (c) PCC, CH_2Cl_2; (d) superhydride, THF 0 °C; (e) Pd/C, H_2, EtOH/EtOAc.

SCHEME 5. Preparation of Fluorinated Norbornane Monomer[a]



[a] Key: R = $CH_2C(CF_3)_2OH$ (a) OsO_4, NMO, THF; (b) $PhCH(OCH_3)_2$, $PhCH_3$, 0 °C, 10 Torr; (c) DIBAL, $PhCH_3$ (d) PCC, CH_2Cl_2; (e) superhydride, THF 0 °C; (f) Pd/C, H_2, EtOH/EtOAc.

reduction with the more stereoselective superhydride afforded the desired isomer **13** in a 91% yield. The benzyl protecting group was quantitatively removed by hydrogenolysis to afford the target model compound **8** (Scheme 4).

The 2,2-bis(trifluoromethyl)hydroxyethyl substituent was investigated because it is sufficiently transparent for 157 nm lithography, and is aqueous base soluble. The *endo*-alkene **14** was oxidized with osmium tetraoxide and precipitated into dichloromethane to afford the *cis*-diol **15**. The large steric bulk of the fluorinated substituent assured solely *exo* dihydroxylation. Benzylidene protection was carried out with *p*-toluenesulfonic acid as the acid catalyst. If the reaction was carried out at room temperature under reduced pressure rather than in refluxing toluene, the *exo*-benzylidene protected diol **16** was isolated in nearly quantitative yields (Scheme 5). The structure was verified by X-ray crystallography.

A single hydroxyl group on **16** was deprotected by reaction with 6 equiv of DIBAL, and although two regioisomers from this reaction were observed by GC, carrying out this reaction under high dilution (5 μM in substrate) provided a 91% yield of a single racemate. X-ray crystallography verified that the deprotection occurred at the hydroxyl β to the HFA substituent, yielding **17**. It is proposed that cleavage occurs in the observed position because of anchimeric assistance from the free hydroxyl group of the fluorinated substituent (Scheme 6). The first equivalent of DIBAL acts to deprotonate this acidic hydroxyl and provides a tethered Lewis acid which preferentially activates the β-ether toward cleavage by a second hydride. Such assistance by free hydroxyls during the DIBAL deprotection of benzylidene groups has been reported previously for threitol systems.[12] Additional support for this mechanism was obtained by protecting the hydroxyl group with a benzyl ether resulting in greatly reduced regioselectivity.

Oxidation using PCC afforded a nearly quantitative yield of the norbornanone **18**, which was converted to the *endo*-alcohol **19** by reduction with superhydride. This reduction was significantly more stereoselective than that of the unsubstituted ketone (**12**) because of the presence of the bulky hexafluorobutanol group on the *endo* face. Finally, catalytic hydrogenolysis of the benzyl protecting group afforded the target compound **20**. The relative stereochemistry of the three substituents was confirmed by X-ray crystallography.

Due to the steric and electronic effects of fluorine incorporation into the norbornene ring structure, previously reported techniques for the synthesis of many norbornene diols failed to provide an effective route to fluorinated analogues. A high yielding, multistep route has been developed to provide synthetic access to the fluorinated norbornanediol, **20**, in 79% overall yield. The unfluorinated *trans*-2-*endo*-3-*exo*-norbornanediol condenses with phosgene to afford poly(norbornene carbonate) and studies of this polymer and its fluorinated analogues are presently underway to evaluate their use as 157 nm photo resists.

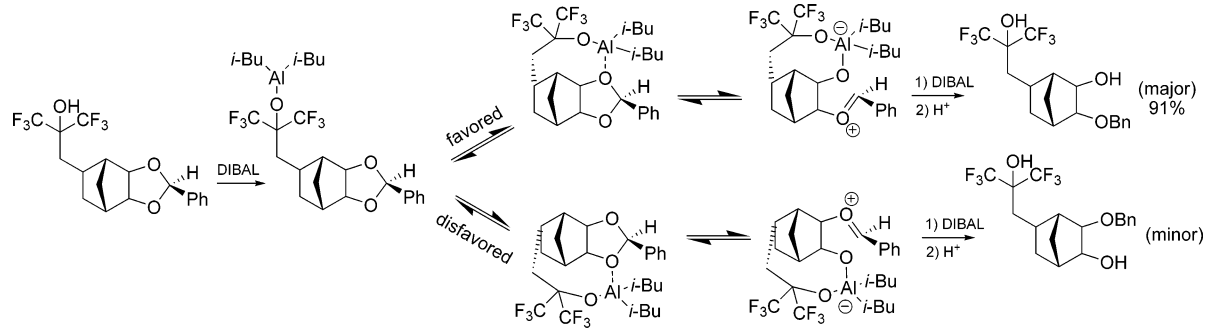
Experimental Section

2-(*exo*-2-*exo*-3-Dihydroxybicyclo[2.2.1]heptan-5-ylmethyl)-1,1,1,3,3,3-hexafluoro-2-propan-2-ol (15). To a round-bottom flask containing 116 g of bicyclo[2.2.1]hept-5-en-2-ylmethyl-1,1,1,3,3,3-hexafluoropropan-2-ol were added 1350 mL of THF, 150 mL of water, and 60 g of *N*-morpholine oxide. The reagents were stirred until dissolved and the reaction vessel was lowered into a water bath. Then 43 mL of a 2.5 wt % solution of osmium tetraoxide was added, and the reaction mixture was stirred at room temperature for 12 h. The solution was reduced in vacuo, and the aqueous mixture extracted 3 times with ethyl acetate. The organic layers were combined, reduced in vacuo, and purified by filtration through a plug of silica gel. The filtrate was then reduced in vacuo, dissolved in a minimal amount of ethyl acetate, and precipitated into dichloromethane yielding 117.6 g of a slightly yellowish powder (91% yield): ^{1}H NMR ($CDCl_3$) 0.66, (m, 1H), 1.16 (d, 1H, J = 10.2, Hz), 1.7−1.9 (m, 3H), 2.0−2.1 (m, 2H), 2.09 (s, 1H), 2.13 (m, 1H), 3.60 (d, 1H, J = 6.0 Hz), 3.93 (d, 1H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) 32.4, 33.9, 34.0, 34.5, 45.5, 49.9, 70.3, 75.7, 77.5 (m, J_{C-F} = 28 Hz), 125.1 (dq, J_{C-F} = 16.8, 287 Hz); ^{19}F NMR ($CDCl_3$) −77.5, (q, 3F, J_{F-F} = 10.0 Hz), −78.7, (q, 3F, J_{F-F} = 10.0 Hz); LRMS (EI) *m*/*z* 308 (3, M^+), 290 (10), 272 (15), 261 (20), 248 (25), 237 (50), 95 (65), 81 (65), 67 (65), 57 (100); HRMS ($[M + H]^+$ calcd = 309.0925, found = 309.0926); FTIR ν = 3385, 2970, 2880, 1416, 1203, 1033 cm^{-1}. Anal. Calcd for $C_{11}H_{14}F_6O_3$: C, 42.87; H, 4.58; F, 36.98. Found: C, 42.90; H, 4.60.

1,1,1,3,3,3-Hexafluoro-2-(4-phenyl-3,5-dioxatricyclo[5.2.1.0^{2,6}]dec-8-ylmethyl)propan-2-ol (16). To a round-bottomed flask containing 109.3 g of **15** were added 200 mL of toluene and 78 g of benzaldehyde dimethoxyacetal. The reaction vessel was cooled in an ice bath to 0 °C, 7.5 g of *p*-toluenesulfonic acid was added, and the reaction mixture was stirred under reduced pressure. After 3 h, the reaction was washed with sodium bicarbonate and extracted with dichloromethane. The organic extracts were combined, reduced in vacuo, and filtered through a plug of silica gel to afford 140 g a white amorphous solid (99% yield): ^{1}H NMR (mixture of *R* and *S* isomers) 0.60, (m, 1H), 1.21 (m, 1H), 1.84 (dd, 1H, J = 8.0, 15.0 Hz), 1.9−2.0 (m, 2H), 2.03 (dd, 1H, J = 6.4, 15.0 Hz), 2.21 (m, 1H, J = 6.0 Hz), 2.42 (m, 1H J = 4.2 Hz), 2.51(d, 1H, J = 3.8 Hz), 3.22 (s, 1H), 4.06 (d, 1H J = 5.9 Hz), 4.35 (d, 1H, J = 5.8 Hz), 5.56 (s, 1H), 7.3−7.4 (m, 3H), 7.5−7.6 (m, 2H); ^{13}C NMR 30.5, 31.7, 32.0, 33.5, 40.7, 45.0, 76.5 (m, J_{C-F} = 29.0 Hz), 78.5, 82.6, 102.7, 123.1 (q, J_{C-F} = 5.0, 287 Hz), 126.8,

(12) Takano, S.; Kurotaki, A.; Sekiguchi, Y.; Satoh, S.; Hirama, M.; Ogasawara, K. *Synthesis* **1986**, 811.

SCHEME 6. Proposed Mechanism for Regioselective Deprotection of 16



128.4, 129.6, 136.0; ^{19}F NMR −76.7, (q, 3F, J_{F-F} = 10.2 Hz), −78.0, (q, 3F, J_{F-F} = 10.2 Hz); LRMS (EI) *m*/*z* 395 (100, M − 1$^+$), 349 (10), 273 (15), 105 (80), 91 (60); HRMS ([M + H]$^+$ calcd = 397.1222, found = 397.1238); FTIR ν = 3338, 3040, 2962, 2879, 1460, 1403, 1214, 1143, 1063 cm^{-1}. Anal. Calcd for $C_{18}H_{18}F_6O_3$: C, 54.55; H, 4.58; F, 28.76. Found: C, 54.58; H, 4.62.

2-(*exo*-2-Benzyloxy-*exo*-3-hydroxybicyclo[2.2.1]heptan-5-ylmethyl)-1,1,1,3,3,3-hexafluoropropan-2-ol (17). To a round-bottomed flask containing 14.0 g of **16** diluted in 500 mL of toluene was added 214 mL of DIBAL (1.5 M solution in toluene) dropwise. The reaction mixture stirred at room temperature for 12 h and cooled to 0 °C, and the excess DIBAL was quenched by adding 0.3 M aq solution of Rochelle's salt dropwise until evolution of gas ceased. The resulting solution was extracted twice with dichloromethane, and the organic fractions were combined and reduced in vacuo. The desired product was isolated by chromatography on silica, (eluent 20% ethyl acetate 80% hexane) as a mixture of enantiomers (yield 91%): ^{1}H NMR (mixture of *R* and *S* isomers) 0.50 (m, 1H), 1.18 (m, 1H), 1.76 (dd, 1H, *J* = 1.6, 10.4 Hz), 1.8−2.0 (m, 3H), 2.11 (m, 1H), 2.23 (d, 1H, *J* = 4.6 Hz), 2.35 (d, 1H, *J* = 2.6 Hz), 3.46 (d, 1H, *J* = 6.2 Hz), 3.70 (m, 1H), 4.10 (d, 1H, *J* = 6.2 Hz), 4.54 (d, 1H, *J* = 11.7 Hz), 4.61 (d, 1H, *J* = 11.7 Hz), 6.05 (s, 1H), 7.2−7.4 (m, 5H); ^{13}C NMR 32.1, 32.3, 33.6, 34.0, 40.8, 48.0, 70.3, 73.1, 77.1 (m, J_{C-F} = 28.4 Hz), 82.3, 124.1 (q, J_{C-F} = 287, 6.2 Hz), 128.2, 128.4, 129.0, 138.3; ^{19}F NMR −76.0, (q, 3F, J_{F-F} = 10.0 Hz), −78.5, (q, 3F, J_{F-F} = 10.0 Hz); LRMS (EI) *m*/*z* 395 (2, M$^+$), 289 (45), 261 (90), 91 (100); HRMS ([M + H]$^+$ calcd = 399.1395, found = 399.1391); FTIR ν = 3489, 3208, 3034, 2965, 2877, 1453, 1207, 1140, 1090 cm^{-1}. Anal. Calcd for $C_{18}H_{20}F_6O_3$: C, 54.27; H, 5.06; F, 28.62. Found: C, 54.37; H, 5.04.

2-(*exo*-2-Benzyloxybicyclo[2.2.1]hept-3-on-5-ylmethyl)-1,1,1,3,3,3-hexafluoropropan-2-ol (18). To a round-bottomed flask containing 12.3 g of **17** diluted in 500 mL of dichloromethane was added 14.0 g of pyridium chlorochromate. The reaction mixture was stirred at room temperature for 12 h, after which time it was filtered through a plug of silica gel with ethyl acetate as eluent. The solvent was removed in vacuo to yield 12.1 g of a lightly brownish viscous liquid (yield 98%): ^{1}H NMR 1.14 (m, 1H), 1.67 (m, 1H), 1.94 (m, 1H), 2.05 (m, 1H), 2.2−2.3 (m, 2H), 2.49 (m, 1H), 2.53 (m, 1H), 2.65 (m, 1H), 3.19 (s, 1H), 3.58 (d, 1H, *J* = 2.8 Hz), 4.62 (d, 1H, *J* = 12 Hz), 4.77 (d, 1H, *J* = 12 Hz), 7.2−7.4 (m, 5H); ^{13}C NMR 31.5, 32.2, 33.2, 35.7, 46.2, 49.2, 72.7, 77.1 (m, J_{C-F} = 28.4 Hz), 123.3 (q, J_{C-F} = 288, 20.0 Hz), 128.2, 128.3, 128.7, 138.4, 214.3; ^{19}F NMR −75.2 (q, 3F, J_{F-F} = 10.0 Hz), −79.1 (q, 3F, J_{F-F} = 10.0 Hz); LRMS (EI) *m*/*z* 290 (15), 259 (20), 247 (15), 91 (100); HRMS ([M + H]$^+$ calcd = 397.1221, found =397.1238); FTIR ν = 3336, 2971, 2882, 1744, 1454, 1250, 1086 cm^{-1}. Anal. Calcd for $C_{18}H_{18}F_6O_3$: C, 54.55; H, 4.58; F, 28.76. Found: C, 54.47; H, 4.56.

2-(*exo*-2-Benzyloxy-*endo*-3-hydroxybicyclo[2.2.1]heptan-5-ylmethyl)-1,1,1,3,3,3-hexafluoropropan-2-ol (19). A round-bottomed flask containing 0.169 g of **18** was diluted in 6 mL of THF and cooled to 0 °C. To this solution was added 1.1 mL of lithium triethylborohydride (1 M solution in THF), and the reaction was warmed to room temperature and stirred for 12 h. The reaction mixture was cooled to 0 °C and quenched by addition of concentrated aqueous $NaHSO_4$. The resulting solution was extracted twice with dichloromethane, and the organic fractions were combined and reduced in vacuo. The product was isolated by chromatography on silica, (eluent 11% ethyl acetate 89% hexane) as a mixture of enantiomers (yield 99%): ^{1}H NMR 1.18 (d, 1H, *J* = 11 Hz), 1.20 (d, 1H, *J* = 11 Hz), 1.33 (m, 1H), 1.54 (m, 1H), 1.94 (dd, 1H, *J* = 5.5, 15 Hz), 2.02 (m, 1H), 2.25 (s, 1H), 2.37 (s, 1H), 2.47 (t, 1H, *J* = 13 Hz), 4.54 (d, 1H, *J* = 9.5 Hz), 4.90 (d, 1H, *J* = 9.5 Hz), 7.2−7.4 (m, 5H); ^{13}C NMR 34.4, 38.0, 39.3, 39.5, 46.4, 50.3, 77.5, 77.6, 81.2, 82.7 (m, J_{C-F} = 28.4 Hz) 123.1 (dq, J_{C-F} = 21.3, 288 Hz), 133.4, 133.6, 134.1, 144.6; ^{19}F NMR −73.9, (q, 3F, J_{F-F} = 10.0 Hz), −75.3, (q, 3F, J_{F-F} = 10.0 Hz); LRMS (EI) *m*/*z* 398 (1, M$^+$), 289 (30), 261 (65), 91 (100); HRMS ([M + H]$^+$ calcd = 399.1395 found = 399.1407); FTIR ν = 3460, 3230, 3022, 2960, 2883, 1456, 1202, 1163, 1052 cm^{-1}. Anal. Calcd for $C_{18}H_{20}F_6O_3$: C, 54.27; H, 5.06; F, 28.62. Found: C, 54.34; H, 5.08.

2-(*exo*-2-*endo*-3-Dihydroxybicyclo[2.2.1]heptan-5-ylmethyl)-1,1,1,3,3,3-hexafluoropropan-2-ol (20). To a 100 mL cylindrical glass sleeve was added a stirbar, 1.30 g of **19**, 50 mL of 1:1 ethanol/ethyl acetate, and 40 mg of 10% Pd/C. The sleeve was placed inside a stainless steel Parr reactor and charged with 400 psi of H_2. The reaction vessel was stirred vigorously for 12 h, at which point the reactor was depressurized, refreshed with an additional 20 mg of Pd/C, recharged to 400 psi of H_2, and stirred for an additional 12 h. The reaction vessel was then depressurized and reaction mixture filtered through a Whatman 0.2 μm PTFE filter to remove the Pd/C catalyst. The clear solution was reduced in vacuo to yield the racemic product as a white amorphous solid: yield 99%; ^{1}H NMR 1.31 (ddt, 1H, *J* = 1.4, 2.2, 10.7 Hz), 1.39 (dt, 1H, *J* = 2.0, 10.7 Hz), 1.58 (ddd, 1H, *J* = 2.4, 5.8, 12.5 Hz), 1.73 (dt, 1H, *J* = 4.8, 11.5 Hz), 2.02 (m, 1H), 2.1−2.3 (m, 3H), 2.31 (m, 1H), 2.5 (b, 2H), 3.94 (ddd, 1H, *J* = 1.4, 4.4, 9.2 Hz), 4.01 (ddd, 1H, *J* = 1.3, 4.6, 9.0 Hz); ^{13}C NMR 28.8, 33.5, 34.4, 35.0, 43.8, 45.7, 69.1, 72.2, 77.9 (m, J_{C-F} = 28.4 Hz) 125.1 (dq, J_{C-F} = 22.6, 288 Hz); ^{19}F NMR ($CDCl_3$) −76.1, (q, 3F, J_{F-F} = 10.4 Hz), −80.4, (q, 3F, J_{F-F} = 10.4 Hz); LRMS (EI) *m*/*z* 308 (5, M$^+$), 290 (20), 272 (25), 261 (30), 248 (40), 237 (75), 95 (75), 57 (100); HRMS ([M + H]$^+$ calcd = 309.0925, found = 309.0912); FTIR ν = 1049, 1150, 1200, 2885, 2959, 3227, 3360 cm^{-1}. Anal. Calcd for $C_{11}H_{14}F_6O_3$: C, 42.87; H, 4.58; F, 36.98. Found: C, 43.17; H, 4.56.

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Supporting Information Available: Experimental details and characterizational data for compounds **2**, **6**, and **8**−**13**, as well as crystallographic data for **8**, **16**, **17**, **19**, and **20**. This material is available free of charge via the Internet at http://pubs.acs.org.

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