Selective Diesterification of Diols through Cyclic Ketene Acetal Intermediates

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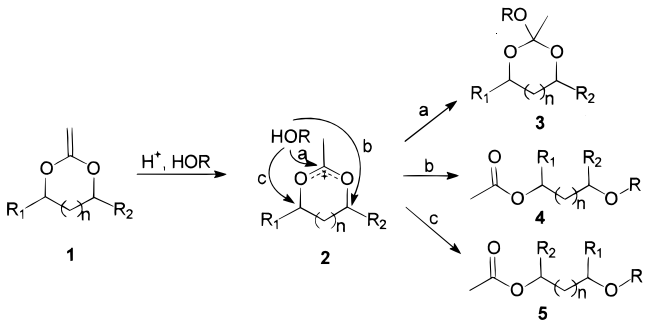
Introduction

Cyclic ketene acetals (CKAs) are easily protonated to generate stable cyclic dioxonium ions. These cations are ambident reagents which undergo nucleophilic attack at three possible locations (see Scheme 1).[1−4] In some of these nucleophilic reactions, CKA polymerization either competed or dominated.[1−3]

Recently, Zhu and Pittman reported the selective preparation of monoacetylated diols via CKAs.[5] The reactive CKAs were directly hydrolyzed by water on the acidic surface of alumina to form monoacetylated diols (conversion of **8** to **9**, Scheme 2) in good yields and very high regioselectivity.

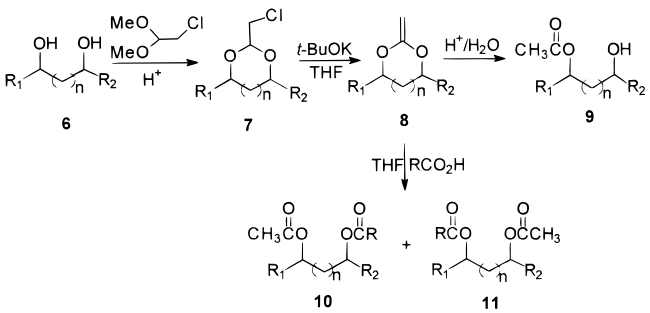
The synthesis of diesters of diols by reacting carboxylic acids with 2-methyl-1,3-dioxonium ion intermediates such as **2** would be of special interest if mixed diesters could be *selectively* prepared from CKA intermediates made from the corresponding diols. In general, a mixed diester can be made via a monoesterification of a diol followed by another esterification of the monoester. However, the monoesterification step can result in a mixture of unreacted diol, monoester. and diester. When an unsymmetrical diol is used, the situation is even more complicated because two different monoesters are possible. Despite numerous attempts,[6−15] improvement of the mono/di acetylation ratios has not been very successful

Scheme 1



n = 0, 1, or 2; R_1, R_2 = H, alkyl or Ph; R = H, alkyl, Ph, Ac, or etc.

Scheme 2



n = 0, 1 or 2 ; R = Me, Et, *i*-Pr, *t*-Bu or Ph ; R_1 = H or Me ; R_2 = H, Me, *t*-Bu or Ph

in attemps to selectively monoesterify diols.[16] No method has been reported to selectively form mixed diesters of diols in a single step.

Despite their potential use in synthesis, selective mixed diesterification and selective hydroxyl group protection/deprotection via esterification[17] represent a challenge. By forming mixed esters, it is possible to selectively cleave one of the esters.[18−21] The regioselective formation of mixed diesters of diols in good yields, developed via the reaction of CKAs with carboxylic acids, is presented in this paper.

Results and Discussion

A. Syntheses of the Diacetates and Mixed Diesters of Symmetrical Diols through Cyclic Ketene Acetal Intermediates. Diesters of three symmetrical diols (ethylene glycol, 1,3-propanediol, and 1,4-butanediol) were synthesized via reactions of carboxylic acids with 2-methylene-1,3-dioxolane (**8a**), 2-methylene-1,3-dioxane (**8b**), and 2-methylene-1,3-dioxepane (**8c**) (Scheme 3, R_1 = R_2 = H). These cyclic ketene acetals were prepared as shown in Scheme 2.[5,22−27,32,33] The reactions between acetic acid and cyclic ketene acetals produced their corresponding diacetates. When propionic acid,

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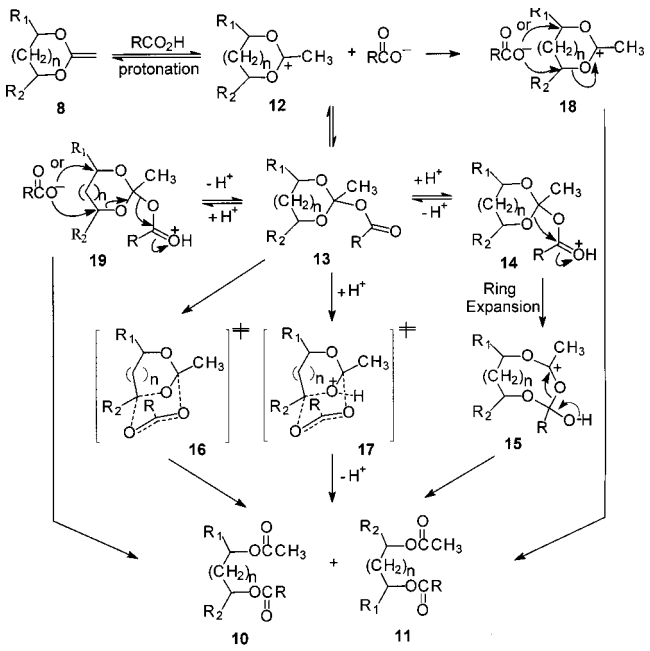
Scheme 3



trimethylacetic acid, or benzoic acid was used, the corresponding mixed diesters were formed. Various methods of addition were explored. The addition of CKAs to a stirred THF solution containing an excess of the carboxylic acid was the preferred mode, generating the highest diester yields while minimizing cationic vinyl polymerization. Addition of carboxylic acid to the CKA gave lower yields. The unisolated cyclic ketene acetal, obtained upon dehydrohalogenation, could be added directly to the carboxylic acid.

Adding Acetic Acid into Neat CKAs. Syntheses of the diacetates of ethylene glycol, 1,3-propanediol, and 1,4-butanediol were attempted first by adding acetic acid dropwise into the corresponding neat CKAs. However, fast cationic vinyl polymerization occurred to give poly(CKA)s when anhydrous acetic acid was added into either 2-methylene-1,3-dioxolane (**8a**) or 2-methylene-1,3-dioxane (**8b**). In contrast, when anhydrous acetic acid was added to stirred neat 2-methylene-1,3-dioxepane (**8c**) at room temperature, 1,4-diacetoxybutane (**10i**) was formed instantly as the only product in 65% isolated yield (GC). These examples demonstrate that the direct addition of carboxylic acid to a CKA solution was not a suitable general technique to obtain diesters.

Adding CKAs into Excess Carboxylic Acid in THF. Diesters of ethylene glycol and 1,3-propanediol were synthesized in good (87−96%) isolated yields (see Table 1) by adding 2-methylene-1,3-dioxolane (**8a**) or 2-methylene-1,3-dioxane (**8b**)/THF solutions to a 5-fold mole excess of various carboxylic acids in THF at 22−25 °C. CKA polymerizations did not occur with this mode of addition. The reactions of 2-methylene-1,3-dioxane (**8b**) were complete in 2 h, whereas the reactions of 2-methylene-1,3-dioxolane (**8a**) took less than 4 h.

1,4-Diacetoxybutane (**10i**) synthesis was also performed by adding 2-methylene-1,3-dioxepane (**8c**)/THF solution into acetic acid/THF solutions. This reaction was very slow, giving less than a 5% (GC area) yield after 12 h. However, when neat **8c** was added, at 90 °C, to a 7-fold excess of neat acid (acetic, proprionic, or trimethylacetic) or to a benzoic acid in THF, the reactions were completed in less than 8 h, giving isolated diester yields from 78% to 89% (Table 1).

Syntheses of Propanediol Diesters Using 2-Methylene-1,3-dioxane (8b) as an Unisolated Intermediate. The isolation of pure CKAs can be difficult because of their high chemical reactivity. Thus, their in situ use for diester synthesis was more practical. Propanediol diesters were synthesized from unisolated 2-methylene-1,3-dioxane to test this idea. The crude CKA/THF solution obtained after dehydrochloronation of 2-chloromethyl-1,3-dioxane was added dropwise to a 10-fold excess of carboxylic acid in THF at room temperature. The reactions were complete in 2 h (followed by GC). After purification by flash chromatography on silica gel, **10e**, **10f**, **10g**, and **10h** were isolated in yields of 61%, 65%, 61%, and 71%, respectively. These yields, based on 2-chloromethyl-1,3-dioxane and over the two reaction steps, were lower than those in reactions using isolated 2-methylene-1,3-dioxane (**8b**).

No evidence was found of diester hydrolysis or transesterification during flash chromatography purifications of 3-acetoxypropylbenzoate (**10h**) over silica gel (94% yield, 97% purity).

B. Syntheses of the Mixed Diesters of Unsymmetrical Diols via Cyclic Ketene Acetal Intermediates. Diesterifications. Mixed diesters of 1,3-butanediol, 1,2-propanediol, 3,3-dimethyl-1,2-butanediol, 2-methyl-2,4-pentanediol, and 1-phenyl-1,2-ethanediol were synthesized by reacting their corresponding CKAs with carboxylic acids in THF at ambient temperature. The regioselectivities to the major/minor isomers varied from 78:22 to 98:2 (see Table 2).

Mixed diesters of 1,3-butanediol were synthesized by adding 4-methyl-2-methylene-1,3-dioxane (**8d**) in THF dropwise to a 5-equiv excess of carboxylic acids (propionic acid, isobutyric acid, trimethylacetic acid, and benzoic acid) dissolved in THF at ∼25 °C with stirring under nitrogen. All reactions were complete in 4 h. Two diester

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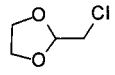
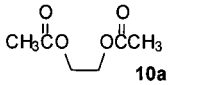
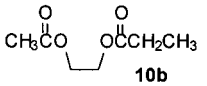
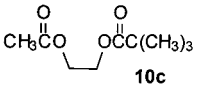
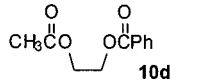
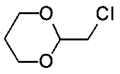
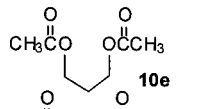
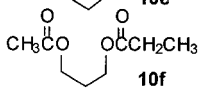
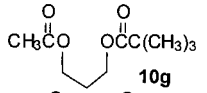
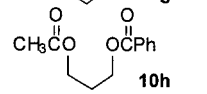
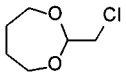
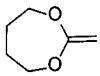
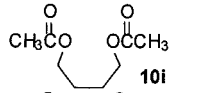
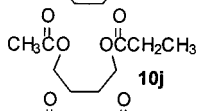
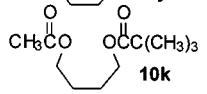
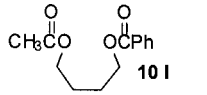
Table 1. Diacetylation of Symmetrical Diols via Cyclic Ketene Acetals

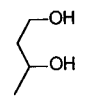
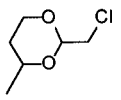
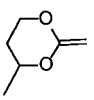
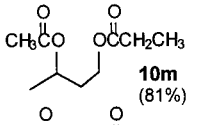
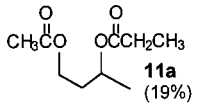
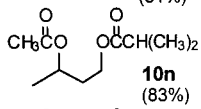
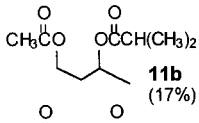
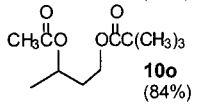
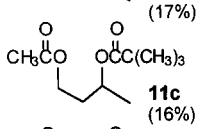
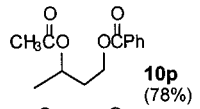
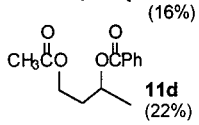
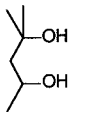
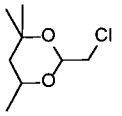
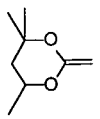
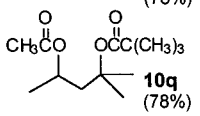
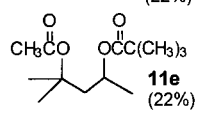
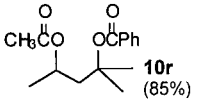
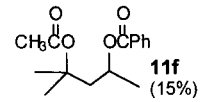
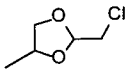
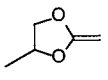
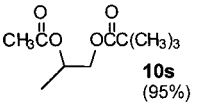
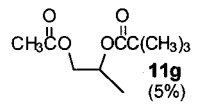
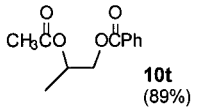
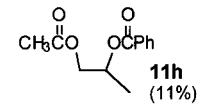
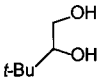
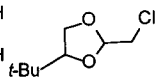
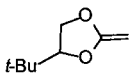
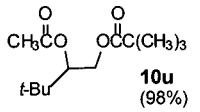
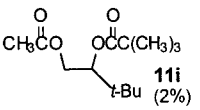
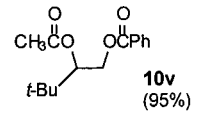
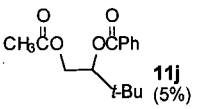
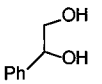
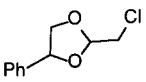
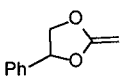
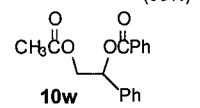
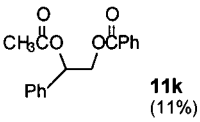
Parent Diol	2-Chloromethyl-1,3-dioxocyclic Acetal [Yield, %]	Cyclic Ketene Acetal [Yield, %]	Carboxylic Acid Used	Diester Product	Yield of Diester (%)
	 [94]	 **8a** [85]	CH_3CO_2H	 **10a**	87
			$CH_3CH_2CO_2H$	 **10b**	92
			$(CH_3)_3CCO_2H$	 **10c**	94
			$PhCO_2H$	 **10d**	95
	 [91]	 **8b** [89]	CH_3CO_2H	 **10e**	87
			$CH_3CH_2CO_2H$	 **10f**	90
			$(CH_3)_3CCO_2H$	 **10g**	87
			$PhCO_2H$	 **10h**	92
	 [38]	 **8c** [88]	CH_3CO_2H	 **10i**	89
			$CH_3CH_2CO_2H$	 **10j**	78
			$(CH_3)_3CCO_2H$	 **10k**	89
			$PhCO_2H$	 **10 l**	84

isomers were formed in each reaction. The major products in each case were the secondary acetates (**10m**−**p** in Table 2) where the incoming carboxylate group was bound to the less hindered primary (terminal) methylene carbon. In each minor product the incoming carboxylate was bound to the more hindered secondary position (e.g., **11a**−**d**). Isomer ratios were determined from the GC peak area ratios. The size of the aliphatic carboxylic acid had little effect on regioselectivity. The major/minor product ratio changed only from 81/19 to 83/17 or 84/16 going from propionic to isobutyric to trimethylacetic acid, respectively. Benzoic acid produced a slightly lower reaction selectivity (major/minor = 78/22). The regioselectivity in the reaction between benzoic acid and 4-methyl-2-methylene-1,3-dioxane (**8d**) was almost unchanged between 10 and 67 °C. The selectivities were 81/19 (10 °C), 78/22 (23−25 °C), and 77/23 (67 °C), respectively. No diesters were formed at 0 °C or below.

Mixed diesters of 2-methyl-2,4-pentanediol were prepared by reacting 4,4,6-trimethyl-2-methylene-1,3-dioxane (**8e**) with either trimethylacetic or benzoic acid at 68 °C (Table 2). The major isomers had the incoming carboxylate function bound to the more hindered tertiary carbon. Thus, reaction of **8e** with trimethylacetic acid formed **10g** as the major isomer (78%), and **11e** was the minor isomer (22%). With benzoic acid, the major product was **10r** (85%), and the minor isomer was **11f** (15%). This selectivity was the opposite of that obtained when 4-methyl-2-methylene-1,3-dioxane (**8d**), 4-methyl-2-methylene-1,3-dioxolane (**8f**), or 4-(*tert*-butyl)-2-methylene-1,3-dioxolane (**8g**) were reacted with carboxylic acids. However, a similar regioselectivity was observed in the reaction of 4-phenyl-2-methylene-1,3-dioxolane (**8h**) with benzoic acid. The major mixed diester obtained was the secondary benzoate (**10w**), and the minor product (**11k**) was the primary benzoate.

The reaction of 4-methyl-2-methylene-1,3-dioxolane (**8f**) with either trimethylacetic acid or benzoic acid at ambient temperature gave the mixed diesters (**10s**, **10t**, **11g**, and **11h**) of 1,2-propanediol. In contrast, a temperature of 67 °C was required to drive the reaction of 4-(*tert*-butyl)-2-methylene-1,3-dioxolane (**8g**) with either tri-

Table 2. Mixed Diester Synthesis via the Cyclic Ketene Acetals of Unsymmetrical Diols

Parent Diol	2-Chloromethyl-1,3-dioxocyclic Acetal [Yield, %]	Cyclic Ketene Acetal [Yield, %]	Carboxylic Acid Used	Diester Products Major Isomer (Selectivity)	Diester Products Minor Isomer (Selectivity)	Diester Yield (%)
	 [92]	 **8d** [75]	$CH_3CH_2CO_2H$	 **10m** (81%)	 **11a** (19%)	83
			$(CH_3)_2CHCO_2H$	 **10n** (83%)	 **11b** (17%)	87
			$(CH_3)_3CCO_2H$	 **10o** (84%)	 **11c** (16%)	72
			$PhCO_2H$	 **10p** (78%)	 **11d** (22%)	95
	 [93]	 **8e** [72]	$(CH_3)_3CCO_2H$	 **10q** (78%)	 **11e** (22%)	52
			$PhCO_2H$	 **10r** (85%)	 **11f** (15%)	59
	 [91]	 **8f** [80]	$(CH_3)_3CCO_2H$	 **10s** (95%)	 **11g** (5%)	88
			$PhCO_2H$	 **10t** (89%)	 **11h** (11%)	84
	 [95]	 **8g** [75]	$(CH_3)_3CCO_2H$	 **10u** (98%)	 **11i** (2%)	90
			$PhCO_2H$	 **10v** (95%)	 **11j** (5%)	83
	 [81]	 **8h** [69]	$PhCO_2H$	 **10w** (89%)	 **11k** (11%)	92

methylacetic acid or benzoic acid to generate the mixed diesters (**10u**, **10v**, **11i**, and **11j**). In each of these four reactions a high regioselectivity to the primary ester of the incoming carboxylate function was observed (Table 2). The primary trimethyl acetate esters in the reactions of trimethylacetic acid with **8f** and **8g** were formed selectively (95% and 98%, respectively). Similarly, the primary benzoates in reactions of benzoic acid with **8f** and **8g** were formed in 89% and 95%, respectively. The regioselectivities in the reactions of 4-(*tert*-butyl)-2-methylene-1,3-dioxolane (**8g**) were higher than those of the corresponding reactions of 4-methyl-2-methylene-1,3-dioxolane (**8f**). Also, trimethylacetic acid gave higher regioselectivities than benzoic acid when reacted with either **8f** or **8g**.

Product identification was based on FTIR, ^{1}H NMR, ^{13}C NMR and GC−MS analyses. Separation of isomer mixtures was sometimes difficult. This perturbed the isomer ratios. Thus, the product mixtures were directly analyzed as obtained.

The INEPT NMR experiment was used to identify the two isomers in each of the reaction mixtures. By applying specific proton frequencies during acquisition, the ^{13}C NMR signals of the carbons which are less than four bonds away from the irradiated proton were enhanced. These ^{13}C NMR spectra were subtracted from the normal ^{13}C spectra (obtained without irradiation) to show only the enhanced ^{13}C signals. The resonance frequency of either the methylene protons or the methine proton adjacent to oxygen was applied and the isomer structures were determined by analyzing which of the two ester carbonyl carbon signals was enhanced.

The ^{1}H NMR analysis of the 1,1-dimethyl-3-acetoxybutyl benzoate (**10r**)/1,3-dimethyl-3-acetoxybutyl benzoate (**11f**) mixture is shown in Figures 1 and 2. The two

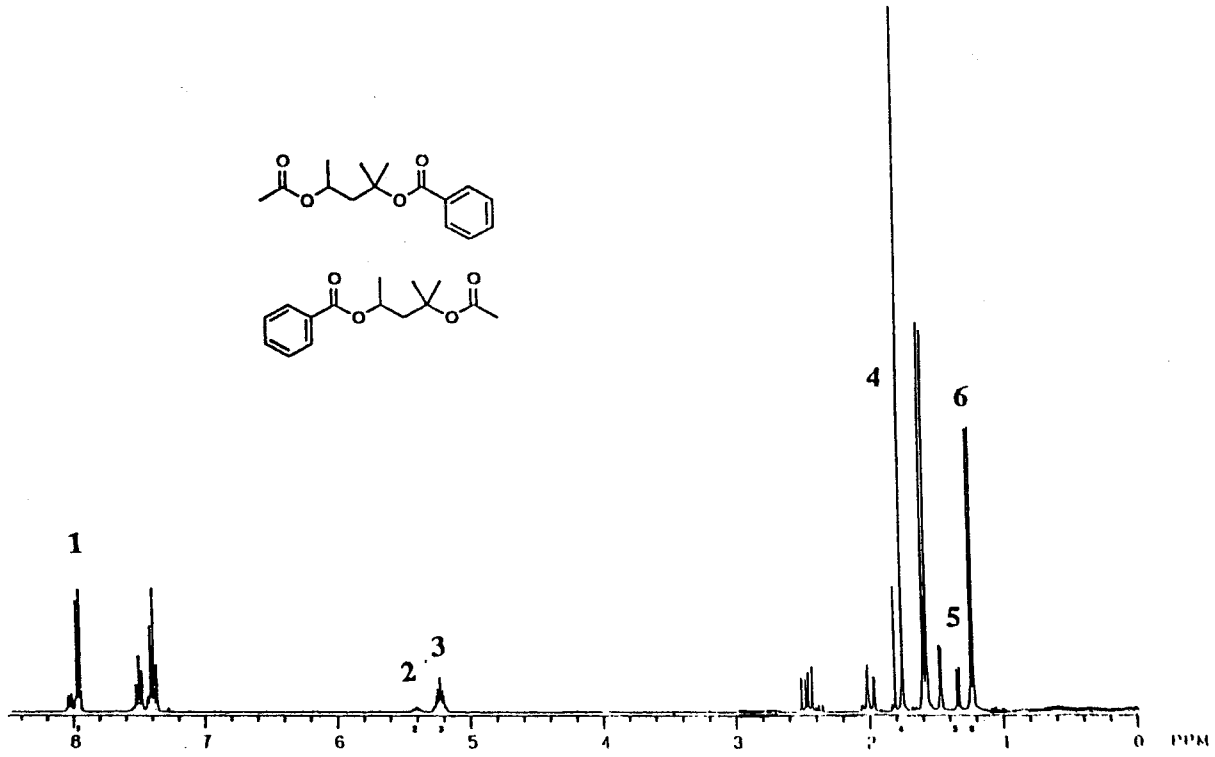


Figure 1. ^{1}H NMR spectrum of the 1,1-dimethyl-3-acetoxybutyl benzoate/1,3-dimethyl-3-acetoxybutyl benzoate mixture obtained by reacting 4,4,6-trimethyl-2-methylene-1,3-dioxane with benzoic acid. The peaks irradiated during the INEPT experience were numbered. Peaks 2 and 3 correspond to the methine protons of the minor and major isomers, respectively.

groups of peaks around 5.24 and 5.43 ppm correspond to the methine protons of the major (85%) and the minor (15%) isomers, respectively. Irradiation of the minor isomer's methine proton (5.43 ppm) enhanced the benzoate carbonyl carbon signal (166.6 ppm) in the ^{13}C NMR spectrum. Irradiation at 5.24 ppm gave signal enhancement of the acetate carbonyl carbon (170.4 ppm). This confirmed 1,1-dimethyl-3-acetoxybutyl benzoate (**10r**) as the major isomer and 1,3-dimethyl-3-acetoxybutyl benzoate (**11f**) as the minor isomer.

C. Reaction Mechanism. Carboxylic acid protonates the nucleophilic exocyclic methylene carbon of a CKA to generate the very stable cyclic dioxonium ion[28] **12** (see Scheme 3), which is in equilibrium with **13**. Three modes of diester formation are envisioned.[4,28,29] Protonation of **13** to **14** followed by ring expansion to **15** and then ring opening would generate diester **10** or **11**. Alternatively, **13** may rearrange via a chairlike transition state **16** or its protonated analogue **17** to **10** or via a corresponding chairlike transition state (not shown in Scheme 3) to **11**. Finally, S_N2 attack of carboxylate anion on C-4 of the cyclic dioxonium ion **12** via the transition states **18** can directly produce **10** and/or **11**. Less likely is carboxylate S_N2 attack at C-4 on protonated **13** (e.g., **19**) giving the diester(s).

Although the mixed esters obtained from symmetrical CKAs **8a**, **8b**, and **8c** could occur via any of these pathways (Scheme 3), the regioselectivities obtained during the formation of mixed diesters from CKAs **8d**−**h** (Table 2) are difficult to rationalize by a mechanism occurring through **13**, **14**, or **15**.[4,29] The regioselectivities observed upon conversion of **8d**, **8f**, and **8g** to their mixed diesters is clearly in agreement with a preferred S_N2 attack of the incoming carboxylate anion at the less hindered carbon adjacent to oxygen of cyclic dioxonium ion **12**. The rate of carboxylate attack would be significantly faster on **12** than on **19**, favoring the route through transition state **18** (although the **13**/**12** concentration ratio may be quite large in the RCOOH/THF medium).

The lack of dependence of the regioselectivity on the size of the incoming carboxylate anion during the conversion of **8d** to mixed diesters is of interest. Replacing propionic acid with trimethylacetic acid in reactions with **8d** only changed the regioselectivity from 81/19 to 84/16 (Table 2). Corresponding reactions of the five-membered ring CKA, 4-methyl-2-methylene-1,3-dioxolane (**8f**), with carboxylic acids exhibited higher selectivities than those of its six-membered ring analogue, 4-methyl-2-methylene-1,3-dioxane (**8d**). For example, the reaction of **8f** and **8d** with benzoic acid had selectivities (major/minor ratio) of 95/5 and 78/22, respectively. This might be the result of somewhat later transition states (such as **18**) during S_N2 attack of carboxylate anions on the more stable 2-methyl-1,3-dioxolane-2-ylium ions than during comparable attack on the 2-methyl-1,3-dioxan-2-ylium ions. Mixed diester formation via reaction of **13** through transition states such as **16** or **17** cannot occur when the five-membered ring CKAs **8f**, **8g**, or **8h** were employed because of steric constraints.

The regioselectivity observed during reactions of carboxylic acids with either 4,4,6-trimethyl-2-methylene-1,3-dioxane (**8e**) or 4-phenyl-2-methylene-1,3-dioxolane (**8h**) was reversed compared to those of **8d**, **8f**, and **8g**. The incoming carboxylate anion becomes bonded to the more substituted carbon in the major isomer in all of the reactions of these two CKAs. In these cases electronic effects must dominate. Stabilization of positive charge at the tertiary carbon of protonated **8e** or the benzylic carbon of protonated **8h** induces charge buildup at these positions (see **12e** hybrid structures and transition state

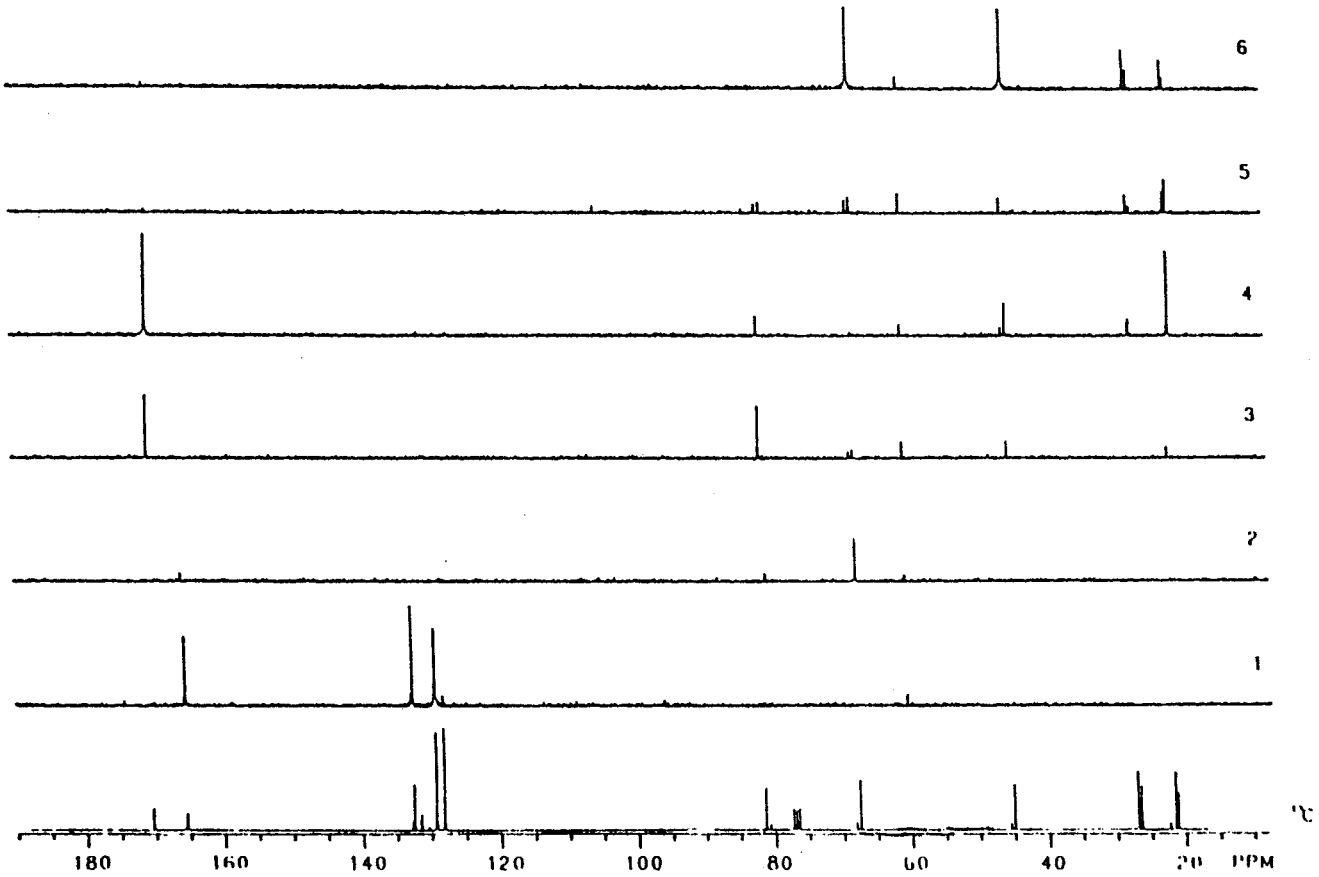
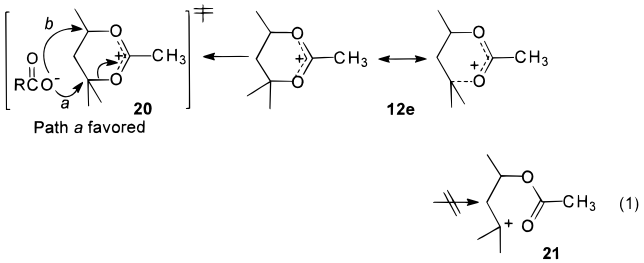


Figure 2. INEPT (^{13}C NMR) spectrum of the 1,1-dimethyl-3-aceotoxybutyl benzoate/1,3-dimethyl-3-acetoxybutyl benzoate mixture obtained by reacting 4,4,6-trimethyl-2-methylene-1,3-dioxane with benzoic acid. The numbers on the right side of the spectrum correspond to the number of the irradiated peak marked on the ^{1}H NMR spectrum (see Figure 1).

20, path a of eq 1). Positive charge buildup and carbon−

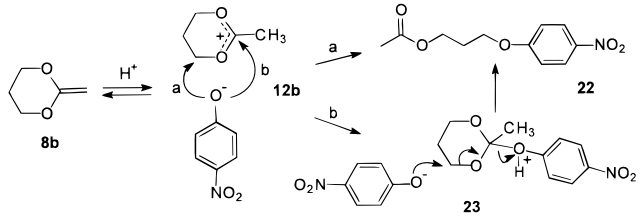


oxygen bond weakening induce carboxylate attack at this tertiary carbon of cation **12e** (or the benzylic carbon of cation **12h**). Thus, **10q** becomes the major mixed diester isomer. Ring opening of the very stable cyclic dioxonium ion **12e** (or **12h**) to tertiary cation **21** (or its corresponding benzylic analogue from **12h**) prior to carboxylate attack can be ruled out. Tertiary carbocation (**21**) or a secondary benzylic cation are far higher energy species than the cyclic dioxonium ions.[4,28]

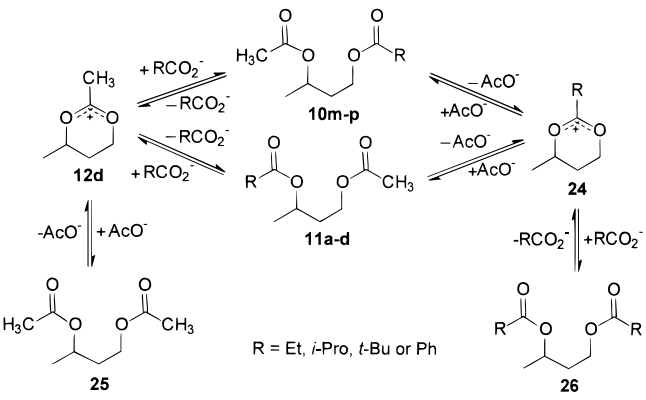
A related reaction used 4-nitrophenol in place of a carboxylic acid. Thus, 2-methylene-1,3-dioxane (**8b**) was reacted with 5 equiv of the acidic 4-nitrophenol in THF to give 3-(4-nitrophenoxy)propyl acetate (**22**) in an isolated yield of 75% (Scheme 4). The reaction proceeds either by nucleophilic attack by *p*-nitrophenoxide ion on cation **12b** or, less likely, through *p*-nitrophenoxide attack on **23**.

Thermodynamic versus Kinetic Control. All of the mechanisms discussed above are under kinetic control.

Scheme 4



Scheme 5



One might argue that equilibria (Scheme 5) between the major (**10m**−**p**) and the minor (**11a**−**d**) isomers may occur through either **12d** or **24**, leading to thermodynamic control of the isomer ratio. If this was actually occurring, **12d** might also react with acetate anion to form diacetate **25**. At the same time **24** might react with

the reagent carboxylate anion to form diester **26**. In fact, neither **25** nor **26** was observed, suggesting that equilibrium control does not exist. This was tested by the following experiments. 1,3-Diacetoxybutane (**25**) was synthesized by reacting 1,3-butanediol with a large excess of acidic anhydride. The isolated 1,3-diacetoxybutane was stirred with 5 equiv of propionic acid in THF either at ambient temperature or at 67 °C. GC analysis of the reaction mixture showed no new products formed during the reaction. Thus the formation of **10m**, **11a**, or **26** did not occur via the equilibria depicted in Scheme 5. Similarly, the bis-2-methylpropanoate diester of 1,3-butanediol when subjected to the reaction conditions did not form new products. Finally, a mixture of **10r** and **11f**, enriched (to 48%) in **11f**, was resubjected to benzoic acid in THF. The isomer ratio was unchanged. It did not approach the 85/15 **10r**/**11f** distribution originally obtained (Table 2). These results suggest stronger acids are needed to effect isomerization, in accord with studies of Paulsen et al.[30,31]

Conclusions

Mixed diesters of symmetrical diols (ethylene glycol, propane diol. and butanediol) can be made in good yield and high purity through the reactions of their corresponding cyclic ketene acetals with carboxylic acids. This was demonstrated in reactions with propionic, trimethylacetic, and benzoic acids. Mixed diesters of unsymmetrical diols (1,3-butanediol, 2-methyl-2,4-pentanediol, 1,2-propanediol, and 3,3-dimethyl-1,2-butanediol) were made in the same manner through cyclic ketene acetals. A pair of isomers was obtained with regioselectivities from 4:1 to 98:2. The major mixed diester isomer of 1,3-butanediol, 1,2-propanediol, or 3,3-dimethyl-1,2-butanediol resulted from attack of the reagent carboxylic acid at the less substituted carbon of the cyclic dioxonium ion. The regioselectivity was presumably controlled by a steric effect exerted during ring-opening nucleophilic attack by the carboxylate anion on the protonated cyclic ketene acetal. However, the major mixed diester isomer obtained from the reaction of carboxylic acid with 2-methyl-2,4-pentanediol or 1-phenyl-1,2-ethanediol was the more highly substituted ester of the reacting acid. An electronic effect manifest at the tertiary C-4 carbon of protonated **8e** or the benzyl carbon of protonated **8h** accounts for the reversal in selectivity. All of the reactions between cyclic ketene acetals and carboxylic acids were under kinetic control.

Experimental Section

Materials. Benzoic acid (99%), sodium hydroxide (99%), sodium sulfate (99%), hexane (99%), acetone (99%), ethyl acetate (99%), methylene chloride (99%), *p*-nitrophenol (99%), acetic anhydride (99%), 1,3-butanediol (99%), and silica gel (grade 9385, 230−400 mesh, 60 Å) were obtained from Aldrich Chemical Co. and were used as received. Trimethylacetic acid (99%), propionic acid (99%), isobutyric acid (99%), and acetic acid (99.8%) were obtained from Aldrich and were stored over molecular sieves (4 Å). THF (99%, Aldrich) was distilled from Na/benzophenone just before use.

A. Preparation of 1,3-Diacetoxypropane (10e) and Mixed Diesters of 1,3-Propanediol through Reactions of Unisolated 2-Methylene-1,3-dioxane (8b) with Carboxylic Acids. 2-Methylene-1,3-dioxane (**8b**) was made from 1,3-propanediol via acetal exchange with chloroacetaldehyde dimethyl acetal, followed by dehydrochlorination in THF with potassium *tert*-butoxide. The dehydrochlorination step is described as follows. 2-Chloromethyl-1,3-dioxane (97.5%, 14.1 g, 0.10 mol) and dried THF (200 mL) were added to a flask (500 mL) and cooled to 5 °C under nitrogen. Potassium *tert*-butoxide (22.5 g, 0.20 mol) and Aliquat 336 (0.8 g, 2 mmol) were then added. The solution was stirred at room temperature for 20 h followed by heating at reflux for an additional 3 h. After the mixture cooled to room temperature, pentane (anhydrous, 80 mL) was added, and the reaction mixture separated into a liquid and a solid phase. The clear upper solution was removed under nitrogen by syringe. The rest of the solution was then quickly filtered, and the precipitate was washed with anhydrous pentane (40 mL). The combined solution was concentrated by distilling pentane and part of the THF (94.5 g, containing about 10.0 g (0.10 mol) 2-methylene-1,3-dioxane (**8b**)).

Diesters of 1,3-propanediol (1,3-diacetoxypropane (**10e**), 3-acetoxypropyl propionate (**10f**), 3-acetoxypropyl trimethyl acetate (**10g**), and 3-acetoxypropyl benzoate (**10h**)) were prepared by reacting the unisolated 2-methylene-1,3-dioxane (**8b**) with acetic acid, propionic acid, trimethylacetic acid, and benzoic acid, respectively, in THF. In a typical experiment, benzoic acid (11.2 g, 91 mmol) and THF (20 mL) were added into a flask (100 mL). The concentrated CKA/THF solution (8.4 g, containing about 8.9 mmol of **8b**) was then added dropwise into the acid/THF solution under nitrogen over a 10 min period, followed by stirring at room temperature for 4 h. THF was removed at 50 °C in vacuo (100 mmHg). The reaction product was dissolved in methylene chloride (90 mL), extracted with cold (∼5 °C) aqueous NaOH (10 wt %, 3 × 75 mL), washed with water (100 mL), and dried over Na_2SO_4. After filtration through a short plug of silica gel, methylene chloride was removed at room temperature in vacuo (100 mmHg) to give a crude product (1.86 g, 84% GC purity, 79% yield). A further flash column (silica gel) separation using 20% acetone in hexane eluent gave 3-acetoxypropyl benzoate (**10h**) (1.45 g, 97% GC purity, clear colorless oil, isolated yield 71.1%).

1,3-Diacetoxypropane (**10e**), 3-acetoxypropyl propionate (**10f**), and 3-acetoxypropyl trimethyl acetate (**10g**) were prepared using similar procedures and scales and are listed below.

1,3-Diacetoxypropane (10e). Isolated yield: 61.3% (94% GC purity, clear liquid). FTIR (KBr): 2971, 2860, 1741, 1230 cm^{-1}. ^1H NMR ($CDCl_3$, 300 MHz): δ 1.90 (p, 2H, J = 6.3 Hz), 2.01 (s, 6H), 4.06 (t, 4H, J = 6.3 Hz). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.6, 27.7, 60.9, 170.8. GC/MS (EI): 161.1 ($M^+ + 1$, <1), 117.0 (3), 100.0 (22), 72.1 (19), 61.0 (27), 42.9 (100). GC/MS (CI): 161.0 ($M^+ + 1$, 25), 101.0 (100).

3-Acetoxypropyl Propionate (10f). Isolated yield: 64.7% (92% GC purity, clear liquid). FTIR (KBr): 2968, 2929, 2855, 1741, 1241, 1185, 1083 cm^{-1}. ^1H NMR ($CDCl_3$, 300 MHz): δ 1.16 (t, 3H, J = 7.5 Hz), 1.90 (m, 2H), 2.07 (s, 3H), 2.36 (q, 2H, J = 7.5 Hz), 4.17 (m, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 8.9, 20.7, 27.4, 27.8, 60.8, 61.0, 170.9, 174.3. GC/MS (EI): 175.1 ($M^+ + 1$, <1), 114.1 (18), 100.0 (33), 75.0 (20), 57.2 (100), 42.9 (93). GC/MS (CI): 175.1 ($M^+ + 1$, 2), 115.1 (90), 101.1 (100).

3-Acetoxypropyl Trimethyl Acetate (10g). Isolated yield: 60.8% (98% GC purity, clear liquid). FTIR (KBr): 2972, 2909, 2876, 1742, 1733, 1286, 1242, 1159, 1050, cm^{-1}. ^1H NMR ($CDCl_3$, 300 MHz): δ 1.20 (s, 9H), 1.98 (p, 2H, J = 6.3 Hz), 2.06 (s, 3H), 4.15 (m, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.9, 27.1, 27.9, 38.7, 60.8, 61.0, 171.0, 178.4. GC−MS (EI): 71.0 (100), 57.0 (50), 43.1 (35). GC−MS (CI): 203.1 ($M^+ + 1$, 12), 143.2 (89), 101.1 (100).

3-Acetoxypropyl Benzoate (10h). Isolated yield: 71.1% (97% GC purity, clear oil). FTIR (KBr): 3070, 2968, 2909, 1740, 1721, 1277, 1242, 1177, 1047 cm^{-1}. ^1H NMR ($CDCl_3$, 300 MHz): δ 2.06 (s, 3H), 2.12 (m, 2H), 4.25 (t, 2H, J = 6.3 Hz), 4.42 (t, 2H, J = 6.2 Hz), 7.45 (m, 2H), 7.57 (m, 1H), 8.05 (m, 2H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.9, 28.0, 61.1, 61.5, 128.3, 129.7, 130.0, 133.0, 166.4, 171.0. GC−MS (EI): 222.1 (M^+, 1), 165.0 (21), 105.0 (100), 76.9 (74), 51.0 (48), 42.9 (96). GC−MS (CI): 223.1 ($M^+ + 1$, 6), 163.0 (96), 101.1 (100).

B. Preparation of 1,3-Diacetoxypropane and Mixed Diesters of 1,3-Propanediol by Reacting Isolated 2-Methylene-1,3-dioxane (8b) with Carboxylic Acids. Diesters of 1,3-propanediol (1,3-diacetoxypropane (**10e**), 3-acetoxypropyl propionate (**10f**), 3-acetoxypropyl trimethyl acetate (**10g**), and 3-acetoxypropyl benzoate (**10h**)) were also prepared by reacting isolated 2-methylene-1,3-dioxane (**8b**) with carboxylic acids

(acetic acid, propionic acid, trimethylacetic acid, and benzoic acid, respectively) in THF. THF (5 mL) was charged to a base-washed flask (20 mL) by syringe and then frozen with liquid nitrogen. 2-Methylene-1,3-dioxane (**8b**) (0.34 g, 3.4 mmol) was directly distilled (50 mmHg, 85 °C) via a short path distillation into the frozen THF. After warming to room temperature under nitrogen, the resulting solution was placed into an addition funnel with more THF (10 mL). A flask (100 mL) was charged with trimethylacetic acid (2.75 g, 26.6 mmol) and THF (20 mL). The CKA/THF solution was then added dropwise into the acid/THF solution under nitrogen over 20 min. This solution was stirred at room temperature under nitrogen for 2 h and worked up, as described in the previous section, to give 3-acetoxypropyl trimethyl acetate (**10g**) (0.62 g, 96.2% GC purity, clear liquid, 86.7% isolated yield). The isolated yields (based on the weight and GC purity of the final products) obtained in similar preparations of 1,3-diacetoxypropane (**10e**), 3-acetoxypropyl propionate (**10f**), and 3-acetoxypropyl benzoate (**10h**), on similar scales, were 86.9% (95% GC purity, clear liquid), 90.5% (95% GC purity, clear liquid), and 92.1% (98% GC purity, clear oil), respectively. Their ^{1}H and ^{13}C NMR spectra and GC retention times were identical to those reported in section A.

C. Preparation of 1,2-Diacetoxyethane and Mixed Diesters of Ethylene Glycol by Reacting Isolated 2-Methylene-1,3-dioxolane (8a) with Carboxylic Acids. Diesters of ethylene glycol (1,2-diacetoxyethane (**10a**), 2-acetoxyethyl propionate (**10b**), 2-acetoxyethyl trimethyl acetate (**10c**), and 2-acetoxyethyl benzoate (**10d**)) were prepared by reacting 2-methylene-1,3-dioxolane (**8a**) with acetic acid, propionic acid, trimethylacetic acid, and benzoic acid, respectively, in THF. These diesters were prepared by the same procedure on the same scale as those described in section A.

1,2-Diacetoxyethane (10a). Isolated yield: 87.3% (92% GC purity, clear liquid). FTIR (KBr): 2962, 2890, 1743, 1223, 1053 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 2.09 (s, 6H), 4.28 (s, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.7, 62.1, 170.7. GC−MS (EI): 147.1 ($M^+ + 1$, <1), 86.1 (23), 73.1 (10), 43.0 (100). GC−MS (CI): 147.1 ($M^+ + 1$, 1), 87.1 (100).

2-Acetoxyethyl Propionate (10b). Isolated yield: 92.6% (97% GC purity, clear liquid). FTIR (KBr): 2997, 2889, 1743, 1234, 1181, 1064 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.15 (t, 3H, J = 7.6 Hz), 2.09 (s, 3H), 2.37 (q, 2H, J = 7.6 Hz), 4.28 (s, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 9.0, 20.8, 27.3, 62.0, 62.2, 170.8, 174.2. GC−MS (EI): 161.1 ($M^+ + 1$, <1), 100.1 (12), 57.0 (100), 43.0 (68). GC−MS (CI): 161.0 ($M^+ + 1$, 1), 101.1 (80), 87.1 (100).

2-Acetoxyethyl Trimethyl Acetate (10c). Isolated yield: 94.0% (97% GC purity, clear liquid). FTIR (KBr): 2974, 2913, 1744, 1734, 1286, 1232, 1157, 1066, 1049 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.21 (s, 9H), 2.07 (s, 3H), 4.27 (s, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.7, 27.0, 38.7, 61.9, 62.1, 170.7, 178.2. GC−MS (EI): 189.1 ($M^+ + 1$, <1), 85.1 (42), 57.0 (100), 43.0 (45). GC−MS (CI): 189.0 ($M^+ + 1$, 3), 129.1 (69), 87.1 (100).

2-Acetoxyethyl Benzoate (10d). Isolated yield: 95.5% (99% GC purity, clear liquid). FTIR (KBr): 3070, 2963, 1743, 1723, 1602, 1279, 1232, 1177, 1111, 1063, 1027 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 2.10 (s, 3H), 4.43 (t, 2H, J = 6.9 Hz), 4.52 (t, 2H, J = 6.9 Hz), 7.45 (m, 2H), 7.58 (m, 1H), 8.05 (m, 2H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.8, 62.1, 62.7, 128.4, 129.6, 129.7, 133.1, 166.3, 170.7. GC−MS (EI): 208.1 (M^+, 1), 165.1 (5), 148.1 (5) 105.1 (100), 77.0 (28), 43.0 (35). GC−MS (CI): 209.0 ($M^+ + 1$, 3), 149.1 (73), 105.0 (61), 87.1 (100).

D. Preparation of 1,4-Diacetoxybutane and Mixed Diesters of 1,4-Butanediol by Reacting Isolated 2-Methylene-1,3-dioxepane (8c) with Carboxylic Acids. Diesters of 1,4-butanediol (1,4-diacetoxybutane (**10i**), 4-acetoxybutyl propionate (**10j**), 4-acetoxybutyl trimethyl acetate (**10k**), and 4-acetoxybutyl benzoate (**10*l***)) were prepared by reacting 2-methylene-1,3-dioxepane (**8c**) with carboxylic acids (Table 1) as described in section A.

1,4-Diacetoxybutane (10i). Isolated yield: 88.9% (98% GC purity, clear liquid). FTIR (KBr): 2968, 1740, 1236, 1046 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.71 (m, 4H), 2.06 (s, 6H), 4.10 (m, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.9, 25.2, 63.9, 171.0. GC−MS (EI): 114.0 (11), 73.0 (20), 71.0 (40), 54.0 (100). GC−MS (CI): 175.1 ($M^+ + 1$, 40), 115.1 (100).

4-Acetoxybutyl Propionate (10j). Isolated yield: 78.0% (94% GC purity, clear liquid). FTIR (KBr): 2964, 1739, 1239, 1186, 1084, 1042 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.14 (t, 3H, J = 7.6 Hz), 1.71 (m, 4H), 2.06 (s, 3H), 2.33 (q, 2H, J = 7.6 Hz), 4.10 (m, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 9.1, 20.9, 25.2, 27.5, 63.7, 63.9, 171.0, 174.4. GC−MS (EI): 114 (8), 75 (6), 73 (10), 71 (27), 57 (100), 54 (74). GC−MS (CI): 189.0 ($M^+ + 1$, 50), 129.1 (90), 115.2 (100).

4-Acetoxybutyl Trimethyl Acetate (10k). Isolated yield: 89.0% (97% GC purity, clear oil). FTIR (KBr): 2972, 1741, 1730, 1285, 1239, 1159, 1042 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.20 (s, 9H), 1.71 (m, 4H), 2.06 (s, 3H), 4.09 (m, 4H). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.9, 25.2, 25.3, 27.2, 38.7, 63.8, 64.0, 171.1, 178.5. GC−MS (EI): 173 (1), 114 (16), 85 (12), 71 (15), 57 (100). GC−MS (CI): 217.1 ($M^+ + 1$, 35), 157.1 (80), 115.1 (100), 85.1 (50), 57.1 (34).

4-Acetoxybutyl Benzoate (10l). Isolated yield: 84.1% (94% GC purity, clear oil). FTIR (KBr): 3065, 2959, 1739, 1720, 1275, 1242, 1113, 1027 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.83 (m, 4H), 2.06 (s, 3H), 4.14 (t, 2H, J = 6.2 Hz), 4.36 (t, 2H, J = 6.1 Hz), 7.44 (m, 2H), 7.57 (m, 1H), 8.03. ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.9, 25.3, 25.4, 63.9, 64.4, 128.3, 129.5, 130.2, 132.9, 166.5, 171.1. GC−MS (EI): 236 (M^+, 2), 114.0 (20), 105.0 (100), 76.9 (40), 71.0 (30), 54 (85). GC−MS (CI): 237.0 ($M^+ + 1$, 50), 177.1 (100), 115.1 (97), 105.0 (80).

E. Preparation of Mixed Diesters of 1,3-Butanediol by Reacting Isolated 4-Methyl-2-methylene-1,3-dioxane (8d) with Carboxylic Acids. Diesters of 1,3-butanediol were prepared by reacting 4-methyl-2-methylene-1,3-dioxane (**8d**) with specific carboxylic acids in THF (Table 2).

Mixture of 3-Acetoxybutyl Propionate (10m) and 1-Methyl-3-acetoxypropyl Propionate (11a). Isolated yield: 82.5% (95% overall GC purity, clear liquid). Composition (GC area): 80.7% 3-acetoxybutyl propionate (**10m**) and 19.3% 1-methyl-3-acetoxypropyl propionate (**11a**). FTIR (KBr) of the mixture: 2980, 2943, 1738, 1244, 1188, 1085, 1020 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl propionate (**10m**) δ 1.14 (t, 3H, J = 7.5 Hz), 1.26 (d, 3H, J = 6.3 Hz), 1.88 (m, 2H), 2.04 (s, 3H), 2.33 (q, 2H, J = 7.6 Hz), 4.12 (t, 2H, J = 6.4 Hz), 5.02 (m, 1H); for 1-methyl-3-acetoxypropyl propionate (**11a**) δ 1.14 (t, 3H, J = 7.5 Hz), 1.26 (d, 3H, J = 6.3 Hz), 1.89 (m, 2H, 2.05 (s, 3H), 2.31 (q, 2H, J = 7.6 Hz), 4.11 (t, 2H, J = 6.4 Hz), 5.02 (m, 1H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl propionate (**10m**) δ 8.9, 19.9, 21.1, 27.4, 34.6, 60.5, 67.7, 170.4, 174.3; for 1-methyl-3-acetoxypropyl propionate (**11a**) δ 9.0, 19.9, 20.8, 27.7, 34.6, 60.7, 67.4, 170.9, 173.8. GC−MS: for 3-acetoxybutyl propionate (**10m**) EI 99.1 (15), 71.0 (20), 57 (100), 55.0 (20), 42.9 (94); CI 189 ($M^+ + 1$, 5), 129 (100), 115 (65); for 1-methyl-3-acetoxypropyl propionate (**11a**) EI 99.1 (10), 71.1 (12), 57.0 (100), 55.0 (29), 42.9 (54); CI 189 ($M^+ + 1$, 3), 129 (39), 115 (100).

Mixture of 3-Acetoxybutyl Isobutyrate (10n) and 1-Methyl-3-acetoxypropyl Isobutyrate (11b). Isolated yield: 86.9% (97% overall GC purity, clear liquid). Composition (GC area): 83.0% 3-acetoxybutyl isobutyrate (**10n**) and 17.0% 1-methyl-3-acetoxypropyl isobutyrate (**11b**). FTIR (KBr): 2978, 2946, 1738, 1243, 1193, 1159, 1079, 1018 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl isobutyrate (**10n**) δ 1.16 (d, 6H, J = 7.0 Hz), 1.26 (d, 3H, J = 6.3 Hz), 1.89 (m, 2H), 2.04 (s, 3H), 2.54 (m, 1H), 4.11 (t, 2H, J = 6.4 Hz), 5.01 (m, 1H); for 1-methyl-3-acetoxypropyl isobutyrate (**11b**) δ 1.16 (d, 6H, J = 7.0 Hz), 1.25 (d, 3H, J = 6.3 Hz), 1.89 (m, 2H), 2.05 (s, 3H), 2.54 (m, 1H), 4.13 (t, 2H, J = 6.3 Hz), 5.01 (m, 1H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl isobutyrate (**10n**) δ 18.8, 20.0, 21.1, 33.8, 34.7, 60.4, 67.7, 170.4, 176.9; for 1-methyl-3-acetoxypropyl isobutyrate (**11b**) δ 18.8, 19.9, 20.8, 34.0, 34.7, 60.7, 67.3, 170.9, 176.5. GC−MS: for 3-acetoxybutyl isobutyrate (**10n**) EI 115.1 (6), 99.1 (10), 71.1 (65), 61.0 (8), 55.0 (23), 42.9 (100); CI 203 ($M^+ + 1$, 4), 143 (100), 115 (65); for 1-methyl-3-acetoxypropyl isobutyrate (**11b**) EI 131.1 (2), 115.1 (9), 99.1 (6), 71.1 (63), 55.0 (59), 42.9 (100); CI 203 ($M^+ + 1$, 2), 143 (30), 115 (100).

Mixture of 3-Acetoxybutyl Trimethyl Acetate (10o) and 1-Methyl-3-acetoxypropyl Trimethyl Acetate (11c). Isolated yield: 71.6% (96% overall GC purity, clear oil). Composition (GC area): 83.9% 3-acetoxybutyl trimethyl acetate (**10o**) and 16.1% 1-methyl-3-acetoxypropyl trimethyl acetate (**11c**). FTIR (KBr): 2977, 1736, 1732, 1286, 1243, 1159, 1045 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl trimethyl acetate (**10o**) δ 1.20 (s,

9H), 1.27 (d, 3H, J = 6.3 Hz), 1.89 (m, 2H), 2.04 (s, 3H), 4.10 (t, 2H, J = 6.4 Hz), 5.00 (m, 1H); for 1-methyl-3-acetoxypropyl trimethyl acetate (**11c**) δ 1.19 (s, 9H), 1.22 (d, 3H, J = 6.3 Hz), 1.89 (m, 2H), 2.05 (s, 3H), 4.10 (t, 2H, J = 6.4 Hz), 5.00 (m, 1H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl trimethyl acetate (**10o**) δ 20.0, 21.1, 27.0, 34.6, 38.5, 60.5, 67.6, 170.3, 178.3; for 1-methyl-3-acetoxypropyl trimethyl acetate (**11c**) δ 19.8, 20.8, 26.9, 34.6, 38.5, 60.6, 67.2, 170.8, 177.8. GC−MS: for 3-acetoxybutyl trimethyl acetate (**10o**) EI 115.1 (8), 99.1 (10), 85.1 (25), 57.0 (100), 42.9 (76); CI 217 (M^+ + 1, 3), 157 (100), 115 (45); for 1-methyl-3-acetoxypropyl trimethyl acetate (**11c**) EI 115.1 (16), 85.1 (18), 71.0 (20), 57.0 (100), 55.0 (53), 43.0 (69); CI 217 (M^+ + 1, 1), 157 (35), 115 (100).

Mixture of 3-Acetoxybutyl Benzoate (10p) and 1-Methyl-3-acetoxypropyl Benzoate (11d). Isolated yield: 95.2% (97% overall GC purity, clear oil). Composition (GC area): 78.4% 3-acetoxybutyl benzoate (**10p**) and 21.6% 1-methyl-3-acetoxypropyl benzoate (**11d**). FTIR (KBr): 3066, 2980, 1737, 1720, 1277, 1243, 1113, 1027 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl benzoate (**10p**) δ 1.30 (d, 3H, J = 6.3 Hz), 2.02 (s, 3H), 2.04 (m, 2H), 4.38 (m, 2H), 5.12 (m, 1H), 7.43 (m, 2H), 7.55 (m, 1H), 8.03 (m, 2H); for 1-methyl-3-acetoxypropyl benzoate (**11d**) δ 1.39 (d, 3H, J = 6.3 Hz), 2.00 (s, 3H), 2.04 (m, 2H), 4.19 (m, 2H), 5.29 (m, 1H), 7.43 (m, 2H), 7.55 (m, 1H), 8.03 (m, 2H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 3-acetoxybutyl benzoate (**10p**) δ 20.0, 21.1, 34.8, 61.2, 67.9, 128.2, 129.4, 130.1, 132.8, 166.3, 170.4; for 1-methyl-3-acetoxypropyl benzoate (**11d**) δ 20.0, 20.7, 34.8, 60.8, 68.6, 128.2, 129.4, 130.1, 132.8, 165.9, 170.6. GC−MS: 3-acetoxybutyl benzoate (**10p**) EI 236.2 (M^+, 1), 193.2 (2), 176.1 (4), 161.1 (8), 122.1 (10), 105.1 (100), 99.1 (8), 77.1 (24), 71.1 (10), 43.0 (47); CI 237 (M^+ + 1, 5), 177 (100), 115 (53); for 1-methyl-3-acetoxypropyl benzoate (**11d**) EI 176.1 (3), 148.2 (2), 134.1 (8), 105.0 (100), 77.1 (25), 71.1 (16), 42.9 (42); CI 237 (M^+ + 1, 3), 177 (45), 115 (100).

F. Preparation of Mixed Diesters of 2-Methyl-2,4-pentanediol by Reactions of Isolated 4,4,6-Trimethyl-2-methylene-1,3-dioxane (8e) with Carboxylic Acids. Diesters of 2-methyl-2,4-pentanediol were prepared on the same scale by reacting 4,4,6-trimethyl-2-methylene-1,3-dioxane (**8e**) with trimethylacetic acid or benzoic acid in THF as described in section A.

Mixture of 1,1-Dimethyl-3-acetoxybutyl Trimethyl Acetate (10q) and 1,3-Dimethyl-3-acetoxybutyl Trimethyl Acetate (11e). Isolated yield: 52.1% (98% overall GC purity, clear oil). Composition (^{1}H NMR integration): 78.3% 1,1-dimethyl-3-acetoxybutyl trimethyl acetate (**10q**) and 21.7% 1,3-dimethyl-3-acetoxybutyl trimethyl acetate (**11e**). FTIR (KBr): 2979, 1738, 1726, 1290, 1246, 1128, 1050, 1018, cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 1,1-dimethyl-3-acetoxybutyl trimethyl acetate (**10q**) δ 1.16 (s, 9H), 1.24 (d, 3H, J = 6.3 Hz), 1.44 (two singlets, 6H), 2.02 (s, 3H), 2.05 (m, 2H), 5.08 (m, 1H); for 1,3-dimethyl-3-acetoxybutyl trimethyl acetate (**11e**) δ 1.18 (s, 9H), 1.21 (d, 3H, J = 6.3 Hz), 1.45 (two singlets, 6H, 1.97 (s, 3H), 2.05 (m, 2H), 5.08 (m, 1H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 1,1-dimethyl-3-acetoxybutyl trimethyl acetate (**10q**) δ 21.4, 21.5, 25.8, 26.8, 27.1, 39.2, 46.1, 67.7, 80.4, 170.3, 177.7; for 1,3-dimethyl-3-acetoxybutyl trimethyl acetate (**11e**) δ 21.3, 22.5, 26.0, 26.9, 27.0, 38.7, 45.8, 67.4, 80.8, 170.3, 177.7. GC−MS (EI): for 1,1-dimethyl-3-acetoxybutyl trimethyl acetate (**10q**) 169.2 (1), 143.1 (9), 85.0 (19), 83.0 (100), 56.6 (57); for 1,3-dimethyl-3-acetoxybutyl trimethyl acetate (**11e**) 226.2 (5), 184.3 (6), 82.9 (100), 56.6 (95).

Mixture of 1,1-Dimethyl-3-acetoxybutyl Benzoate (10r) and 1,3-Dimethyl-3-acetoxybutyl Benzoate (11f). Clear oil, isolated yield: 59.4%. Composition (^{1}H NMR integration): 85.0% 1,1-dimethyl-3-acetoxybutyl benzoate (**10r**) and 15.0% 1,3-dimethyl-3-acetoxybutyl benzoate (**11f**). FTIR (KBr): 3066, 2981, 1736, 1715, 1276, 1249, 1114, 1026 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 1,1-dimethyl-3-acetoxybutyl benzoate (**10r**) δ 1.25 (d, 3H, J = 6.3 Hz), 1.60 (two singlets, 6H), 1.77 (s, 3H), 2.01 (q, 1H, J = 15.2 and 2.9 Hz), 2.49 (q, 1H, J = 15.2 and 8.9 Hz), 5.25 (m, 1H), 7.41 (m, 2H), 7.52 (m, 1H), 7.98 (m, 2H); for 1,3-dimethyl-3-acetoxybutyl benzoate (**11f**) δ 1.36 (d, 3H, J = 6.3 Hz), 1.49 (two singlets, 6H), 1.83 (s, 3H), 2.04 (q, 1H, J = 15.2 and 2.9 Hz), 2.40 (q, 1H, J = 15.2 and 8.9 Hz), 5.43 (m, 1H), 7.43 (m, 2H), 7.52 (m, 1H), 8.05 (m, 2H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 1,1-dimethyl-3-acetoxybutyl benzoate (**10r**) δ 21.1, 21.5, 26.5 and 27.0, 45.0, 67.5, 81.4, 128.1, 129.3, 131.5, 132.5, 165.5, 170.4; for 1,3-dimethyl-3-acetoxybutyl benzoate (**11f**) δ 21.5, 21.6, 26.4, 26.8, 45.6, 68.1, 81.0, 128.2, 129.4, 130.5, 132.8, 166.6, 170.4. GC−MS (EI): for 1,1-dimethyl-3-acetoxybutyl benzoate (**10r**) 204.2 (3), 188.6 (1), 142.2 (43), 105.0 (100), 83.2 (62), 77.0 (29); for 1,3-dimethyl-3-acetoxybutyl benzoate (**11f**) 204.1 (3), 189.1 (1), 105.0 (100), 82.0 (50), 77.0 (28), 67.0 (48), 54.6 (35).

G. Preparation of Mixed Diesters of 1,2-Propanediol by Reactions of Isolated 4-Methyl-2-methylene-1,3-dioxolane (8f) with Carboxylic Acids. Diesters of 1,2-propanediol were prepared by reacting 4-methyl-2-methylene-1,3-dioxolane (**8f**) with trimethylacetic acid and benzoic acid in THF as described in section A.

2-Acetoxypropyl Trimethyl Acetate (10s) and 1-Methyl-2-acetoxyethyl Trimethyl Acetate (11g). Isolated yield: 87.7% (93% overall GC purity, clear oil). Composition (GC area): 95% 2-acetoxypropyl trimethyl acetate (**10s**) and 5% 1-methyl-2-acetoxyethyl trimethyl acetate (**11g**). FTIR (KBr): 2979, 1742, 1739, 1285, 1240, 1154, 1082, 1020 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 2-acetoxypropyl trimethyl acetate (**10s**) δ 1.20 (s, 9H), 1.25 (d, 3H, J = 6.3 Hz), 2.04 (s, 3H), 4.04 (q, 1H, J = 14.8 and 6.4 Hz), 4.14 (q, 1H, J = 14.8 and 3.4 Hz), 5.15 (m, 1H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 2-acetoxypropyl trimethyl acetate (**10s**) δ 16.4, 21.0, 27.1, 38.7, 65.8, 68.1, 170.3, 178.0.

2-Acetoxypropyl Benzoate (10t) and 1-Methyl-2-acetoxyethyl Benzoate (11h). Isolated yield: 84.4% (92% GC purity, clear oil). Composition (GC area): 89% 2-acetoxypropyl benzoate (**10t**) and 11% 1-methyl-2-acetoxyethyl benzoate (**11h**). FTIR (KBr): 3070, 2988, 1741, 1725, 1277, 1238, 1111, 1072, 1027 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 2-acetoxypropyl benzoate (**10t**) δ 1.34 (d, 3H, J = 6.3 Hz), 2.06 (s, 3H), 4.31 (q, 1H, J = 14.8 and = 6.4 Hz), 4.40 (q, 1H, J = 14.8 and 3.4 Hz), 5.30 (m, 1H), 7.44 (m, 2H), 7.56 (m, 1H), 8.03 (m, 2H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 2-acetoxypropyl benzoate (**10t**) δ 16.4, 21.0, 66.4, 68.1, 128.3, 129.5, 129.6, 133.0, 166.1, 170.3.

H. Preparation of Mixed Diesters of 3,3-Dimethyl-1,2-butanediol by Reactions of Isolated 4-(*tert*-Butyl)-2-methylene-1,3-dioxolane (8g) with Carboxylic Acids. Diesters of 3,3-dimethyl-1,2-butanediol were prepared by reacting 4-(*tert*-butyl)-2-methylene-1,3-dioxolane (**8g**) with trimethylacetic acid and benzoic acid in THF as described in A.

3,3-Dimethyl-2-acetoxbutyl Trimethyl Acetate (10u) and 1-(*tert*-Butyl)-2-acetoxyethyl Trimethyl Acetate (11i). Isolated yield: 90.2% (92% GC purity, colorless oil). Composition (GC area): 98% 3,3-dimethyl-2-acetoxybutyl trimethyl acetate (**10u**) and 2% 1-(*tert*-butyl)-2-acetoxyethyl trimethyl acetate (**11i**). FTIR (KBr): 2972, 1736, 1284, 1239, 1153, 1063, 1029 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 3,3-dimethyl-2-acetoxybutyl trimethyl acetate (**10u**) δ 0.97 (s, 9H), 1.17 (s, 9H), 2.08 (s, 3H), 4.01 (q, 1H, J = 14.5 and 9.0 Hz), 4.35 (q, 1H, J = 14.5 and 3.2 Hz), 5.00 (q, 1H, J = 9.0 and 3.2 Hz). ^{13}C NMR ($CDCl_3$, 300 MHz): for 3,3-dimethyl-2-acetoxybutyl trimethyl acetate (**10u**) δ 20.8, 26.0, 27.0, 33.5, 38.7, 63.4, 77.5, 170.3, 178.3.

3,3-Dimethyl-2-acetoxybutyl Benzoate (10v) and 1-(*tert*-Butyl)-2-acetoxyethyl Benzoate (11j). Isolated yield: 82.6% (90% GC purity, clear oil). Composition (GC area): 95% 3,3-dimethyl-2-acetoxybutyl benzoate (**10v**) and 5% 1-(*tert*-butyl)-2-acetoxyethyl benzoate (**11j**). FTIR (KBr): 3069, 2964, 1741, 1725, 1277, 1237, 1111, 1062, 1027 cm^{-1}. ^{1}H NMR ($CDCl_3$, 300 MHz): for 3,3-dimethyl-2-acetoxybutyl benzoate (**10v**) δ 1.02 (s, 9H), 2.08 (s, 3H), 4.31 (q, 1H, J = 14.5 and 9.0 Hz), 4.55 (q, 1H, J = 14.5 and 3.2 Hz), 5.15 (q, 1H, J = 9.0 and 3.2 Hz), 7.43 (m, 2H), 7.55 (m, 1H), 7.99 (m, 2H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 3,3-dimethyl-2-acetoxybutyl benzoate (**10v**) δ 20.9, 26.0, 33.6, 64.1, 77.6, 128.4, 129.6, 129.9, 133.0, 166.4, 170.6.

I. Preparation of Mixed Acetate Benzoate Diesters of 1-Phenyl-1,2-ethanediol by Reactions of Isolated 4-Phenyl-2-methylene-1,3-dioxolane (8h) with Benzoic Acid. Diesters of 1-phenyl-1,2-ethanediol were prepared by reacting 4-phenyl-2-methylene-1,3-dioxolane (**8h**) with benzoic acid in THF as described in section A. Two isomers (1-phenyl-2-acetoxyethyl benzoate (**10w**) and 2-phenyl-2-acetoxyethyl benzoate (**11k**)) were obtained as a colorless oil in 92% combined yield. The composition (GC area) of the mixture was 89% **10w** and 11% **11k**. ^{1}H NMR ($CDCl_3$, 300 MHz): for 1-phenyl-2-acetoxyethyl benzoate (**10w**) (major isomer) δ 2.03 (s, 3H), 4.42 (q, 1H, J =

12.5 and = 3.5 Hz), 4.49 (q, 1H, J = 12.4 and 6.8 Hz), 6.25 (q, 1H, J = 6.8 and 3.5 Hz), 7.29−7.60 (m, 8H), 8.10 (d, 2H). ^{13}C NMR ($CDCl_3$, 300 MHz): for 1-phenyl-2-acetoxyethyl benzoate (**10w**) (major isomer) δ 20.7, 66.1, 74.0, 126.6, 128.4, 128.6, 128.7, 129.6, 129.7, 133.1, 136.5, 165.5, 170.6.

J. Preparation of 3-(4-Nitrophenoxy)propyl Acetate (22) from Isolated 2-Methylene-1,3-dioxane (8b) and 4-Nitrophenol. 3-(4-Nitrophenoxy)propyl acetate (**22**) was prepared by reacting isolated 2-methylene-1,3-dioxane (**8b**) with 4-nitrophenol in THF following the same procedures described above. The crude product was further purified by a flash column (silica gel) separation using 50/50 (v/v) ethyl acetate/hexane mixture as the eluent to give 3-(4-nitrophenoxy)propyl acetate (0.9 g, 98% GC purity, a waxlike solid, mp 66−67 °C) in 74% isolated yield. FTIR (KBr): 3110, 3082, 2980, 2952, 2900, 2838, 1938, 1799, 1736, 1606, 1590, 1503, 1472, 1423, 1346, 1246, 1184, 1112, 1049, 1018, 968, 901, 857, 756, 694, 662, 642, 605, 517 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.07 (s, 3H), 2.17 (m, 2H), 4.15 (t, 2H, J = 6.6 Hz), 4.28 (t, 2H, J = 6.3 Hz), 6.96 (d, 2H, J = 9.0 Hz), 8.20 (d, 2H, J = 9.0 Hz). ^{13}C NMR ($CDCl_3$, 300 MHz): δ 20.8, 28.3, 60.8, 65.2, 114.4, 125.8, 141.5, 163.7, 170.9.

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