could be isolated (72%, bp 120 °C (0.1 mmHg)): $[\alpha]^{RT}_{578}$ +6.20° (*c* 2, EtOH, 96%), corresponding to an enantiomeric excess of 94% (*R* enantiomer). Quinine as a catalyst gave the *S* enantiomer in 85% ee: IR 1840 cm^{-1} (C=O) 2-oxetanone; ^{1}H NMR δ 2.0 (3 H, s, CH_3), 3.5 (2 H, dd, CH_2). Recrystallization of reaction products from the quinidine and quinine reaction from a suitable quantity of methylcyclohexane, by cooling to 4 °C, gave both the *R* and the *S* enantiomer, enantiomerically pure, $[\alpha]^{RT}_{578}$ +6.57° (*c* 2, EtOH, 96%) (*R* enantiomer), mp 40–41 °C.

Anal. Calcd for $C_5H_5O_2Cl_3$: C, 29.52; Cl, 52.28; H, 2.48. Found: C, 29.20f Cl, 52.28; H, 2.43.

4-(Dichlorophenylmethyl)-2-oxetanone. In 50 mL of toluene, 3.1 g (16.5 mmol) of (dichlorophenyl)acetaldehyde was reacted with ketene, using 79 mg (0.2 mmol) of quinidine as a catalyst at −25 °C. After workup 3.4 g (14.7 mmol) of the 2-oxetanone could be isolated (89%, bp 100 °C (0.1 mmHg)), $[\alpha]^{RT}_{578}$ −35.7° (*c* 1, EtOH, 96%), corresponding to an enantiomeric excess of 90%. Quinine in the same reaction gave a product, $[\alpha]^{RT}_{578}$ +27.0° (*c* 1, EtOH, 96%), corresponding to an enantiomeric excess of 68%. Recrystallization of 3.1 g of a portion, $[\alpha]^{RT}_{578}$ −35.7°, from methylcyclohexane yielded 1.9 g of a crystalline product, $[\alpha]^{RT}_{578}$ −39.5° (*c* 1, EtOH, 96%), optically pure, mp 36–36.5 °C: IR 1845 cm^{-1} (C=O) 2-oxetanone; ^{1}H NMR δ 3.5 (2 H, d, CH_2), 4.9 (1 H, t, CH), 7.1–7.9 (5 H, m, C_6H_5).

Anal. Calcd for $C_{10}H_8Cl_2O_2$: C, 51.98; Cl, 30.68; H, 3.49. Found: C, 51.73; Cl, 30.73; H, 3.41.

4-(Trichloromethyl)-4-(4-chlorophenyl)-2-oxetanone. With approximately a 5-fold excess of ketene, starting with 1.05 g (4 mmol) of trichloro-4-chloroacetophenone, in 10 mL of toluene, using 90 mg (0.28 mmol) of quinidine as a catalyst, 810 mg (2.7 mmol, 68%) of the 2-oxetanone could be isolated, $[\alpha]^{RT}_{578}$ −51.5° (*c*, 1, toluene), corresponding to an enantiomeric excess of 90%. Quinine yielded a product, $[\alpha]^{RT}_{578}$ +37.9° (*c* 1, toluene), corresponding to 65% ee. Recrystallization of the product from the quinidine reaction from methylcyclohexane afforded a white crystalline material, $[\alpha]^{RT}_{578}$ −57.4° (*c* 1, toluene), enantiomerically pure, mp 148–149 °C: IR 1840 cm^{-1}, (C=O) 2-oxetanone; ^{1}H NMR δ 3.9 (2 H, dd, CH_2), 7.3 (4 H, dd, C_6H_4).

Anal. Calcd for $C_{10}H_6Cl_4O_2$: C, 40.04; Cl, 47.28; H, 2.02. Found: C, 40.03; Cl, 47.08; H, 2.07.

4-(Trichloromethyl)-4-(4-nitrophenyl)-2-oxetanone. From 3.1 g (11.5 mmol) of trichloro-*p*-nitroacetophenone, using 89 mg (0.27 mmol) of quinidine in 50 mL of toluene at −25 °C, 3.4 g (11 mmol) of adduct could be isolated (95%), $[\alpha]^{RT}_{578}$ −55.4° (*c* 1, toluene), corresponding to an enantiomeric excess of 89%. Quinine, used as catalyst, gave a product, $[\alpha]^{RT}_{578}$ +39.0° (*c* 1, toluene), 65% ee. Recrystallization of 3.3 g of a portion, $[\alpha]^{RT}_{578}$ −55.4° (*c* 1, toluene), from chloroform yielded 2.5 g of a white crystalline product, $[\alpha]^{RT}_{578}$ −62.5° (*c* 1, toluene), optically pure, mp 188 °C dec: IR 1840 cm^{-1} (C=O) 2-oxetanone; ^{1}H NMR δ 4.0 (2 H, dd, CH_2), 7.9 (4 H, dd, C_6H_4).

Anal. Calcd for $C_{10}H_6Cl_3NO_2$: C, 38.68; Cl, 34.25; N, 4.51; H, 1.95. Found: C, 38.49; Cl, 34.37; N, 4.48; H, 1.94.

Improved Procedure for the Tungstate-Catalyzed Epoxidation of α,β-Unsaturated Acids

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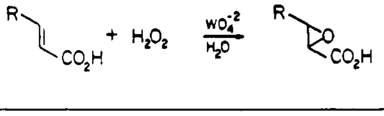
Since its discovery by Payne in 1959,[1] the aqueous, tungstate-catalyzed epoxidation of α,β-unsaturated acids by H_2O_2 has found limited application as an oxidative synthetic method.[2]

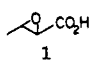
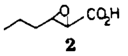
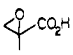
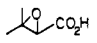
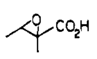
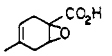


We were attracted to this tungsten-catalyzed process because of the apparent substrate similarity between this reaction and the epoxidation of allylic alcohols with alkyl hydroperoxides catalyzed by titanium[3] and other early transition metal catalysts. In both cases the substrate possesses a functional group, proximate to the olefin undergoing epoxidation, which is capable of coordinating to the metal catalyst. Also intriguing are the apparent dissimilarities (i.e., electron-poor olefin as substrate, H_2O as solvent, H_2O_2 as oxidant). This process has been studied with an eye toward broadening the scope of its synthetic utility, as well as investigating its mechanism.[4]

Table I. Modifications to the Original Payne Epoxidation Procedure for α,β-Unsaturated Acids

		modification	
variable	original	disubstituted	trisubstituted
% catalyst	10	15	10
pH	4–5.5	5.8–6.8	5.8–6.8
T (°C)	60–65	60–65	r.t.

Table II. Products of the Modified Tungsten Epoxidation of α,β-Unsaturated Acids

entry	epoxy acid	time,[a] h	% crude product (purity)[b]	lit. % yield (ref)
1	 **1**	3	83.1 (86)	50[c] (1, 7)
2	 **2**	2	82.0 (88)	
3	 **3**	2	70.7 (91)	
4	 **4**	1.5	76 (>96)	46.7[d] (2b)
5	 **5**	1.75	81.3 (100)	
6	 **6**	2	48.3 (100)[e]	

[a] Reaction followed by TLC. [b] Purity determined by ^{1}H NMR immediately following product isolation. [c] Yield is of purified product. [d] Yield listed is for the total crude material recovered only. No purity was given. [e] Isolated, purified (chromatography), and analyzed as the methyl ester.

Regarding the first of our objectives, a few simple modifications (Table I) of the original epoxidation procedure described by Payne[1] have been found to substantially improve yields of some epoxy acids. Thus, using the modifications in Table I, both di- and trisubstituted unsaturated acids can be epoxidized in high yield (Table II). While the reaction of disubstituted unsaturated acids does not go to completion, the yield of epoxycrotonic acid (**1**) in the crude reaction mixture, when using the modifications, is well above that provided by the literature. Entry

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[1] Payne, G. B.; Williams, P. H. *J. Org. Chem.* **1959**, *24*, 54.

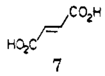
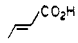
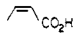
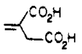
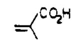
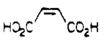
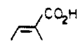
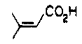
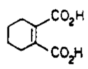
[2] In all, only four substrates have been epoxidized by using this procedure: (a) Aberhart, D. J.; Tann, C.-H. *Biorg. Chem.* **1981**, *10*, 375. (b) Chan, T. H.; Hill, R. K. *J. Org. Chem.* **1970**, *35*, 3519. (c) Creighton, S. M.; Mitchell, D. L. *Can. J. Chem.* **1967**, *45*, 1304. (d) Menger, F. M.; Vasquez, P. C. *J. Org. Chem.* **1982**, *47*, 5400. (e) For tungsten-catalyzed epoxidations under heterogeneous conditions, see: Allan, G. G. U.S. Patent 3 156 709; *Chem. Abstr.* **1965**, *62*, 2762g.

[3] (a) Martin, V. S.; Woodard, S. S.; Katsuki, T.; Yamada, Y.; Ikeda, M.; Sharpless, K. B. *J. Am. Chem. Soc.* **1981**, *103*, 6237. (b) Rossiter, B. E.; Katsuki, T.; Sharpless, K. B. *J. Am. Chem. Soc.* **1981**, *103*, 464. (c) Kirshenbaum, K. S. *Nouv. J. Chim.* **1983**, *7*, 699.

[4] For other mechanistic studies, see: (a) Badasyan, G. V.; Gabrielyan, S. M.; Kamalov, G. L.; Treger, Y. A. *Arm. Khim. Zh.* **1980**, *33*, 794. (b) Saegebarth, K. A. *J. Org. Chem.* **1959**, *24*, 1212. (c) Khante, R. N.; Chandalia, S. B. *Indian J. Chem.* **1981**, *15*, 33. (d) Ahmad, I.; Beg, M. A. *Indian J. Chem.* **1978**, *16A*, 475.

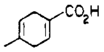
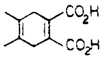
0022-3263/85/1950-1979$01.50/0

Table III. Relative Rates of Epoxidation of Substrate vs. Crotonic Acid (9)

entry	substrate	relative rate[a]
1	 **7**	<0.05
2	 **8**	<0.05
3	 **9**	1.00
4	 **10**[b]	1.65[c]
5	 **11**	2.13
6	 **12**	2.45
7	 **13**	2.48
8	 **14**	4.10
9	 **15**	19.3
10	 **16**[d]	≫20[e]

[a] A general procedure is given in the Experimental Section. [b] Made by the procedure of Heathcock et. al.; see ref 8. [c] Relative rate for this substrate was taken as the ratio of the time it took **9** to reach 20% conversion divided by the time it took **10** to reach 20% conversion. These values were measured by ^{1}H NMR (see Experimental Section). [d] Made by the procedure of Bailey and Amstutz, see ref 9. [e] Only **16** reacted.

Table IV. Regioselectivity of Epoxidation

entry	substrate	relative rate[a] conjugated to nonconjugated
1	 **19**[b]	1.38
2	 **20**[c]	≫20[d]

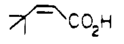
[a] A general procedure is given in the Experimental Section. [b] Made by the procedure of Hoppmann and Weyerstahl; see ref 12. [c] Made by the procedure of Kycherov et. al.; see ref 13. [d] Measured by ^{1}H NMR. To the limits of detection no 4,5-epoxide was formed.

6 demonstrates that the tungstate-catalyzed method of epoxidation can provide easy access to some epoxy acids which would otherwise be difficult to synthesize. For example, the powerful new potassium peroxomonosulfate/ketone epoxidizing reagent of Curci[5] would be expected to yield the 4,5-epoxy compound exclusively. All the unsaturated acids (including **17**, vide infra) were epoxidized with retention of double-bond geometry.[6]

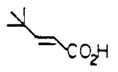
To probe the mechanism of the tungstate-catalyzed epoxidation reaction, relative rates of some 28 pairs of unsaturated acids were determined. A representative sample of rates relative to crotonic acid (**9**) is shown in Table III.

Entries 1, 3, 8, and 9 corroborate the findings of Ahmad and Beg[4d] that the oxidizing species acts as an electrophile; i.e., increasing the nucleophilicity of the double bond increases the reaction rate.

From the relative rates in Table III, one can see that a β-cis-alkyl substituent (**10**) or an α-alkyl substituent (**12**) are both rate enhancing. Even the sterically encumbered *cis*-4,4-dimethyl-2-pentenoic acid (**17**) reacted faster than the less strained trans isomer **18**.[11] A similar cis/trans relative rate relationship has been observed with peracids.[12]



17



18

Relative Rate
17 to 18
1.31

In the intramolecular competition between an isolated olefin and an α,β-unsaturated acid (Table IV, **19**), epoxidation occurred with little regioselectivity. However, it should be noted that all other electrophilic epoxidizing reagents would be expected to yield the 4,5-epoxy compound exclusively. In the case of diacid **20** (Table IV), epoxidation was highly regioselective. To the limits of detection, epoxidation occurred only at the conjugated, electron-deficient olefin. This regioselectivity occurred in spite of the presence of an electron-rich, tetrasubstituted double bond.

From Table III (entries 1 and 7), one can see that maleic acid (**13**) reacts faster than both crotonic (**9**) and fumaric (**7**) acids. This ordering contradicts that reported by Beg.[4d] (Beg reported that crotonic acid (**9**) reacts faster than fumaric acid (**7**), which, in turn, reacts faster than maleic acid (**13**).) It is indeed surprising that the double bond of **13**, being more electron deficient than the corresponding double bond in **9**, should be epoxidized faster. At first glance one might attribute the observed reactivity to the presence of two acid groups, each capable of independently coordinating to the tungsten catalyst; (cf. Table III, entry 5). However, this idea alone cannot account for the results since fumaric acid (**7**), also possessing two acid functions on one double bond, is much slower than **9**.

In order to explain this apparent anomaly, one must consider the catalyst system. Tungstates are known to be polymeric in acidic, neutral, and mildly basic aqueous solutions.[15] The distribution of molecular complexes in a solution of polytungstates is affected by many factors, especially pH and concentration. We believe that the catalytic system involved here is also a complex mixture of tungstate species which in principle may exhibit different catalytic activities. We postulate that the two syn carboxylic acid groups enable **13** and related cases (e.g., **20**) to bind to the metal in a bidentate fashion. This chelation, which is not possible for the monodentate acids and is geometrically impossible for diacids such as fumaric

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(5) Curci, R.; Fiorentino, M.; Troisi, L. *J. Org. Chem.* **1980**, *45*, 4758.

(6) Liwschitz, Y.; Rabinsohn, Y.; Perera, D. *J. Chem. Soc.* **1962**, 1116.

(7) Mohrig and co-workers prepared pure epoxycrotonic acid in 36% yield after recrystallization from CH_2Cl_2. Crude product yield was 48%: Mohrig, J. R.; Vreede, P. J.; Schultz, S. C.; Fierke, C. A. *J. Org. Chem.* **1981**, *46*, 4655.

(8) Taschner, M. J.; Rosen, T. J.; Heathcock, C. H. In "Organic Syntheses"; Semmelhack, M. F., Ed., in press.

(9) This relative rate was very sensitive to the percent conversion of the fast reacting substrate (**15**). The value 19.3 was obtained as an average of three values (all within a 15% spread in conversion of **15**) and had a standard deviation of 0.71. At other percent conversions of **15** (75%, 96%), the relative rate of **9** vs. **15** was 46 and 155, respectively.

(10) Bailey, M. E.; Amstutz, E. D. *J. Am. Chem. Soc.* **1956**, *78*, 3828.

(11) Epoxidation of **17** and **18** yield products with different ^{1}H NMR spectra. No cis/trans isomerization was seen. See supplementary material section.

(12) Plesnicar, B. In "Oxidation in Organic Chemistry, Pt. C", Trahanovsky, W. S., Ed.; Academic Press: New York, 1978; Chapter 3, p 238.

(13) Hoppmann, A.; Weyerstahl, P. *Chem. Ber.* **1974**, *107*, 1102.

(14) Kycherov, V. F.; Grugoreva, N. Y.; Zemskova, I. I. *Zh. Obsch. Khim.* **1961**, *31*, 457.

(15) Cotton, F. A.; Wilkinson, G. "Advanced Inorganic Chemistry", 4th ed.; Wiley: New York, 1980; Chapter 22, p 852.

Table V. Inhibitory Effect of Maleic Acid (13) on the Reaction of Crotonic Acid (9)

entry	reaction	$T_{0.2}$, min	
		maleic	crotonic
1	maleic	6.2	
2	crotonic		15.7
3	both competing	6.3	19.4

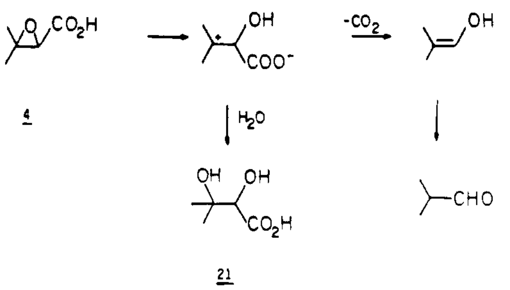
(7), potentially creates a difference in the relative affinities of competing substrates for the catalyst. It may also have the effect of changing the distribution of catalytic species in the solution. This would mean that the observed increase in relative rate over the expected value is due *not* to an increase in the rate of the oxygen transfer step but rather to one or both of the putative phenomena suggested above.

To test the proposed chelation effect we ran the following reactions. The first is seen in Table III, entry 2. The monomethyl ester of maleic acid (8) reacts at a rate comparable to that of fumaric acid (7). Both acid functions are apparently necessary in order for strong chelation to occur.

The results of another set of reactions are shown in Table V. In two separate reactions (1.0 equiv of substrate, 0.1 equiv of catalyst, 20 equiv of H_2O_2, 60–65 °C), the time necessary for 20% reaction to occur ($T_{0.2}$) was measured for crotonic (9) and maleic (13) acids.[16] In another reaction, the $T_{0.2}$ values were measured with the substrates competing for a limited number of catalytic sites (1.0 equiv of 9, 1.0 equiv of 13, 0.1 equiv of catalyst, 20 equiv of H_2O_2, 60–65 °C).[16]

The presence of maleic acid (13) clearly slows the epoxidation of crotonic acid (9) as evidenced by the longer time (almost 4 min) it took crotonic acid (9) to reach 20% conversion in the presence of maleic acid (13), as opposed to without maleic acid (13). On the other hand, the $T_{0.2}$ of maleic acid (13) was unaffected, within experimental error, by the presence of crotonic acid (9). The inhibitory effect that maleic acid (13) exerts on the reaction of crotonic acid (9) supports the idea of bidentate chelation.

Interestingly, 3-methyl-2-butenoic acid (Table III, 15) was epoxidized at a much faster rate relative to crotonic acid (9) than one would expect for a trisubstituted acid (i.e., compared to (*E*)-2-methyl-2-butenoic acid (14)). A possible explanation for this result derives from the fact that the epoxide of 15 (i.e., 4) is expected to be less stable than any of the other epoxides in Table III. Epoxide 4 can



(1)

be expected to decompose by one of the pathways outlined in eq 1.[17] The pathway leading to 21 is especially likely considering that the tungstate system is also known to catalyze the hydroxylation of olefins via the epoxide.[4b]

Table VI. Additive Effect on the Relative Rate of Epoxidation of 9 vs. 15

entry	additive	pH	ratio additive/catalyst	relative rate[a]
1	picolinic acid	5.5	1.19	3.0
2	no additive	5.5		5.1
3	ethylene glycol	5.5	1.19	14.9
4	D-(−)-butanediol[b]	5.5	1.21	23.2
5	*dl*-lactic acid	5.4	1.20	25.0
6	L-(+)-tartaric acid[b]	5.5	1.19	28.9

[a] Relative rates were determined in the same manner as in the previous competition experiments (see Experiments Section). [b] No asymmetric induction was observed in the epoxy acid products.

If 21 is formed in the reaction mixture, it could be expected to chelate to the tungsten catalyst[18] in a manner similar to that of diacids such as 13. Table VI shows the results of a series of competition experiments between crotonic acid (9) and 3-methyl-2-butenoic acid (15) in the presence of various polydentate additives. The tungstate, H_2O_2, and an additive were mixed in one flask while the reactants were dissolved in water at 60–65 °C in a second flask. After a few minutes the "performed" catalyst was added to the hot solution of the substrates. After reaction was complete, the relative rates were calculated as before. It is noteworthy that the highest relative rates occur with additives (entries 3–6) that have structural features similar to those of 21.[19]

Also apparent from Table VI is the effect of preforming the catalyst, without an additive, by mixing the tungstate and H_2O_2 prior to reaction. The relative rate under these conditions (entry 2) is 5.1 compared to a relative rate under standard conditions of 19.3 (Table III, entry 9).[20] In addition, a ^{1}H NMR spectrum of a heated mixture of tungstate, H_2O_2, and tartaric acid in D_2O revealed the presence of several tartrate complexes. These observations support the concept of a variable distribution of catalytic species.

In conclusion, the simple modifications presented here to the original Payne epoxidation procedure should increase the scope and synthetic utility of the process.

Experimental Section

Infrared (IR) spectra were measured with a Perkin-Elmer Model 597 grating infrared spectrometer. The 1601-cm^{-1} absorption band of polystyrene film was used to calibrate the chart paper. Proton nuclear magnetic resonance (^{1}H NMR) spectra were measured with Brucker 250-MHz or 270-MHz spectrometers. When the solvent was $DCCl_3$, tetramethylsilane (Me_4Si) was used as an internal standard; however, when the solvent was D_2O, the standard was chloroacetic acid. The singlet of chloroacetic acid was set at δ 4.0. Elemental analyses were performed by the Robertson Laboratory Inc., Florham Park, NJ. Measurement of pH was achieved by using a digital mini VWR Model 49 pH meter.

All substrates were commercially available and used without further purification except crotonic acid which was recrystallized from water. $Na_2WO_4\cdot 2H_2O$, NaOD, and D_2O were obtained from Aldrich and chloroacetic acid was obtained from Eastman Kodak.

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[16] The reaction was carried out in a ^{1}H NMR tube and also followed by ^{1}H NMR. $T_{0.2}$ was determined from a line fitted to a plot of time vs. % conversion by a least squares analysis. In each case a straight line was obtained ($r^2 > 0.99$). In all cases there was deviation from the line beginning between 30% and 60% conversion.

[17] House, H. O. "Modern Synthetic Reactions"; Benjamin/Cummings: Reading, MA, 1972; p 670.

[18] (a) Baillie, M. J.; Brown, D. H. *J. Chem. Soc.* **1961**, 3691. (b) Brown, D. H.; Forsyth, D. *J. Chem. Soc.* **1962**, 1837. (c) Rabenstein, D. L.; Greenberg, M. S.; Saetre, R. *Inorg. Chem.* **1977**, *16*, 1241. (d) Sheldon, R. A.; Kochi, J. K. "Metal-Catayzed Oxidations of Organic Compounds"; Academic Press: New York, 1981; p 62.

[19] The relative rate of 14 to 15, determined in a manner similar to that used in determining the relative rates in Table III (i.e., direct competition under the standard conditions) is 1.0. This number, taken together with the relative rates in Table III (entries 8 and 9) for 14 and 15 vs. 9 seems to indicate that the change in the catalyst caused by formation of 21 during the course of the reaction increases selectivity, not just toward 15 but also toward other trisubstituted unsaturated acids.

[20] Interestingly, the value 5.1 compares favorably with the value of 4.1 for the competition of trisubstituted acid 14 vs. 9 (Table III, entry 8) under the standard conditions.

All were used without further purification.

In general, after ^1H NMR analysis of the crude reaction mixture, the epoxy acids were converted to the methyl esters by reaction with diazomethane and purified by column chromatography for further analysis.

General Procedure for the Epoxidation of Disubstituted α,β-Unsaturated Acids (Preparation of Products 1–3). Crotonic acid (**9**) (98%, 0.1797 g, 2.05 mmol), 0.15 equiv of $Na_2WO_4 \cdot 2H_2O$ (0.1020 g, 0.31 mmol) and 6 mL of H_2O were placed in a flask. The mixture was heated to 60–65 °C and stirred magnetically. Dissolution of the solid acid was aided by the periodic addition of 1 N KOH. After the solid was completely dissolved, the pH of the solution was adjusted to 6.2 by the addition of 1 N KOH and/or 1 N H_2SO_4. After ca. 10 min of additional stirring, 1.2 equiv of aqueous H_2O_2 (10.57 M, 0.23 mL, 2.43 mmol) was added. The pH of the reaction mixture was kept between 5.8 and 6.8.

After 3 h no further reaction could be detected by TLC (40% EtOAc/hexane). The mixture was acidified to pH <2.0 with 50% H_2SO_4, saturated with ammonium sulfate, and extracted 5× with diethyl ether (ca. 60 mL total). The organic extracts were combined, dried ($MgSO_4$), filtered, and evaporated to yield 0.1735 g (83.1%) of crude (2*S**,3*R**)-2,3-epoxybutanoic acid (**1**) which was judged by ^1H NMR to be 86% pure (14% starting material).

Crude product: ^1H NMR ($DCCl_3$) δ 6.80–6.96 (m, 0.14 H, $CH_3CH{=}$), 5.72 (dd, *J* = 15.1, 1.1 Hz, 0.14 H, $HO_2CCH{=}$), 2.92 (m, 1.72 H, epoxide hydrogens), 1.82 (d, *J* = 4.3 Hz, 2.58 H, CH_3), 1.29 (dd, *J* = 9.2, 1.2 Hz, 0.42 H, CH_3).

Pure methyl ester: ^1H NMR ($DCCl_3$) δ 3.78 (s, 3 H, OCH_3), 3.21–3.27 (m, 2 H), 1.40 (d, *J* = 5.0 Hz, 3 H, CH_3); IR (neat) 2960, 2940, 1755, 1740, 1445, 1425, 1380, 1340, 1300, 1210, 1150, 1040, 1010, 875 cm^{-1}. Anal. Calcd for $C_5H_8O_3$: C, 51.72; H, 6.94; Found: C, 51.63; H, 7.07.

General Procedure for the Epoxidation of Trisubstituted α,β-Unsaturated Acids (Preparation of Products 4–6). 3-Methyl-2-butenoic acid (**15**) (0.200 g, 2.00 mmol), 0.1 equiv of $Na_2WO_4 \cdot H_2O$ (0.067 g, 0.20 mmol), and 6 mL of H_2O were placed in a flask at room temperature. The mixture was stirred magnetically and dissolution of the solid acid was aided by the periodic addition of 2 N KOH. After the solid was completely dissolved, the pH of the solution was adjusted to 6.2 by the addition of 1 N KOH and/or 1 N H_2SO_4. After ca. 10 min of additional stirring at room temperature, 1.2 equiv of aqueous H_2O_2 (10.57 M, 0.23 mL) was added. The pH of the reaction mixture was kept between 5.8 and 6.8.

After 1.5 h the reaction was judged complete by TLC (40% EtOAc/hexane). The mixture was acidified to pH <2.0 with 50% H_2SO_4, saturated with ammonium sulfate, and extracted 5× with diethyl ether (ca. 60 mL). The organic extracts were combined, dried ($MgSO_4$), filtered, and evaporated to yield 0.176 g of 2,3-epoxy-3-methylbutanoic acid (**4**) (76%) as a colorless, viscous liquid which was immediately analyzed by ^1H NMR and found to be >96% pure. The epoxy acid slowly decomposed even in a 0 °C refrigerator.

^1H NMR ($DCCl_3$): δ 7.0 (br s, 1 H, COOH), 3.41 (s, 1 H, CH), 1.46 (s, 3 H, CH_3), 1.44 (s, 3 H, CH_3); methyl ester, IR (neat) 2980, 2958, 1755, 1440, 1380, 1320, 1290, 1210, 1125, 1055, 1028, 870, 820, 765 cm^{-1}.

General Procedure for the Determination of Relative Rates in the Absence of Chelating Additives. Crotonic acid (**9**) (0.1772 g, 2.06 mmol), 2-methylpropenoic acid (**12**) (0.1784 g, 2.07 mmol), chloroacetic acid (0.112 g, 1.19 mmol) [as an internal standard], $Na_2WO_4 \cdot 2H_2O$ (0.0666 g, 0.20 mmol), and 6 mL of D_2O were placed in a 25-mL, round-bottomed flask. The pH was adjusted to 5.5 by the addition of 30% NaOD in D_2O. The solution was magnetically stirred and heated to 60–65 °C. Upon complete dissolution of the acids, a 1-mL aliquot (T_0) was removed and 0.6 equiv of 30% aqueous H_2O_2 (0.11 mL, 1.07 mmol) was added. After 30–60 min a second aliquot (T_1) was removed. The aliquots were analyzed by ^1H NMR and the percent of **9** and percent of **12** in T_1 were determined to be 78.2% and 54.8%, respectively. The relative rate of epoxidation of **12** to **9** was determined by the formula[3a,21]

$$\frac{K_1}{K_2} = \frac{\ln (1 - [A]/[A_0])}{\ln (1 - [B]/[B_0])} = \frac{\ln (0.548)}{\ln (0.782)} = 2.45$$

Where [A] and [B] are the concentrations, in the T_1 aliquot, of the fast and slow reacting acids, respectively, and [A_0] and [B_0] are the initial concentrations of the fast and slow reacting acids, respectively.

General Procedure for the Determination of Relative Rates in the Presence of Chelating Additives. Crotonic acid (**9**) (0.173 g, 2.01 mmol), 3-methyl-2-butenoic acid (**15**) (0.205 g, 2.05 mmol), chloroacetic acid (0.180 g, 1.91 mmol), and 6 mL of D_2O were placed in a 25-mL flask (A). The mixture was stirred magnetically and the temperature was raised to 64 °C. As the acids dissolved, the pH of the solution was adjusted to 5.5 by addition of 30% N NaOD in D_2O. A 1-mL aliquot (T_0) was removed for analysis.

Sodium tungstate dihydrate (0.056 g, 0.17 mmol), ethylene glycol (0.013 g, 0.21 mmol, 1.2 equiv to catalyst), and 1 mL of D_2O were placed in a second flask (B). After the contents of flask B were stirred for 10–20 min, 0.3 equiv of aqueous H_2O_2 (0.063 mL, 0.61 mmol) was added and the solution was stirred for 5 additional minutes. The contents of flask B was then added to flask A.

The reaction mixture was allowed to stir for 30 min at 60–65 °C after which a 1-mL aliquot (T_1) was removed. Analysis of the aliquots by ^1H NMR showed that the percent of **9** and percent of **15** remaining in T_1 were 95.7% and 52.0%, respectively. The relative rate of **15** to **9** was determined to be 14.9 by the above formula.[3a,21]

General Procedure for the Determination of $T_{0.2}$. Maleic acid (**13**) (0.234 g, 2.02 mmol), chloroacetic acid (0.188 g, 2.00 mmol), and $Na_2WO_4 \cdot 2H_2O$ (0.066 g, 0.20 mmol) were dissolved in 6.5 mL of D_2O. The pH of the solution was adjusted to 5.5 by the addition of 30% NaOD in D_2O and the volume was adjusted to 7.0 mL by adding D_2O. A 1-mL portion of the solution was removed and placed in a ^1H NMR tube. The tube was sealed with a septum and heated in a ^1H NMR probe to 63 °C. After a time = 0 spectrum was taken, the tube was removed from the probe, 10 equiv of 30% aqueous H_2O_2 (0.30 mL, 2.91 mmol) was added by syringe, the time was noted, and the tube was quickly returned to the hot probe. Spectra were taken at convenient intervals and a plot of % maleic acid vs. time yielded a line (r^2 = 0.9956) in the region of interest (0–30% conversion). Representative data appear below. The 20% conversion time was determined to be 6.29 min. Repeated trials yielded values that averaged to 6.19 min and varried by less than 5%.

time (min)	% maleic acid
0	100
3.82	86.6
6.68	79.0
7.72	75.9

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Registry No. 1, 96150-05-9; 1 methyl ester, 59123-20-5; **2**, 96096-69-4; **3**, 38649-35-3; **4**, 4374-53-2; **5**, 96096-70-7; **6**, 96096-71-8; **6** methyl ester, 96096-78-5; **7**, 110-17-8; **7** epoxide, 22734-83-4; **8**, 3052-50-4; **8** epoxide, 96096-72-9; **9**, 3724-65-0; **10**, 503-64-0; **10** epoxide, 96096-73-0; **11**, 97-65-4; **11** epoxide, 94853-87-9; **12**, 79-41-4; **13**, 110-16-7; **13** epoxide, 16533-72-5; **14**, 80-59-1; **15**, 541-47-9; **16**, 635-08-5; **16** epoxide, 96096-74-1; **17**, 1577-94-2; **17** epoxide, 96096-76-3; **18**, 16666-45-8; **18** epoxide, 96096-77-4; **19**, 53312-53-1; **20**, 91061-82-4; **20** epoxide, 96096-75-2; **21**, 1756-18-9; chloroacetic acid, 79-11-8; (*E*)-2-hexenoic acid, 13419-69-7; picolinic acid, 98-98-6; ethylene glycol, 107-21-1; D-(−)-butanediol, 6290-03-5; *dl*-lactic acid, 598-82-3; L-(+)-tartaric acid, 87-69-4.

Supplementary Material Available: Procedure for the preparation of *cis*-4,4-dimethyl-2-pentenoic acid (**17**); ^1H NMR data for **2**, **3**, **5**, **6** (Table II), **17**, **18**, and the epoxide of **17**; IR data for **3**, **5**, **6**, **17**, **18**, and the epoxide of **17**; and elemental analysis date for **3**, **6**, and the epoxide of **17** (4 pages). Ordering information is given on any current masthead page.

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(21) Williams, D. R., M.S. Dissertation, Massachusetts Institute of Technology, Cambridge, MA, 1972, p 68.