effect as well as a perturbation study of substitution effects is now in progress in our laboratory.

General Remarks

In Table V the energies calculated by various semiempirical or nonempirical methods are compared with experimental data. The estimates of computing time for a single energy calculation calculated by an IBM 370/148 computer are presented in Table VI. It is seen that this method is rapid enough to enable such advanced techniques as full energy minimization and analysis of the Hessian matrix for medium-sized molecules (10-40 atoms) and it seems to be of sufficient accuracy for mechanistic studies.

Nonempirical calculations are consistent with the thinking of physicists, the goal being the evaluation of observables as exactly as possible. Topological calculations are consistent with the thinking of chemists; they can give a deeper insight into how individual functional groups participate in a given reaction and which substitutents, catalysts, or solvents have a favorable effect on the reaction rate. This point of view will be pursued in subsequent papers. It should be noted that at least in principle this method can be extended by removal of all semiempirical approximations and by the inclusion of nonneighbor interactions. This promises better results but with the necessary loss of simplicity and performance. Construction of topological energy hypersurfaces and a subsequent ab initio study of pertinent structures suggested by the topological treatment seems to be a promising way. The possible incorporation of the topological procedure into programs for searching chemical syntheses[32a,b] and heuristic investigations in the structure-reactivity projects[32c] should also be considered.

Acknowledgment. The basis of this topological treatment originated in numerous enlightening discussions with Dr. J. Kopecký from the Institute of Hygiene and Epidemiology, Prague. The author is very grateful to Dr. R. Zahradník and Dr. P. Čársky from our Institute as well as to Professor B. A. Hess from Vanderbilt University, Nashville, TN, for stimulating discussions and assistance.

Registry No. Ethylene, 74-85-1; butadiene, 106-99-0.

(32) (a) Ugi, I.; Gillespie, P. D. *Angew. Chem.* **1971**, *83*, 980, 982; (b) Corey, E. J.; Johnson, A. P.; Long, A. K. *J. Org. Chem.* **1980**, *45*, 2051; (c) Hansch, C. *Acc. Chem. Res.* **1969**, *2*, 232.

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Absolute Configuration of 1,2-Disubstituted *trans*-Cyclodecenes Based on Chemical Correlation with (+)-Dimethyl (2*R*)-2-Butyl-2-methyloctanedioate

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Abstract: The absolute configuration of (−)-*trans*-1,2-dimethylcyclodecene (**4**) has been determined to be *R* through chemical correlation with (+)-dimethyl (2*R*)-2-butyl-2-methyloctanedioate (**13**). Diester **13** was prepared from (+)-(4a*S*)-4a-methyl-2,3,4,4a,5,6,7,8-octahydronaphthalen-2-one (**12**) through a sequence involving Eschenmoser fragmentation of the related epoxy ketone, hydrogenation of the resulting acetylenic side chain, oxidative cleavage of the derived cyclohexanone trimethylsilyl enol ether, and two-carbon malonic ester homologation of the hydroxy ester thus produced. The enantiomer of enone (+)-**12** and closely related congeners have been well studied by optical rotatory dispersion, and a precursor of enone (+)-**12** has been converted to a natural steroid, thereby establishing the absolute configuration.

Thirty years ago, Blomquist noted that *trans*-cyclononene (**2**) is "asymmetric" and "should exist in two enantiomorphic modifications".[1] Ten years later, Cope et al. resolved *trans*-cyclooctene using a chiral amine-platinum(II) complex.[2] They subsequently applied their resolution methodology to *trans*-cyclononene and found that the separable diastereomeric complexes gave optically active product only if the liberated alkene was immediately cooled to −78 °C.[3] Racemization took place at room temperature with a half-life of less than 20 s. Analogous treatment of the resolved *trans*-cyclodecene-platinum(II)-amine complex led only to racemic alkene, even at low temperature. These findings indicate that racemization of *trans*-cycloalkenes via rotation of the bridging methylene chain about the double bond has an energy barrier that decreases with increasing ring size (Figure 1).

Roberts and Binsch[4] estimated a rotational barrier of 11 kcal/mol for *trans*-cyclodecene (**3**) through variable-temperature ^{1}H NMR analysis. Using these results and Cope's racemization kinetic studies, they calculated half-lives for *trans*-cyclooctene, *trans*-cyclononene, and *trans*-cyclodecene of 10^5 years, 10 s, and 10^{-4} s, respectively, at room temperature.

Attemps at the isolation of other optically active *trans*-cycloalkenes have generally not been successful. Cope[5] prepared (+)-*cis*,*trans*-1,5-cyclooctadiene from resolved (*cis*-4-cyclooctenyl)dimethylamine, and Hill[6] obtained both (+)- and (−)-*trans*,*trans*-2-isopropylidene-5,9-dimethylcyclodecadienone(germacrone) from the resolved alcohols.

(1) Blomquist, A. T.; Liu, L. H.; Bohrer, J. C. *J. Am. Chem. Soc.* **1952**, *74*, 3643-7.

(2) Cope, A. C.; Ganellin, C. R.; Johnson, H. W., Jr. *J. Am. Chem. Soc.* **1962**, *84*, 3192-3. Cope, A. C.; Ganellin, C. R.; Johnson, H. W., Jr.; Van Auken, T. V.; Winkler, H. J. S. *Ibid.* **1963**, *85*, 3276-9.

(3) Cope, A. C.; Banholzer, K.; Keller, H.; Pawson, B. A.; Whang, J. J.; Winkler, H. J. S. *J. Am. Chem. Soc.* **1965**, *87*, 3644-9.

(4) Binsch, G.; Roberts, J. D. *J. Am. Chem. Soc.* **1965**, *87*, 5157-62.

(5) Cope, A. C.; Howell, C. F.; Knowles, A. *J. Am. Chem. Soc.* **1962**, *84*, 3191-2.

(6) Hill, R. K.; Fracheboud, M. G.; Sawada, S.; Carlson, R. M.; Yan, S-J. *Tetrahedron Lett.* **1978**, 945-8.

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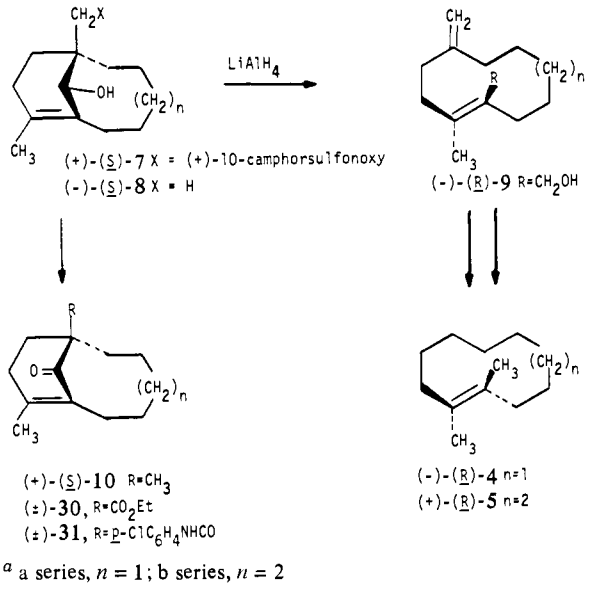
1, $n = 8$; R = H 4, $n = 10$, R = CH_3
2, $n = 9$; R = H 5, $n = 11$, R = CH_3
3, $n = 10$; R = H 6, $n = 12$, R = CH_3

Figure 1. Interconversion of (*R*)- and (*S*)-*trans*-cycloalkenes.

Scheme I



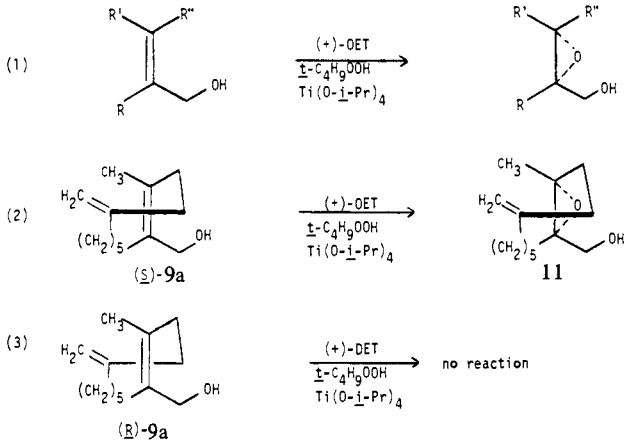
[a] a series, $n = 1$; b series, $n = 2$

We recently described a synthesis of optically active 1,2-disubstituted cyclodecenes and cycloundecenes (−)-**9a** and (−)-**9b** via fragmentation–reduction of the resolved camphorsulfonates (+)-**7a** and (+)-**7b** (Scheme I).[7] These optically stable cycloalkenes were further transformed to (−)-*trans*-1,2-dimethylcyclodecene (**4**) and (+)-*trans*-1,2-dimethylcycloundecene (**5**). Thus, as might be expected, the replacement of H by CH_3 (e.g., **3** vs. **4**) raises the rotational energy barrier of the bridging carbon chain in *trans*-cycloalkenes.

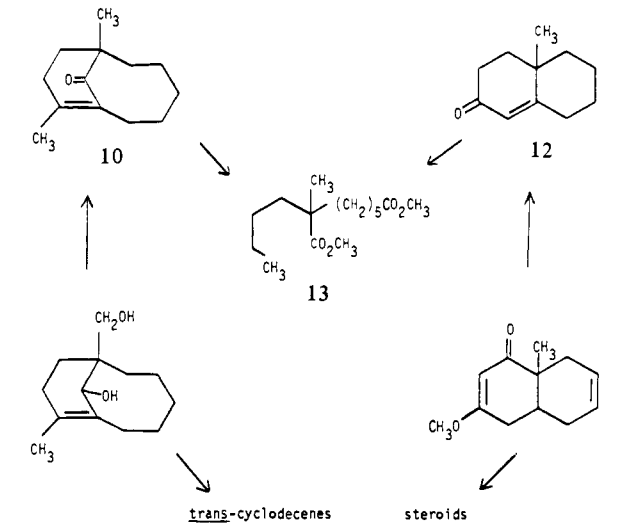
Cope and Mehta[8] showed (−)-*trans*-cyclooctene (**1**) to have the *R* configuration[9] through chemical correlation with (+)-(2*R*,3*R*)-tartaric acid. Our assignment of absolute configuration to cycloalkenes **4** and **5** was based upon the ORD curves of enones (+)-**10a** and (+)-**10b**. These enones were obtained via oxidation of alcohols (−)-**8a** and (−)-**8b**, the hydrogenolysis byproducts of the aforementioned fragmentation–reduction reaction. Both (+)-**10a** and (+)-**10b** showed strong positive Cotton effects in the 300-nm n–π^* region and strong negative Cotton effects in the 225-nm π–π^* region, consistent with the *R* configuration.[10] The related (−)-**4** and (+)-**5** could therefore be surmized to possess the *S* configuration.[9]

Scott and Wrixon[11] examined a large number of optically active olefinic compounds and formulated a symmetry rule that correlates absolute configuration with the Cotton effect of the 200-nm π–π^* transition. Only one *trans*-cycloalkene, (−)-(*R*)-*trans*-cyclooctene, was available for their studies. It showed a negative Cotton effect. We were surprised to find that *trans*-cycloalkenes (−)-**9a** and (−)-**9b** likewise showed negative Cotton effects at 210–215 nm since we had assigned the *S* configuration on the basis of the ORD curve of enones (+)-**10a** and (+)-**10b** as noted above. The dimethyl compounds (−)-**4** and (+)-**5** also showed negative Cotton effects.

Scheme II



Scheme III

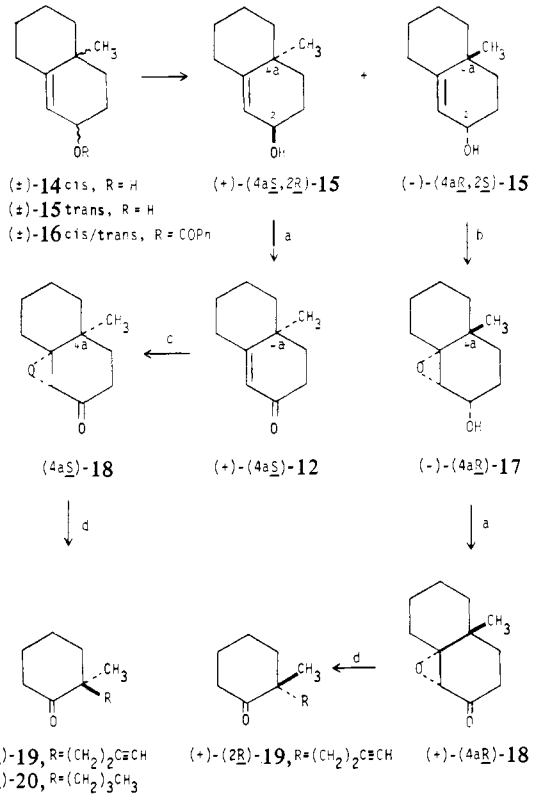


Sharpless and Katsuki[12] found that the reagent derived from dialkyl tartrates, *tert*-butyl hydroperoxide, and titanium isopropoxide exhibits exceedingly high steric preferences in the epoxidation of the double bond of allylic alcohols. In all examples thus far examined, (+)-diethyl tartrate [(+)-DET] directs epoxidation to the underside of the double bond when the system is oriented as shown in Scheme II. When we subjected racemic (±)-**9a** to the Sharpless–Katsuki epoxidation, the recovered allylic alcohol had a rotation of −65°, a value close to that found for (−)-**9a** prepared from camphorsulfonate (+)-**7a**. As shown in Scheme II, the bridging carbon chain should block the underside of the double bond in the *R* enantiomer. The recovered (−)-allylic alcohol **9a** should accordingly possess the *R* configuration.[9] However, the ORD curve of enone (+)-**10a** indicated the *S* configuration for allylic alcohol (−)-**9a**.

At this point we felt that our configurational assignments of olefins (−)-**9a** and (−)-**9b** required further examination. Our efforts at growing crystals of camphorsulfonate (+)-**7** suitable for X-ray structure analysis failed. We therefore decided to carry out a chemical correlation of enone (+)-**10a** with a substance of unassailable stereochemical integrity.

(7) Marshall, J. A.; Konicek, T. R.; Flynn, K. E. *J. Am. Chem. Soc.* **1980**, *102*, 3287–8. Marshall, J. A. *Acc. Chem. Res.* **1980**, *13*, 213–8.
(8) Cope, A. C.; Mehta, A. S. *J. Am. Chem. Soc.* **1964**, *86*, 5626–30.
(9) The rules for assigning absolute configuration to *trans*-cycloalkenes are delineated in: Cahn, R. S.; Ingold, C. K.; Prelog, V. *Angew. Chem., Int. Ed. Engl.* **1966**, *5*, 385–416; see p 402.
(10) Snatzke, G. *Tetrahedron* **1965**, *21*, 413–39. Moffitt, W.; Woodward, R. B.; Moscowitz, A.; Klyne, W.; Djerassi, C. *J. Am. Chem. Soc.* **1961**, *83*, 4013–8.
(11) Scott, A. I.; Wrixon, A. D. *Tetrahedron* **1970**, *26*, 3695–3715; see pp 3706–9.
(12) Sharpless, K. B.; Katsuki, T. *J. Am. Chem. Soc.* **1980**, *102*, 5976–8. Martin, U. S.; Woodard, S. S.; Katsuki, T.; Yamada, Y.; Ikeda, M.; Sharpless, K. B. *Ibid.* **1981**, *103*, 6237–40.

Scheme IV[a]



[a] (a) $HCrO_3Cl{\cdot}C_5H_5N$, CH_2Cl_2. (b) (+)-Diisopropyl tartrate, t-C_4H_9OOH, $Ti(O\text{-}i\text{-}C_3H_7)_4$. (c) H_2O_2, NaOH, C_2H_5OH. (d) p-$TsNHNH_2$, HOAc.

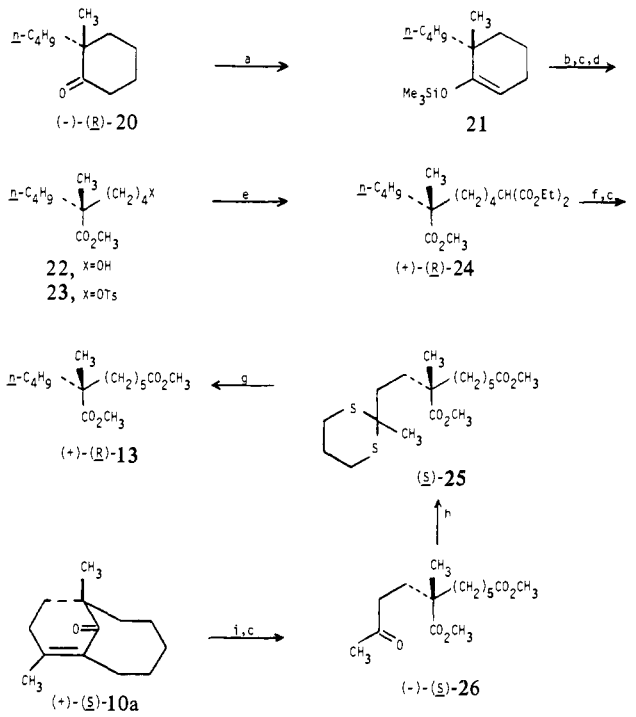
The stereochemical reference selected for this correlation was the naphthalenone **12**. This enone and its congeners were extensively studied by Djerassi and co-workers in their pioneering work on the octant rule.[13] Furthermore, a direct precursor of this enone has been converted to known steroids via the Woodward synthesis,[14] thus independently confirming the absolute configuration. We envisioned a degradation sequence (Scheme III) whereby enone **12** of known absolute configuration would be converted to an optically active derivative, diester **13**. The same diester would then be prepared from enone (+)-**10a**, the cornerstone of our assignment of absolute configuration to cycloalkenes **9a** and **4**. The relationship between suspect enone (+)-**10a** and enone **12** of established configuration could then be ascertained simply by a comparison of the sign of rotation of diester **13** derived from each. In effect, the approach forges a stereochemical link between *trans*-cycloalkenes and natural steroids.

Hoping to avoid the lengthy Djerassi–Woodward preparation of optically active enone **12**,[13,14] we considered resolution of the racemic material, readily obtained through annulation of 2-methylcyclohexanone with methyl vinyl ketone.[15] Rather than attempt optical resolution of enone **12** per se, we examined Sharpless–Katsuki oxidation[12] of the corresponding allylic alcohol.[15] Reduction of enone **12** with lithium aluminum hydride,[15] or L-Selectride,[16] afforded an 80:20 mixture of the cis and trans racemic alcohols **14** and **15** (Scheme IV). Treatment of this mixture with the (+)-diethyl tartrate derived reagent effected some optical enrichment, but the reaction was slow and inefficient. We reasoned that the equatorial orientation of the hydroxyl grouping in the predominant cis alcohol **14** must prevent its ready participation in the epoxidation reaction. Accordingly, we treated the alcohol mixture with diethyl azodicarboxylate–triphenylphosphine–benzoic acid to effect inversion.[17] Saponification of the resulting benzoate mixture (**16**) afforded a 70:30 mixture of the trans and cis alcohols **15** and **14**. Treatment of this allylic alcohol mixture with the (+)-diisopropyl tartrate derived epoxidation reagent[12] afforded a mixture comprised primarily of epoxy alcohol (−)-**17** and allylic alcohol (+)-**15**, which could be separated by chromatography on silica gel.

Oxidation of the allylic alcohol (+)-**15** with pyridinium chlorochromate[18] yielded the enone **12**, $[\alpha]_D$ +105°. Djerassi and Marshall[13a] found a specific rotation of −196° at 589 nm for the *R* enantiomer of enone **12**. We can therefore estimate an optical purity of 55% for our sample of (*S*)-(+)-**12**.[13b]

Epoxidation of enone (+)-**12** with alkaline hydrogen peroxide gave a mixture (mainly (4a*S*)-**18**) of epoxy ketones.[19] Treatment with (*p*-toluenesulfonyl)hydrazine in acetic acid effected fragmentation to the butynylcyclohexanone (−)-**19**.[20] As a check on the resolution methodology, the epoxy alcohol (−)-**17**, obtained via Sharpless–Katsuki epoxidation of the racemic alcohol mixture **15**/**14**, was oxidized to the epoxy ketone (+)-**18** with pyridinium chlorochromate.[18] Treatment with (*p*-toluenesulfonyl)hydrazine in acetic acid afforded the butynylcyclohexanone (+)-**19**.[20] Comparison of rotations, −37° vs. +41°, for the enantiomeric ketones **19** indicates an optical purity of 61% for (+)-**19**, assuming enone (+)-**12** of 55% optical purity yields ketone (−)-**19** without

Scheme V[a]



[a] (a) Me_3SiCl, Et_3N, DMF. (b) O_3, MeOH, −78 °C; $NaBH_4$; HCl. (c) CH_2N_2, Et_2O, EtOAc. (d) p-TsCl, C_5H_5N, 0 °C. (e) NaH, $CH_2(CO_2Et)_2$, THF. (f) KOH, $(CH_2OH)_2$. (g) Ni(Ra), EtOAc. (h) $CH_2(CH_2SH)_2$, $BF_3{\cdot}Et_2O$, HOAc. (i) O_3, CH_2Cl_2, −78 °C; H_2O_2, HOAc.

(13) (a) Djerassi, C.; Marshall, D. *J. Am. Chem. Soc.* **1958**, *80*, 3986–95. (b) **Note Added in Proof**: C. R. Johnson and J. R. Zeller (*J. Am. Chem. Soc.* **1982**, *104*, 4021–3) obtained enone **12** with specific rotations of −207.0° and +208.3° via their elegant sulfoximine resolution methodology. We can therefore estimate enone (+)-**12** to have an optical purity of 50% and ketone (−)-**19** to have an optical purity of 55%.

(14) Woodward, R. B.; Sondheimer, F.; Taub, D.; Heusler, K.; McLamore, W. M. *J. Am. Chem. Soc.* **1952**, *74*, 4223–51. Barkley, L. B.; Farrar, M. W.; Knowles, W. S.; Raffelson, H.; Thompson, Q. E. *Ibid.* **1954**, *76*, 5014–7. Backley, L. B.; Farrar, M. W.; Knowles, W. S.; Raffelson, H. *Ibid.* **1954**, *76*, 5017–9.

(15) Cf.: Marshall, J. A.; Fanta, W. K. *J. Org. Chem.* **1964**, *29*, 2501–5.

(16) Brown, H. C.; Krishnamurthy, S. *J. Am. Chem. Soc.* **1972**, *94*, 7159–61.

(17) Bose, A. K.; Lal, B.; Hoffman, W. A.; Manhas, M. S. *Tetrahedron Lett.* **1973**, 1619–22.

(18) Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, 2647–50.

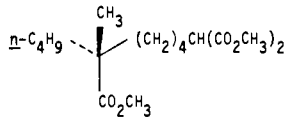
(19) Cf.: Henbest, H. B.; Jackson, W. R. *J. Chem. Soc. C* **1967**, 2459–62.

(20) Eschenmoser, A.; Felix, D.; Ohloff, G. *Helv. Chim. Acta* **1967**, *50*, 708–13.

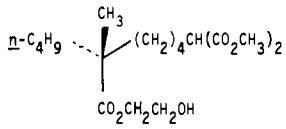
loss or gain of optical purity.[13b]

Hydrogenation of (−)-**19** over palladium led to the butyl derivative (−)-**20**. Cleavage via ozonolysis of the trimethylsilyl enol ether **21**, followed by reductive workup and esterification yielded the hydroxy ester **22** (Scheme V). The tosylate derivative **23** was chain-extended by reaction with diethyl sodiomalonate, followed by hydrolysis, decarboxylation, and esterification to give the predominantly *R* diester **13**, $[\alpha]_D$ +0.94°.

As an aside, it should be noted that our initial effort at hydrolysis of triester (+)-**24** in refluxing ethanol–ethylene glycol–potassium hydroxide for 1 h led to an acidic product, which afforded triesters **28** and **29** upon treatment with diazomethane. The latter (major) project must arise by glycolysis of the hindered carboxyl group of triester (+)-**24** and saponification of the malonic moiety. Triesters **28** and **29** underwent the desired hydrolysis–decarboxylation in refluxing ethylene glycol–potassium hydroxide for 12 h.



28



29

Degradation of enone (+)-**10a** to diester **13** was initiated by ozonolysis followed by oxidative workup and esterification to give the keto diester (−)-**26**. Conversion to the thioketal derivative **25** and desulfurization with Raney nickel led to diester **13** with a rotation of +1.85°.[21] Thus, enones (+)-**10a** and (+)-**12** must *both* have the *S* configuration, and the previously described *trans*-cyclodecenes (−)-**9a** and **4** must have the *R* configuration. This finding necessitates a revision of earlier assignments based upon the ORD curve of enone (+)-**10a**.[7]

While our assignments are strictly applicable only to the 10-membered "a series" (Scheme I), it is likely that the absolute configuration of the 11-membered "b series" must be similarly revised, since both show analogous optical behavior. Cycloalkenes **9a** and **4** thus represent additional proven examples of chiral *trans*-cycloalkenes that obey Scott's symmetry rule for olefins.[11] All were found to exhibit a negative Cotton effect. Alkenes **9b** and **5** likewise show a negative Cotton effect suggestive of the *R* configuration.

Finally, the anomalous Cotton effects of enones (+)-**10a** and (+)-**10b** must be reconsidered. To begin with, we and others have observed certain chemical anomalies for bridgehead enones such as **10**. Thus, enone **30** (Scheme I) can be epoxidized with alkaline hydrogen peroxide but resists all attempts at Michael addition of malonic ester.[22] In a similar vein, we were unable to effect conjugate addition of lithium dimethylcuprate to racemic **10a**.[23] The half-wave reduction potential of enone **10a** was found to be −2.54 V,[23] a surprisingly high value for an enone.[24]

Single-crystal X-ray analysis of the *p*-chloroanilide derivative **31** revealed both a twisted double bond and a 32° distortion from planarity for the enone system.[25] In addition, bond lengths approximating those expected for an isolated carbon–carbon double bond and carbonyl group were found. The ultraviolet spectrum of enone **10a** shows a maximum at 245 nm (ε 3800), indicating inefficient overlap between the carbonyl and the double bond.[26] Thus, conjugation appears to be seriously diminished by steric distortions in enones such as **10**.

If we accept the fact that enone **10a** is effectively a saturated ketone with an isolated double bond, then interpretation of the observed Cotton effects is consistent and straightforward. Application of the octant rule[10] for saturated ketones to the n–π* transition and of Scott's rule[11] for isolated double bonds to the π–π* transition correctly predict the *S* configuration for the (+) enantiomer.

While enone **10b** (λ_{max} 246 nm (ε 6300)), by virtue of its longer bridge, should be less distorted than enone **10a**, the correspondence of their ORD curves suggests a configurational equivalence. We have already noted the close match of ORD curves for olefins (−)-**9a**, (−)-**9b** and (−)-**4**, (+)-**5**.

Experimental Section[27]

(*R*)-(−)-[2-Methyl-5-methylene-(*Z*)-cyclodecenyl]methanol (9a): Kinetic Resolution of (±)-9a. The procedure of Sharpless and Katsuki was followed.[12] A 100-mL flask containing 22 mL of dichloromethane was cooled to −23 °C. The following reagents were added dropwise with stirring in order: 0.77 mL (2.58 mmol) of titanium tetraisopropoxide, 0.53 mL (3.08 mmol) of (+)-diethyl tartrate (5 min wait), 500 mg (2.58 mmol) of allylic alcohol **9a** in 3 mL of dichloromethane, and 0.39 mL (1.29 mmol) of 3.28 M *tert*-butyl hydroperoxide in 1,2-dichloroethane.[28] The resultant solution was stirred for 50 min at −23 °C and quenched with 6.5 mL of 10% tartaric acid. This mixture was stirred at −23 °C for 30 min, followed by 1 h at room temperature. The organic layer was separated, washed once with water, dried over sodium sulfate, and concentrated to give an oil. To a cooled (0 °C) solution of this oil in 24 mL of ether was added dropwise, with stirring, 7.5 mL of 40% sodium hydroxide. The resultant two-phase mixture was stirred at 0 °C for exactly 30 min. The organic layer was separated, washed with brine, dried over sodium sulfate, and concentrated to give the products. Purification by column chromatography (silica gel, 50% ethyl acetate–hexane) yielded 154 mg (62%) of (−)-**9a** and 81 mg (30%) of epoxide (1*S*,2*R*)-**11**.

(−)-**9a**: IR (film) ν 3400, 3060, 2940, 2860, 1640, 1460, 990, 900 cm^{-1}; ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.1–1.6 (m), 1.87 (s, C-2 CH_3), 1.9–2.9 (m), 4.18 (AB q, $\Delta\nu$ = 58.8, J_{AB} = 12 Hz, CH_2O–), 4.85 (s, C=CH_2); $[\alpha]^{20}_D$ −64.7° (*c* 3.63, $CDCl_3$). Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.4; H, 11.4.

(**1*S*,2*R*)-11**: IR (film) ν 3425, 3150, 2925, 2850, 1640, 1470, 1390, 1060, 1040, 910 cm^{-1}; ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.4–2.3 (m), 1.55 (s, C-2 CH_3), 3.8 (t, *J* = 12 Hz, CH_2O–), 3.92 (s, OH), 4.95 (s, C=CH_2).

(4a*S*)-(+)-4a-Methyl-2,3,4,4a,5,6,7,8-octahydronaphthalen-2-one (12). The procedure of Corey and Suggs was modified.[18] To a cooled (0 °C) solution of 25 g (0.156 mol) of pyridinium chlorochromate and 30 g of oven-dried Celite in 900 mL of dichloromethane was added dropwise, with stirring, 8.71 g (52.47 mmol) of allylic alcohol (+)-**15** containing 10% of enone **12** (see below) in 100 mL of dichloromethane. The mixture was stirred at room temperature overnight. The slurry was diluted with ether and filtered through Florisil with the aid of ether. Concentration of the filtrate gave 7.6 g (88%) of enone **12** as a clear, colorless oil: $[\alpha]^{22}_D$ +105° (*c* 7.28, $CHCl_3$); IR (film) ν 2925, 2850, 1680, 1620, 1450, 1330, 1290, 1230, 860 cm^{-1}; NMR ($CDCl_3$, Me_4Si) δ 1.27 (s, C-4a CH_3), 1.3–2.0 (m), 2.1–2.5 (m), 5.7 (s, C=CH). Anal. Calcd for $C_{11}H_{16}O$: C, 80.50; H, 9.83. Found: C, 80.17; H, 9.83.

(+)-Dimethyl (2*R*)-2-Butyl-2-methyloctanedioate (13). A. From Triester (+)-24. A solution of 600 mg (1.68 mmol) of triester (+)-**24** and 675 mg (12.0 mmol) of potassium hydroxide in 10 mL of ethylene glycol and 4 mL of absolute ethanol was heated to reflux for 1 h. After cooling, the mixture was poured into water, washed once with ether to remove neutral impurities, cooled, and acidified.

The product was extracted with ether to afford 515 mg of crude acid; IR (film) ν 3400–2400, 2950, 2875, 1735, 1480, 1460, 1400, 1230, 1180, 1100, 1060, 890 cm^{-1}.

Ethereal diazomethane, prepared as previously described from 21 mL of 50% potassium hydroxide and 2.76 g (26.2 mmol) of *N*-methyl-*N*-nitrosourea,[29] was added to a cooled (0 °C) solution of 515 mg of the crude acid in 25 mL of ethyl acetate and 25 mL of ether. The resultant solution, after standing at room temperature overnight, was washed with 10% sodium hydroxide and brine and dried over magnesium sulfate. Removal of solvent gave a crude product, which was chromatographed (silica gel, 30% ethyl acetate–hexane) to yield 118 mg of triester **28**: IR

(21) Using this value of +1.85° for pure diester **13**, it is calculated that the sample of (+)-**13** obtained from enone (+)-**12** of 50% optical purity (see footnote 13b) should have a rotation of +0.92°. The value of +0.94° actually found is in close agreement with the calculated.

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(film) ν 2950, 2850, 1760, 1740, 1480, 1440, 1390, 1350, 1220, 1160 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, J = 6 Hz, CH_3CH_2), 1.10 (s, C-7 CH_3), 1.0–2.0 (m), 3.35 (t, J = 7 Hz, C-2 CH), 3.65 (s, C-7 CO_2CH_3), 3.75 (s, C-1 and C-2 CO_2CH_3).

The column was eluted with ethyl acetate to give 200 mg of triester **29**: IR (film) ν 3500, 2950, 2850, 1760, 1740, 1480, 1440, 1350, 1250, 1210, 1170, 1080, 1060 cm^{-1}; NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, J = 6 Hz, CH_3CH_2), 1.15 (s, C-7 CH_3), 1.1–2.0 (m), 2.55 (br s, OH), 3.35 (t, J = 7 Hz, C-2 CH), 3.75 (s, CO_2CH_3) 4.0 (AA'BB' m, $-CH_2CH_2O-$).

Each of the above esters was saponified separately according to Warne.[30] A solution of 118 mg (0.357 mmol) of the trimethyl ester **28** and 200 mg (3.57 mmol) of potassium hydroxide in 5 mL of ethylene glycol was heated to reflux for 12 h. The mixture was cooled, poured into water, and washed with ether. The aqueous layer was cooled to 0 °C and acidified, and the product was isolated with ether to yield 86 mg (99%) of diacid: ^1H NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, J = 6 Hz, CH_3CH_2), 1.10 (s, C-2 CH_3), 1.0–1.8 (m), 2.3 (t, J = 6 Hz, CH_2CO_2-), 15.2 (br s, CO_2H).

A solution of 200 mg (0.56 mmol) of the glycol ester **29** and 300 mg (5.4 mmol) of potassium hydroxide in 5 mL of ethylene glycol was heated to reflux for 12 h. The product was isolated as described above to afford 195 mg of an oil identical with the diacid prepared from triester **28**, as described above.

The samples were combined and esterified as follows: A yellow, ethereal solution of diazomethane, prepared from 25 mL of 50% potassium hydroxide and 3.0 g (29.1 mmol) of *N*-methyl-*N*-nitrosourea,[29] was added to a cooled (0 °C) solution of 281 mg (1.15 mmol) of the above-described diacid in 25 mL of ethyl acetate. The solution was allowed to warm to room temperature. After 2 h, the solution was washed with 10% sodium hydroxide and brine and dried over magnesium sulfate. Removal of solvent under reduced pressure yielded a crude product, which was purified by column chromatography (silica gel, 25% ethyl acetate–hexane) to give 113 mg (36%) of diester (+)-**13** as a clear, colorless oil: $[\alpha]^{22}_D$ +0.94° (*c* 10.15, $CDCl_3$); IR (film) ν 2925, 2875, 1740, 1480, 1450 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, J = 6 Hz, CH_3CH_2), 1.1 (s, C-2 CH_3), 1.05–1.8 (m), 2.28 (t, J = 9 Hz, CH_2CO_2-), 3.63 (s, CO_2CH_3). Anal. Calcd for $C_{15}H_{28}O_4$: C, 66.14; H, 10.36. Found: C, 66.01; H, 10.32.

B. From Keto Ester 26. The procedure of Sondheimer was followed.[31] To a stirred, cooled (0 °C) mixture of 563 mg (1.98 mmol) of keto diester **26** and 0.37 mL (3.4 mmol) of 1,3-propanedithiol was added dropwise 0.20 mL (1.63 mmol) of boron trifluoride etherate. The resultant solution was stirred at room temperature for 20 min and cooled to 0 °C, and 2 mL of methanol was added. Isolation of the crude product with ethyl acetate yielded 595 mg (82%) of thioketal **25**, which was used without further purification: IR (film) 2925, 2850, 1740, 1450, 1220 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 1.1–2.1 (m), 1.14 (s, C-2 CH_3), 1.53 (s, CH_3CS), 2.28 (t, J = 9 Hz, CH_2CO_2-), 2.8 (m, CH_2S), 3.65 (s, CO_2CH_3).

A solution of 595 mg (1.61 mmol) of thioketal **25** in 10 mL of absolute ethanol was added to a slurry of 9.4 g of freshly prepared Raney nickel catalyst in 40 mL of absolute ethanol.[32] The resultant mixture was heated to reflux for 30 min, cooled to room temperature, and filtered through a pad of Celite with the aid of absolute ethanol. The filtrate was concentrated under reduced pressure to give a semisolid residue, which was taken up in ethyl acetate, washed with 10% sodium hydroxide and brine, and dried over magnesium sulfate. Removal of solvent under reduced pressure gave an oil, which was purified by column chromatography (silica gel, 25% ethyl acetate–hexane) and short-path distillation (oven temperature 100–105 °C, 0.03 torr) to afford 100 mg (23%) of diester **13** as a clear, colorless oil: $[\alpha]^{D}_{20}$ +1.85° (*c* 4.32, $CDCl_3$); IR (film) ν 2925, 2875, 1740, 1480, 1450 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, J = 6 Hz, CH_3CH_2), 1.1 (s, C-2 CH_3), 1.05–1.8 (m), 2.28 (t, J = 9 Hz, CH_2CO_2-), 3.63 (s, CO_2CH_3). Anal. Calcd for $C_{15}H_{28}O_4$: C, 66.14; H, 10.36. Found: C, 66.29; H, 10.04.

(±)-4a-Methyl-2,3,4,4a,5,6,7,8-octahydronaphthalen-2-ols 14 and 15. The procedure of Bose was followed.[17] To a stirred solution of 54.4 g (0.329 mol) of the 85:15 mixture of alcohols **14**/**15**,[15] 86 g (0.328 mol) of triphenylphosphine, and 40 g (0.328 mol) of benzoic acid in 1 L of tetrahydrofuran was added dropwise 54.3 mL (0.345 mol) of diethyl azodicarboxylate over a 30-min period. The resultant solution was stirred at room temperature for 18 h. After concentration at reduced pressure, the solid triphenylphospine oxide was separated by suction filtration. The filtrate was concentrated under reduced pressure to give an oil, which was purified by preparative high-pressure liquid chromatography (1% ethanol–hexane) to yield 50 g (56%) of isomeric benzoates **16** as a clear, colorless oil: IR (film) ν 2925, 2875, 1720, 1670, 1610, 1590, 1460, 1280, 1130, 930 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 1.08 [s, CH_3 (*trans*-benzoate)], 1.13 [s, CH_3 (*cis*-benzoate)], 1.2–2.3 (m), 5.45 (m, C=CH), 7.4 (m), 8.1 (m).

Saponification of the benzoate mixture was conducted according to Bose.[17] A solution of 50 g (0.185 mol) of benzoate **16** and 40 g (0.70 mol) of potassium hydroxide in 1 L of distilled methanol was heated to reflux for 3 h. The solution was then cooled and concentrated under reduced pressure to an oil. Isolation of the product with hexane gave 27.6g (90%) of a clear oil. GLC analysis (6 ft × 0.125 in., 2% Carbowax on Chromasorb W, 140 °C) showed this oil to be a 70:30 mixture of *trans*:*cis* alcohols **15** and **14**:[15] IR (film) ν 3300, 2900, 2840, 1660, 1450, 1360, 1050, 1000 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 1.03 [s, CH_3 (trans alcohol)], 1.1 [s, CH_3 (cis alcohol)], 1.2–2.3 (m), 3.2 (br s, OH), 4.1 (m, CHO), 5.3 [s, C=CH (cis alcohol)], 5.43 [d, C=CH (trans alcohol)].

(4a*S*)-(+)-4a-Methyl-2,3,4,4a,5,6,7,8-octahydronaphthalene-2-ol (15): Kinetic Resolution of (±)-15. The procedure of Sharpless was modified.[12] To a cooled (−78 °C) flask containing 385 mL of dichloromethane was added dropwise, with stirring, the following reagents: 14.8 mL (0.05 mol) of titanium tetraisopropoxide, 12.6 mL (0.06 mol) of (+)-diisopropyl tartrate in 10 mL of dichloromethane (5 min wait), 27.6 g (0.166 mol) of the 70:30 mixture of allylic alcohols **15** and **14** in 20 mL of dichloromethane, and 30 mL (0.10 mol) of 3.28 M *tert*-butyl hydroperoxide in 1,2-dichloroethane.[28] The mixture was allowed to stand in the freezer (−35 °C). After 7.5 h, the ratio of epoxy to allylic alcohols was 0.9 as measured by GLC. The mixture was poured into a cooled (0 °C) solution of 15 mL of water in 800 mL of reagent-grade acetone and allowed to warm to room temperature. Attempts to filter the milky precipitate were unsuccessful. The solution was concentrated and diluted with 200 mL of dichloromethane, and 100 mL of 10% tartaric acid was added. This two-phase mixture was stirred until the aqueous layer was clear. The organic layer was separated and concentrated under reduced pressure. To a cooled (0 °C) solution of the concentrate in 1 L of ether was added ice-cold 40% sodium hydroxide with stirring until the layers were clear. The ethereal solution was separated, washed with brine, and dried over sodium sulfate. Removal of solvent at reduced pressure gave 24 g of an oil, which was purified by column chromatography (silica gel, 30% ethyl acetate–hexane) to give three fractions: 1.39 g (10%) of enriched (+)-**15**, 8.71 g (63%) of enriched (+)-**15** contaminated with 10% of enone **12**, and 12.0 g (80%) of epoxy alcohol (−)-**17**.

(+)-**15**: IR (film) ν 3300, 2900, 2840, 1660, 1450, 1360, 1050, 1000 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 1.03 (s, CH_3), 1.2–2.3 (m), 3.2 (br s, OH), 4.1 (m, CHO), 5.43 (d, C=CH), peaks at δ 1.1 and 5.3 were also present indicating contamination by the cis-alcohol **14**. Anal. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.91. Found: C, 79.39; H, 10.64.

(+)-**15** contaminated with 10% of enone **12**: $[\alpha]^{20}_D$ +112.7° (*c*, 6.42, $CHCl_3$). This fraction was taken on without further purification.

(−)-**17**: $[\alpha]^{22}_D$ −88.2° (*c* 4.05, $CHCl_3$); IR (film) ν 3400, 2925, 2850, 1450, 1160, 1000, 910, 850, 750 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.9–2.1 (m), 1.05 (s, C-4a CH_3), 2.6 (br s, OH), 3.15 (d, J = 4.5 Hz, CHCO), 4.05 (m, C*H*OH).

(2*S*)-(−)-2-(3-Butynyl)-2-methylcyclohexanone (19). The procedure of House was followed.[33] To a stirred, cooled (0 °C) solution of 7.6 g (46.3 mmol) of enone (+)-**12** and 13.4 mL (0.139 mol) of 30% hydrogen peroxide in 75 mL of distilled methanol was added dropwise 3.9 mL (23.4 mmol) of 6 N sodium hydroxide over 1 h. The mixture was stirred at room temperature for 1.5 h. Isolation with ether gave 6.0 g (72%) of epoxy ketone **18** as an oil: IR (film) ν 2950, 2875, 1715, 1460, 1250, 930, 870, 760 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 1.1 [s, C-4aCH_3 (cis epoxide)], 1.23 (s, C-4a CH_3 (trans epoxide)], 1.3–2.5 (m), 2.95 [s, CHO– (trans epoxide)], 3.03 [s, CHO– (cis epoxide)].

Fragmentation of epoxy ketone **18** was effected according to Eschenmoser.[20] To a solution of 5.0 g (27.8 mmol) of epoxy ketone **18** in 60 mL of dichloromethane cooled to 0 °C were added 60 mL of glacial acetic acid and 5.23 g (28.08 mmol) of recrystallized *p*-toluenesulfonylhydrazine.[34] The solution was stirred for 2 h at 0 °C and 1 h at room temperature. Workup with ether and purification by short-path distillation (oven temperature 100–105 °C, 0.25 torr; lit.[35] bp 76–80 °C, 1.0 torr) gave 2.88 g (63%) of alkynyl ketone **19** as a clear, colorless oil: $[\alpha]^{20}_D$ −37.3° (*c* 13.37, $CHCl_3$); IR (film) ν 3280, 2925, 2850, 2130, 1710, 1460, 1390, 1140, 1100 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 1.1 (s, C-2 CH_3), 1.5–2.5 (m). This material was used directly without further purification.

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(2*R*)-(−)-2-Butyl-2-methylcyclohexanone (20). To a stirred slurry of 2.04 g of palladium-on-carbon catalyst in 125 mL of ethyl acetate, which had been equilibrated under a hydrogen atmosphere, was added 3.38 g (20.6 mmol) of alkynyl ketone (−)-**19** in 20 mL of ethyl acetate. After 3 h, 500 mL of hydrogen had been taken up, and the slurry was then filtered through a pad of Celite with the aid of ethyl acetate. Removal of solvent and short-path distillation at 140–145 °C (oven temperature) at 40 torr (lit.[36] bp 116–118 °C, 20 torr) gave 2.1 g (61%) of ketone **20** as a volatile oil: $[\alpha]^{22}_D$ −20.9° (*c*, 27.68, $CHCl_3$); IR (film) ν 2925, 2850, 1710, 1480, 1460, 1390, 1140 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.9 (t, J = 9 Hz, CH_3CH_2), 1.02 (s, C-2 CH_3), 1.2–1.9 (m), 2.35 (m, $CH_2C{=}O$).

(+)-Methyl (2*R*)-2-Butyl-2-methyl-6-hydroxyhexanoate (22). The procedure of House was modified.[37] A solution of 2.1 g (12.5 mmol) of ketone (−)-**20**, 10 mL of distilled triethylamine, and 4.0 mL (31 mmol) of trimethylchlorosilane in 20 mL of dimethylformamide was heated to reflux for 22 h, at which time TLC showed an absence of the starting ketone. The mixture was cooled, poured into 300 mL of hexane, and filtered. The filtrate was washed rapidly with two 50-mL portions of ice-cold 5% sodium bicarbonate and brine and dried over sodium sulfate. Removal of solvent at reudced pressure yielded 3.0 g (100%) of silyl enol ether **21** as a yellow oil, which was used immediately. No trace of the ketone could be detected in the infrared spectrum: IR (film) ν 2925, 2850, 1660, 1475, 1250, 1180, 900, 850 cm^{-1}.

Ozonolysis was effected according to Heathcock.[38] A stream of ozone was bubbled through a cooled (−78 °C) solution of 3.0 g (12.5 mmol) of silyl enol ether **21** in 30 mL of dry methanol and 3 mL of dry dichloromethane until a deep blue color persisted (20 min). The excess ozone was purged with nitrogen, 500 mg of sodium borohydride was added, and the mixture was stirred at −78 °C for 1 h. The solution was then treated with an additional 1.5 g of sodium borohydride and allowed to warm slowly to room temperature. The solvents were removed at reduced pressure. The concentrate was diluted with ether and extracted with 10% sodium hydroxide. The basic extracts were cooled (0 °C) and acidified, and the product was isolated with ether to afford 1.08 g (43%) of a viscous oil, which was esterified immediately: IR (film) ν 3200, 2950, 2850, 1715, 1480, 1340 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.93 (t, J = 6 Hz, CH_3CH_2), 1.15 (s, C-2 CH_3), 1.0–1.75 (m), 3.63 (t, J = 6 Hz, CH_2O), 7.6 (br s, OH).

An ethereal solution of diazomethane prepared from 27.25 mL of 50% potassium hydroxide and 3.5 g (34.0 mmol) of *N*-methyl-*N*-nitrosourea[29] was added to an ice-cold solution of 1.08 g (5.45 mmol) of the above acid in 50 mL of ethyl acetate. The resultant solution was allowed to stand at room temperature for 3 h, washed with 10% sodium hydroxide and brine, and dried over magnesium sulfate. Removal of solvents at reduced pressure and column chromatography (silica gel, 25% ethyl acetate–hexane) afforded 500 mg of ester (+)-**22** as a clear, colorless oil: $[\alpha]^{22}_D$ +0.38° (*c* 26.4, $CHCl_3$); IR (film) ν 3400, 2950, 2900, 1740, 1480, 1390, 1060, 770 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.9 (t, J = 6 Hz, CH_3CH_2), 1.13 (s, C-2 CH_3), 1.0–1.7 (m), 3.4 (s, OH), 3.5 (t, J = 7.5 Hz, CH_2O), 3.65 (s, CO_2CH_3). This material was used directly without further purification.

(+)-Ethyl (2*R*)-2-Carboethoxy-7-carbomethoxy-7-methylundecanoate (24). The procedure of Marshall and Royce was followed.[39] To a stirred, cooled (0 °C) solution of 472 mg (2.18 mmol) of hydroxy ester (+)-**22** in 0.5 mL of pyridine was added 455 mg (2.39 mmol) of *p*-toluenesulfonyl chloride in 0.5 mL of pyridine. After 4 h at 0 °C, the solution was poured into ether, washed with 5% hydrochloric acid and brine, and dried over magnesium sulfate. Removal of solvent under reduced pressure yielded 809 mg (100%) of tosylate **23** as an oil, which was taken on without further purification: IR (film) ν 2900, 2830, 1740, 1600, 1480, 1375, 1180, 940, 810, 660 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, J = 6 Hz, CH_3CH_2), 1.12 (s, C-2 CH_3), 1.0–1.7 (m), 2.43 (s, $CH_3C_6H_4$) 3.63 (s, CO_2CH_3), 4.0 (t, J = 7.5 Hz, CH_2O), 7.57 (AB q, $\Delta\nu$ = 18 Hz, J = 4.5 Hz).

To a cooled (0 °C), stirred slurry of 105 mg (4.38 mmol) of washed sodium hydride in 3 mL of tetrahydrofuran was added dropwise 0.67 mL (4.38 mmol) of diethyl malonate in 3 mL of tetrahydrofuran. After 15 min, a solution of 809 mg (2.19 mmol) of tosylate **23** in 3 mL of tetrahydrofuran was added. The resultant mixture was heated to reflux for 4 h. Isolation of the crude product with ether and purification by column chromatography (silica gel, 30% ethyl acetate–hexane) gave two fractions. The first contained 240 mg of triester (+)-**24**: $[\alpha]^{22}_D$ +0.72° (*c* 16.3, $CHCl_3$); IR (film) ν 2950, 2850, 1760, 1725, 1480, 1380, 1220, 1170, 1040, 870 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.88 (t, J = 6 Hz, CH_3CH_2), 1.1 (s, C-7 CH_3), 1.26 (t, J = 6 Hz, $CO_2CH_2CH_3$), 1.0–2.0 (m), 3.28 [t, J = 7.5 Hz, $CH(CO_2R)_2$], 3.65 (s, CO_2CH_3), 4.15 (q, J = 6, $CO_2CH_2CH_3$). Anal. Calcd for $C_{18}H_{32}O_6$: C, 62.77; H, 9.36. Found: C, 62.87; H, 9.10. The second fraction contained 440 mg of (+)-**24** contaminated with diethyl malonate. Both fractions were used in the next step to prepare diester (+)-**13**.

(−)-Dimethyl (2*R*)-2-Methyl-2-(3-oxobutyl)octanedioate (26). A stream of ozone was bubbled through a cooled (−78 °C) solution of 1.2 g (6.25 mmol) of enone (+)-**10a** in 55 mL of dichloromethane until a deep blue color persisted (20 min). The excess ozone was purged with nitrogen at −78 °C. To this solution were added with stirring 24 mL of glacial acetic acid and 9 mL of 30% hydrogen peroxide at 0 °C. The solution was then warmed to room temperature and stirred for 24 h. The mixture was poured into dilute brine solution, and the product was isolated with ethyl acetate. The residual acetic acid was distilled under reduced pressure with toluene, to leave 1.61 g (100%) of the diacid as a viscous oil. This compound was used without further purification; IR (film) ν 3200, 2900, 2850, 1740, 1710, 1480 cm^{-1}.

A solution of diazomethane in ether was prepared from 63 mL of 50% KOH and 8.0 g (77.7 mmol) of *N*-methyl-*N*-nitrosourea in 312 mL of ether according to Arndt.[29] To a cooled (0 °C) solution of 1.61 g (6.25 mmol) of the diacid in 200 mL of ethyl acetate was decanted the yellow, ethereal solution of diazomethane. This solution was allowed to warm to room temperature and stand for 30 min. The solution was washed with 10% sodium hydroxide and brine and dried. Removal of solvents at reduced pressure afforded an oil, which was purified by column chromatography (silica gel, 50% ethyl acetate–hexane) and short-path distillation (oven temperature 124 °C, 0.03 torr) to give 600 mg (39%) of keto diester **26**, a clear, colorless oil: $[\alpha]^{20}_D$ −2.26° (*c* 49.15, $CHCl_3$); IR (film) ν 2950, 2850, 1730, 1710, 1480, 1450, 1200, 1180 cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 1.1–1.9 (m), 1.1 (s, C-2 CH_3), 2.1 (s, $CH_3C{=}O$),d 2.28 (t, J = 9 Hz, CH_2CO_2), 2.38 (t, J = 9 Hz, $CH_2C{=}O$), 3.62 (s, CO_2CH_3). Anal. Calcd for $C_{15}H_{26}O_5$: C, 62.9; H, 9.15. Found: C, 62.5; H, 9.0.

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Registry No. (*R*)-**9a**, 83648-91-3; (*S*)-**9a**, 83648-92-4; (±)-**9a**, 83648-93-5; (+)-**10a**, 83679-36-1; (1*S*,2*R*)-**11**, 83606-02-4; (*S*)-**12**, 4087-39-2; (*R*)-**13**, 83606-03-5; (±)-**14**, 83606-04-6; (+)-**15**, 83648-94-6; (±)-**15**, 83606-05-7; (±)-**16** (isomer 1), 83606-06-8; (±)-**16** (isomer 2), 83606-07-9; (−)-**17**, 83606-08-0; (+)-(4a*R*)-**18**, 83648-95-7; (−)-**19**, 83606-09-1; (−)-**20**, 83606-10-4; (*R*)-**21**, 83606-11-5; (*R*)-**22**, 83615-46-7; (*R*)-**22** (acid), 83606-12-6; (*R*)-**23**, 83606-13-7; (*R*)-**24**, 83615-47-8; (*S*)-**25**, 83606-14-8; (S)-**26**, 83606-15-9; (*S*)-**26** (diacid), 83606-16-0; (*R*)-**28**, 83606-17-1; (*R*)-**28** (diacid), 83606-18-2; (*R*)-**29**, 83606-19-3; diethyl malonate, 105-53-3.

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