material. Only about 100 mg of crude C_{60}/C_{70} mixture has been successfully resolved per run on a 2 in. i.d. × 4 ft length preparative column containing CSP 1 bonded to 60 μm irregular silica particles. Normally, this column will separate 20 g per run of a soluble racemate having a separation factor similar to that of the C_{60}/C_{70} mixture.

Acknowledgment. We are grateful to Professor John Shapley and Dr. Scott Koefod for providing the crude mixture of C_{60} and C_{70} used in this study. This work was supported by grants from the National Science Foundation and Department of Education Advanced Opportunities in Chemistry Graduate Fellowship.

Articles

A Comparison of (Chloromethyl)- and (Iodomethyl)zinc Cyclopropanation Reagents

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A study comparing the rate of cyclopropanation of a range of olefins using (chloromethyl)- and (iodomethyl)zinc reagents is described. The (chloromethyl)zinc reagent derived from diethylzinc and chloroiodomethane is generally more reactive than the (iodomethyl)zinc analogue. The use of 1,2-dichloroethane as the solvent for these reactions was shown to be a crucial factor necessary to achieve clean, rapid, high-yielding cyclopropanations. The well-known directing effect of proximal oxygen substituents on the stereochemical outcome of "Simmons-Smith" cyclopropanations was shown to hold for the (chloromethyl)zinc reagent as well. The diethylzinc/chloroiodomethane reagent system in 1,2-dichloroethane should prove to be a valuable alternative to traditional (iodomethyl)zinc-based cyclopropanation reagents.

Introduction and Background

The discovery[1] that treatment of an ethereal suspension of a zinc/copper couple with diiodomethane generates an organometallic reagent[2] that transforms olefins into cyclopropanes was a watershed event in cyclopropane chemistry. This is evidenced not only by the impressive array of olefins successfully cyclopropanated by this procedure[3] (or the subsequent improvements and modifications[4,5]), but also by its acceptance as a primary method of synthesizing cyclopropanes for both mechanistic and synthetic efforts.[3,6] Although the initial method of preparation of the zinc/copper couple was cumbersome, several synthetically more accessible and reproducible methods quickly followed.[4] Notable among these are the organozinc reagents prepared from either Et_2Zn/CH_2I_2[5] or ZnI_2/CH_2N_2.[7] The species generated by these methods displayed similar reactivity toward olefins as the classic Simmons-Smith reagent. That all of these reagents possess, at least in part, the "(iodomethyl)zinc" (ICH_2ZnX) moiety was firmly established by chemical transformations.[3,7]

The synthetic utility of the Simmons-Smith cyclopropanation derives from the following characteristics: (1) stereospecificity (strict retention of olefin geometry), (2) generality with regard to olefin structure, and (3) the syn-directing effect of hydroxyl and ether functions.[8,9] Recent reports of highly diastereoselective cyclopropanations of olefins bearing recoverable[10] or nonrecoverable[11] chiral auxiliaries which utilize Simmons-Smith

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reagents greatly extend its utility and attest to the versatility and endurance of this reaction.

Continued interest in cyclopropane chemistry[12] as well as recent advances in enantioselective catalysis using organozinc reagents[13] prompted us to begin a study of the structure and reactivity of (halomethyl)zinc species. The "Furukawa" modification, namely treatment of Et_2Zn with CH_2I_2, was deemed particularly amenable for study for several reasons: (1) this procedure employs easily metered reagents and thus strict control of reagent stoichiometry, (2) the reagents are known to be homogeneous, and (3) the absence of zinc salts avoids the complication of Schlenk-type equilibria (e.g., eq 1). The successful employment

$$2\ \text{"}ICH_2ZnI\text{"} \rightleftharpoons \text{"}(ICH_2)_2Zn\text{–}ZnI_2\text{"} \qquad (1)$$

of noncoordinating solvents using this procedure is an added benefit (vide infra). The initial phase of our investigation involved the determination of the solution and solid state structure of the "Wittig–Furukawa" reagents. In a recent report we disclosed the spectroscopic and crystallographic characterization of bis(halomethyl)zinc complexes derived from both diiodomethane and (chloroiodo)methane.[14] During the course of this work, we were surprised to discover that the (chloromethyl)zinc reagents are far more reactive than (iodomethyl)zinc reagents, contrary to what might be expected a priori.

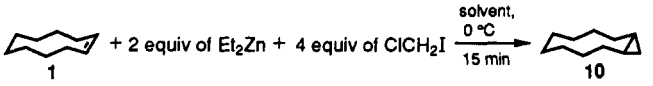
Wittig[7b] was the first to examine the reactivity of (chloromethyl)zinc chloride ($ClCH_2ZnCl$) and bis(chloromethyl)zinc ($(ClCH_2)_2Zn$). These reagents, prepared from $ZnCl_2$ and ethereal CH_2N_2, were found to behave similarly to ICH_2ZnI and $(ICH_2)_2Zn$. On the basis of quenching experiments, Simmons and co-workers[1c] concluded that the reagent prepared from $ClCH_2I$ and zinc–copper couple has "(iodomethyl)zinc" linkages, apparently due to a halogen-exchange process. Presumably, the initially formed $ClCH_2ZnI$ (or $(ClCH_2)_2Zn/ZnI_2$[1c]) is converted to ICH_2ZnCl (or $(ICH_2)_2Zn/ZnCl_2$) under the reaction conditions (refluxing Et_2O). Similar iodide for chloride displacements are well-documented for (halomethyl)zinc species.[1,7] The methods of preparation used by Wittig and Simmons necessitate the use of ethereal solvents, which dramatically attentuate the reactivity of (halomethyl)zinc species (vide infra). Later, Miyano and co-workers reported a series of experiments on the $Et_2Zn/ClCH_2I/O_2$ system which showed that, for a variety of simple olefins, the (chloromethyl)zinc reagent affords slightly higher yields than those obtained with the (iodomethyl)zinc analogue.[15] No direct comparisons were performed by these workers so we decided to reinvestigate this reaction with the aim of improving its generality.[16]

Table I. NMR Data for "XCH_2Zn" Species[a]

entry	reagent	solvent	^1H (ppm)	^{13}C (ppm)	ref
1	$(ClCH_2)Zn$	acetone	2.54	~29[b]	14b
2	$(ClCH_2)Zn$/DME	acetone	2.56	~29[b]	14b
3	$(ClCH_2)Zn$/DME	benzene	2.71	29.60[c]	14a
4	$BrCH_2ZnBr$	THF	2.1–2.3	14.4	17
5	$(BrCH_2)Zn$	THF	3.1	–	17
6	$(ICH_2)Zn$	acetone	1.34	−16.62	14b
7	$(ICH_2)Zn$/DME	acetone	1.34	−18.30	14b
8	$(ICH_2)Zn$/DME	benzene	1.40	−19.67[b]	14a

[a] The spectra referred to in entries 1–3 and 6–8 were obtained at 300 MHz (^1H), 75.5 MHz (^{13}C), at a concentration of 0.80–1.00 M in the solvent specified. The spectra referred to in entries 4 and 5 were obtained at 360 MHz (^1H), 75.5 MHz (^{13}C); concentrations were not specified. [b] This signal was obscured by the acetone-d_6 heptet. [c] $^1J_{CH}$ = 133 Hz. [d] $^1J_{CH}$ = 132 Hz.

Table II. Cyclopropanation of 1 with $Et_2Zn/ClCH_2I$ in Various Solvents



entry	solvent	yield 10,[a] %	recovd 1,[a] %
1	DCE	94	0
2	Et_2O	<1	97
3	toluene	75	18
4	benzene	83	13
5	hexane	7	91

[a] GC yields using cyclododecane as an internal standard.

Results

Solution Structure of $(XCH_2)_2Zn$. An extensive NMR investigation of the nature of (halomethyl)zinc reagents has been carried out in the context of our structural studies.[14b] Presented in Table I are the relevant spectroscopic comparisons for the purpose at hand. That the Et_2Zn/ICH_2Cl system generated a different organometallic species than the Et_2Zn/CH_2I_2 system was clearly evident from their NMR spectra. For example, the 1,2-dimethoxyethane (DME) complexes of $(ClCH_2)_2Zn$ and $(ICH_2)_2Zn$ in benzene-d_6 displayed resonances for the (halomethyl)zinc moiety at 2.71 and 1.40 ppm, respectively, in the ^1H NMR spectra, and 29.60 and −19.67 ppm, respectively, in the ^{13}C NMR spectra. The solvent effect on chemical shift for either $(ClCH_2)_2Zn$ or $(ICH_2)_2Zn$ was negligible as the resonance positions were hardly changed in acetone-d_6 with or without added DME. For comparison purposes, the chemical shifts for $BrCH_2ZnBr$ and $(BrCH_2)_2Zn$ in THF-d_8 reported by Fabisch and Mitchell[17] are also included.

Solvent Effect on Cyclopropanation. Initial experiments with the $Et_2Zn/ClCH_2I$ reagent system were run in benzene at 0 °C using *cis*-cyclodecene (1) as the substrate. A 2:1 stoichiometry of dihalomethane to Et_2Zn was used throughout this study. By analogy to Seyferth's results with the well-characterized bis(halomethyl)mercury and (halomethyl)mercury halide reagents[18] we expected bis(halomethyl)zinc compounds to be more reactive than mono(halomethyl)zinc compounds. Although the reactions conducted in benzene were rapid at 0 °C (<30 min for

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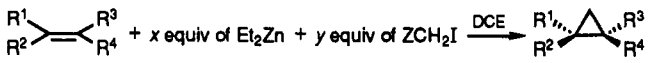
Table III. Comparison of $Et_2Zn/ClCH_2I$ with Et_2Zn/CH_2I_2 Using Olefins 1–7[a]



entry	olefin	x	y	Z	GC yield, % (product)[b]	recovd olefin,[b] %	isolated yield, %	time, min (temp, °C)
1	1	2.0	4.0	Cl	94 (10)	0	85	15 (0)
2	1	2.0	4.0	I	12 (10)	88	–[d]	15 (0)
3	2	5.0	10.0	Cl	92 (11)	1	84	60 (23)
4	2	5.0	10.0	I	88 (11)	12	–[d]	60 (23)
5	3	2.0	4.0	Cl[c]	96 (12)	0	93	30 (0)
6	3	2.0	4.0	I[c]	16 (12)	81	–[d]	30 (0)
7	4	2.0	4.0	Cl	100 (13)	0	99	15 (0)
8	4	2.0	4.0	I	96 (13)	4	–[d]	15 (0)
9	5	3.0	6.0	Cl	100 (14)	0	85	90 (–23)
10	5	3.0	6.0	I	85 (14)	15	–[d]	90 (–23)
11	6	2.0	4.0	Cl[c]	89 (15)	<1	93	30 (0)
12	6	2.0	4.0	I[c]	41–74 (15)	27–33	–[d]	30 (0)
13	7	2.0	4.0	Cl	64 (16)	1	–[d]	15 (0)
14	7	2.0	4.0	I	98 (16)	0	99	15 (0)

[a] GC reactions were run on a 0.25-mmol scale at 0.20 M under Ar. Preparative-scale reactions were run on a 1–2-mmol scale at 0.20–0.25 M under Ar. [b] GC yields using cyclododecane as an internal standard. Average of two runs. Reproducibility ±3%. [c] Reaction using "preformed" reagent. See text for explanation. [d] Not determined.

complete consumption of olefin), a myriad of byproducts were observed by GC. Control experiments established that the observed byproducts were derived from reaction with the benzene solvent. Since (halomethyl)zinc reagents are electrophilic they should react much less readily with electron-poor aromatic compounds.[3,19] Indeed, clean, quantitative conversion of 1 to the cyclopropane could be achieved using chlorobenzene as solvent. However, for preparative purposes, chlorobenzene was considered to be an inconvenient solvent due to its low volatility (bp 132 °C).

We then turned our attention to 1,2-dichloroethane (DCE), a solvent not normally used in organozinc chemistry, presumably due to its potential reactivity. As the results in Table II demonstrate, DCE was found to be a superior solvent for this reaction. Treatment of a 2:1 mixture of $Et_2Zn/1$ with 4 equiv of $ClCH_2I$ at 0 °C quickly (<10 min) resulted in near-quantitative conversion to the cyclopropane: no byproducts were observed by GC analysis. In contrast, the reaction in benzene or toluene generated several byproducts, inseparable from the desired cyclopropane, and the reactions were slower. The use of ethereal solvents (Et_2O, THF) was undesirable, as the rate of reaction was dramatically decreased. The failure of hexane to act as an efficent medium for cyclopropanation was apparently due to the insolubility of the (halomethyl)zinc reagent. Upon addition of $ClCH_2I$ to $Et_2Zn/1$ rapid formation of an air-sensitive white precipitate was observed. These solvent effects were found to be qualitatively similar for a range of olefins, including allylic ethers and alcohols.

Substrate Generality. In order to test the scope of this reaction, we examined a variety of representative olefins that have been subjected to either the classical Simmons–Smith or Furukawa procedures. Figure 1 depicts the substrates examined in this study. Aliphatic olefins (**1, 2**) as well as those with directing oxygen functionalities (**3, 4, 5**) were chosen as simple achiral substrates to gauge the relative reactivity of the $Et_2Zn/ClCH_2I$ and Et_2Zn/CH_2I_2 systems. The stereodirecting effect of allylic oxygen substituents was explored using chiral (racemic) substrates **6** and **7**. Finally, the response of the Mash (**8**)[10e] and Yamamoto (**9**)[10d] chiral auxiliaries was also examined.

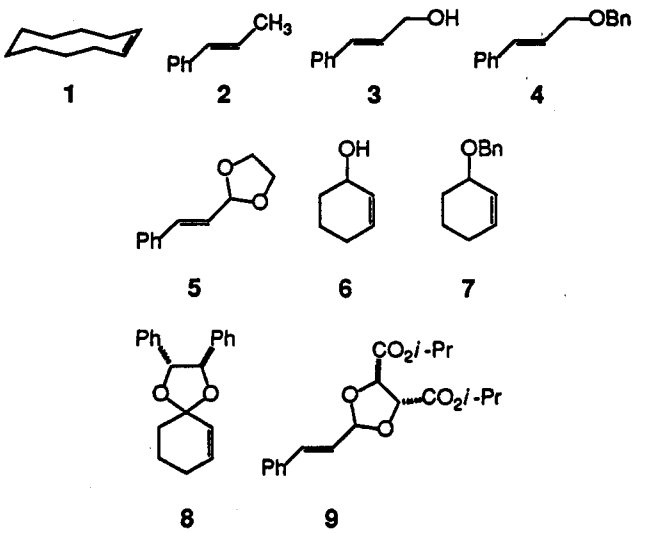


Figure 1. Representative olefin substrates under study.

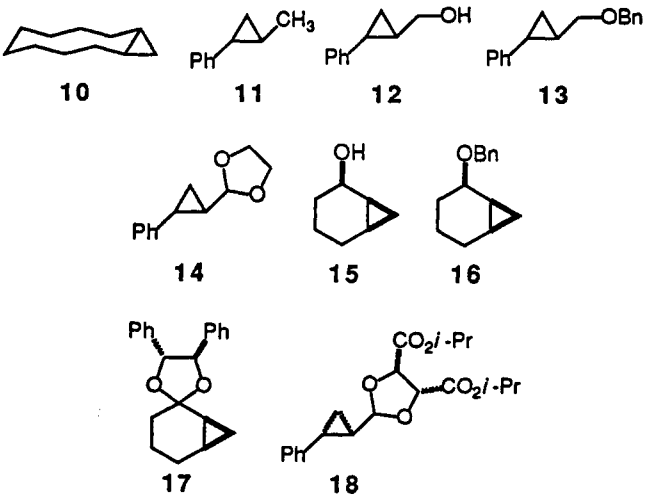


Figure 2. Cyclopropane products for Tables III and IV.

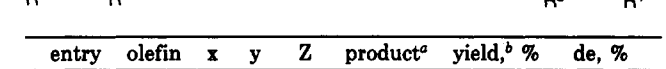
(19) Furukawa has reported the cyclopropanation of aromatic compounds. (a) Nishimura, J.; Furukawa, J.; Kawabata, N.; Fujita, T. *Tetrahedron* **1970**, *26*, 2229. (b) Nishimura, J.; Furukawa, J.; Kawabata, N. *Bull. Chem. Soc. Jpn.* **1970**, *43*, 2195. (c) Miyano, S.; Hashimoto, H. *Bull. Chem. Soc. Jpn.* **1973**, *46*, 3257. (d) Lehnert, E. K.; Sawyer, J. S.; Macdonald, T. L. *Tetrahedron Lett.* **1989**, *30*, 5215.

Reactivity Comparison. Direct rate comparisons of the $Et_2Zn/ClCH_2I$ and Et_2Zn/CH_2I_2 systems were conducted for substrates 1–7, and the results of these experiments are compiled in Table III. The product cyclopropanes are depicted in Figure 2. Preliminary experiments established the reaction conditions that were required for complete conversion of each substrate to cyclopropane using the $ClCH_2I/Et_2Zn$ reagent. The same conditions were used for the CH_2I_2/Et_2Zn reagent as indicated in Table III. For olefins **1**, **2**, **4**, **5**, and **7**, the protocol was identical to that used in the solvent study described above. For the allylic alcohols **3** and **6**, the (halomethyl)zinc reagents were formed prior to addition of the olefin (vide infra). All of the reactions in Table III were conducted using degassed solvents under 1 atm of argon. GC yields were calculated versus cyclododecane as an internal standard using relative response factors. Isolated yields refer to products purified by silica gel chromatography and bulb-to-bulb distillation.

The data in Table III clearly reveal the superiority of $Et_2Zn/ClCH_2I$ relative to Et_2Zn/CH_2I_2 in terms of rate of reaction. This is particularly evident for the cyclopropanation of the simple aliphatic substrate *cis*-cyclodecene **1** (entries 1–2). The cyclopropanation of (*E*)-1-phenylpropene, **2** (entries 3–4), points out one of the potential drawbacks of the zinc-based cyclopropanations. Styrenes typically react sluggishly with Simmons–Smith reagents,[3] and complete consumption of **2** could only be attained at the expense of slightly lower yields, presumably due to reaction with the aromatic ring.

The tremendous rate acceleration due to allylic oxygen functions is evident from the data in entries 5–10 compared to the results with the parent styrene (entries 3–4). The different reaction conditions used for substrates **3**–**5** deserve special attention. Although the typical procedure used for cyclopropanations using Et_2Zn/CH_2I_2 involves treatment of the olefin with Et_2Zn followed by addition of CH_2I_2, we have found this protocol to be very inefficient for the cyclopropanation of allylic alcohols. Presumably, initial reaction of the alcohol with diethylzinc formed a zinc alkoxide aggregate[20,21] which reacted only sluggishly with the dihalomethane to form the (halomethyl)zinc reagent.[22] Thus, formation of the reagent *prior* to addition of the allylic alcohol led to rapid, high-yielding reactions (entries 5 and 11) with the (chloromethyl)zinc reagent, but the reaction with the (iodomethyl)zinc reagent was still sluggish (entries 6 and 12). The benzyl ether **4** was an extremely reactive substrate, however, and underwent cyclopropanation rapidly with both (halomethyl)zinc reagents (entries 7 and 8). The use of an α,β-unsaturated acetal represented another challenge. Conducting the reaction at 0 °C or higher led to destruction of the product, undoubtedly due to acetal ring opening promoted by zinc halide byproducts.[23] Conducting the reaction at −23 °C alleviated this problem (entries 9 and 10). It should be noted that in all of these reactions, the (chloromethyl)zinc reagent gave higher GC conversions than the (iodomethyl)zinc reagent under identical conditions, and the isolated yields using the (chloromethyl)zinc reagent were uniformly high.

Table IV. Directing Effect of Allylic Oxygen Functions



entry	olefin	x	y	Z	product[a]	yield,[b] %	de, %
1	**6**	2	4	Cl[c]	**15**	93	99
2	**6**	2	4	I[c]	**15**	–	>99.5
3	**7**	2	4	Cl	**16**	–	78–85
4	**7**	2	4	I	**16**	99	>99.5
5	**8**	3	6	Cl	**17**	90	90
6	**8**	3	6	I	**17**	–	86
7	**9**	5	10	Cl	**18**	95	82
8	**9**	5	10	I	**18**	–	>90[d]

[a] Reaction using "preformed" reagent. See text for explanation. [b] Isolated yield of major diastereomer (entries 1 and 4) or indicated mixture of diastereomers (entries 5 and 7). [c] Major diastereomer as depicted in Figure 2. [d] Yamamoto reports a 91% de for this reaction using the same stoichiometry and hexane as solvent, but warming to 0 °C before quenching.

The cyclopropanation of 2-cyclohexen-1-ol (**6**) with the preformed (chloromethyl)zinc reagent occurred uneventfully (entry 11), while the use of the (iodomethyl)zinc reagent was characterized by much more sluggish reactions and poor reproducibility (entry 12). Unlike the case of the benzyl ether of cinnamyl alcohol (**4**), however, cyclopropanation of benzyl ether **7** with the (chloromethyl)zinc reagent was problematic (entry 13). Numerous lower retention time peaks in the GC traces of the crude products suggested that debenzylation was a major side reaction, but the reason for the susceptibility of **7**/**16** to such processes is unclear. The (iodomethyl)zinc reagent, on the other hand, reacted very cleanly with **7** (entry 14).

Heteroatom Directing Effects. The influence of proximal oxygen substituents on the stereochemical course of (chloromethyl)zinc cyclopropanations was probed using substrates **6**–**9** (Table IV). Cyclopropanation of **6** with $Et_2Zn/ClCH_2I$ afforded **15** with 99% de (entry 1). The minor trans diastereomer was not detected in reactions using Et_2Zn/CH_2I_2 (entry 2), but the yields were much lower (see Table III, entry 12). On the other hand, cyclopropanation of **7** with $Et_2Zn/ClCH_2I$ afforded **16** with only 78–85% de and in moderate yields (entry 3), while the use of Et_2Zn/CH_2I_2 afforded **16** exclusively in quantitative yield (entry 4). The low diastereoselectivity observed in the cyclopropanation of **7** with the (chloromethyl)zinc reagent could be due to differential rates of destruction of the diastereomeric products, since the cyclopropanation of **6** proceeded with such high selectivity.

The reaction of the cyclic chiral ketal **8**[10c] with $Et_2Zn/ClCH_2I$ at −23 °C for 90 min provided **17** with 90% de in 90% yield. This result was particularly gratifying, as cyclopropanation of this substrate had previously been carried out only with the reagent formed from zinc–copper couple/CH_2I_2.[10e] Reaction of **8** with Et_2Zn/CH_2I_2 afforded **17** with a slightly lower (86%) de, but a notably lower (70–80%) conversion was observed under the same conditions. Likewise, the reaction of chiral acetal **9**[10d] proceeded with good diastereocontrol for both the (chloromethyl)- and (iodomethyl)zinc reagents. Whereas the olefin was completely consumed after 90 min at −23 °C using the $Et_2Zn/ClCH_2I$ system, the Et_2Zn/CH_2I_2 system provided only 78–80% conversion under these conditions using the same quantities of reagents. The greater reactivity of the $Et_2Zn/ClCH_2I$ system did result in reduced diastereoselectivity compared to the Et_2Zn/CH_2I_2 system

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(22) NMR evidence we have obtained supports this view. Treatment of 2-methoxyethanol with Et_2Zn generates an $(CH_3OCH_2CH_2OZnEt)_n$ aggregate.[21] Added $ClCH_2I$ does not result in appreciable formation of $ClCH_2Zn$ species even after 14 h at room temperature. For a related example, see ref 19d.
(23) This problem has been observed previously in the cyclopropanation of silyl enol ethers.[16] Previous workers have found that the use of Et_2O as the reaction solvent or the addition of several equivalents of DME attenuates the rate of this side reaction.

for the Yamamoto substrate, however (82% de versus >90% de).

Discussion

The reason for the higher rate of cyclopropanation observed for the $Et_2Zn/ClCH_2I$ system compared to that of the Et_2Zn/CH_2I_2 system is not clear at present, but several factors can be ruled out. The rate of formation of the (halomethyl)zinc reagents was clearly very rapid using both $ClCH_2I$ and CH_2I_2, as was evident from our NMR studies of these reagents.[14] Furthermore, only trace amounts of dihalomethane were observed in the GC analyses of the crude reaction mixtures for the reactions described in Tables III and IV. Hence, the rate of reagent formation apparently was not playing a role in the observed reactivity difference.

The solubility of the reagents also did not seem to be a factor. Cyclopropanations using both the (chloromethyl)zinc and (iodomethyl)zinc reagents gradually became heterogeneous, but this was to be expected since zinc halide salts were being produced. In the reactions using "preformed" reagents, however, no precipitates were observed until *after* the allylic alcohols were added. Thus, any solubility differences between the two reagents could only be manifested after cyclopropanation had commenced.

The observations of Miyano et al.[15] that oxygen promotes radical formation and thus accelerates the rate of reagent formation in $Et_2Zn/ClCH_2I$ reactions deserve some comment. In the studies described above, oxygen was not intentionally added to the reaction mixtures, yet reagent formation was rapid. The presence of trace amounts of adventitious oxygen (from air in syringe needles, etc.) cannot be ruled out and could be sufficient to catalyze rapid reagent formation in the small-scale (0.1–4 mmol) reactions conducted. In our hands, addition of dry air to these reactions only resulted in destruction of the reagent and prevented complete consumption of starting material. Adventitious oxygen is perhaps not sufficient to promote complete reagent formation in larger scale reactions (10 mmol or greater), according to the results of Miyano and co-workers. This is not unexpected as any number of radical-quenching processes are undoubtedly operative in these reactions. As was pointed out by Miyano, however, the addition of dry air is only necessary to consume *more than 1 equiv* of dihalomethane (versus Et_2Zn). The first equivalent of dihalomethane is consumed rapidly even under a nitrogen atmosphere, suggesting that the accelerated rate of cyclopropanation is due to the formation of the more reactive bis(halomethyl)zinc reagents in the presence of air. This interpretation of the oxygen-accelerated cyclopropanation is consistent with the results of Seyferth concerning the analogous mono- and bis(halomethyl)mercury reagents.[18] In addition, this is also consistent with the general trend observed for reactions of dialkylzinc reagents that the first alkyl group is much more reactive than the second.[20]

Finally, in this context it is interesting to note that Molander and Harring[24] have utilized $ClCH_2I$ in samarium-mediated cyclopropanations of allylic alcohols and found the "(chloromethyl)samarium" reagent to afford better yields in certain cases. The higher yields were attributed to the greater *stability* of the $ClCH_2I$-derived reagent, as these workers noted that the samarium carbenoids decompose exceedingly rapidly. The (presumably) more stable "(chloromethyl)samarium" reagent would thus be a longer lived species and have more of an opportunity to interact with an allylic alcohol in solution. However, the lower steric demands of an "(chloromethyl)samarium" species compared to that of an "(iodomethyl)samarium" species was not ruled out as a rationale for the difference in reactivity. For the (halomethyl)zinc reagents examined in our study, all evidence to date points to "(chloromethyl)zinc" species being *more* reactive and *less* stable than "(iodomethyl)zinc" species. In addition to the more rapid rate of reaction noted above and the facile reaction with aromatic solvents, during the course of our NMR spectroscopic studies of these reagents, we have noted that solutions of $(ClCH_2)_2Zn$ are generally less stable than solutions of $(ICH_2)_2Zn$.[14b]

The experiments described above demonstrate that (chloromethyl)zinc reagents are generally superior to (iodomethyl)zinc reagents for the cyclopropanation of a variety of olefins. In addition, the dramatic rate deceleration of cyclopropanations conducted in Et_2O was quantified for the simple aliphatic substrate *cis*-cyclodecene, and DCE was found to be a useful alternative solvent for these reactions. Finally, the sensitivity of the outcome of the cyclopropanation of allylic alcohols, ethers, and ketals to the experimental conditions was demonstrated, and procedures for rapid, high-yielding conversions of each of these substrates were developed.

Experimental Section

General Experimental. ^1H and ^{13}C NMR spectra were recorded at 300 MHz ^1H (75.5 MHz ^{13}C) or 500 MHz ^1H (125.8 MHz ^{13}C) in deuteriochloroform ($CDCl_3$) with either tetramethylsilane (TMS) (0.00 ppm ^1H, 0.00 ppm ^{13}C) or chloroform (7.26 ppm ^1H, 77.00 ppm ^{13}C) as an internal reference unless otherwise stated. Chemical shifts are given in δ; multiplicities are indicated as br (broadened), s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), exch (exchangeable); coupling constants, J, are reported in hertz. Infrared spectra were recorded on an IBM FTIR-32 spectrometer. Peaks are reported (cm^{-1}) with the following relative intensities: s (strong, 67–100%), m (medium, 40–67%), w (weak, 20–40%), and br (broad). Mass spectra were obtained using ionization voltages of 70 and 10 eV. Data are reported in the form m/z (intensity relative to base = 100). Elemental analyses were performed by the University of Illinois Microanalytical Service Laboratory.

Analytical thin-layer chromatography was performed on Merck silica gel plates with F-254 indicator. Visualization was accomplished by UV light, iodine, or *p*-anisaldehyde solution. Solvents for extraction and chromatography were technical grade and distilled from the indicated drying agents: dichloromethane (CH_2Cl_2), pentane, hexane–$CaCl_2$; diethyl ether (Et_2O), *tert*-butyl methyl ether (TBME)–$CaSO_4/FeSO_4$; ethyl acetate (EtOAc)–K_2CO_3. Column chromatography was performed with 32–63-μm silica gel (Woelm). Analytical gas chromatography (GC) was performed using a Hewlett-Packard 50-m HP-5 capillary column. The injector temperature was 225 °C, the detector temperature was 300 °C, and the column head pressure was 17.5 psi. Temperature programs are reported in the following form: initial temperature (time, min), temperature ramp rate (deg/min), final temperature (time, min). Melting points are corrected. Boiling points (bp) for bulb-to-bulb ("Kugelrohr") distillations correspond to uncorrected air bath temperatures.

All reactions were performed under a dry nitrogen or argon atmosphere in oven- and/or flame-dried glassware, except for those reactions utilizing water as a solvent, which were run in air. "Brine" refers to a saturated aqueous solution of NaCl. Unless otherwise specified, solutions of NH_4Cl, $NaHCO_3$, KOH, NaOH, and $Na_2S_2O_3$ are aqueous solutions. Diiodomethane, chloroiodomethane, *cis*-cyclodecene (1), and cinnamyl alcohol (3) were obtained from commercial sources and distilled before use. Diethylzinc was used as received. The substrates 6,[26] 8,[10g] and

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9[10d] were prepared by the literature procedures.

***trans*-3-(Benzyloxy)-1-phenylpropene (4).** In a 250-mL three-neck flask fitted with an addition funnel, a 60% suspension of NaH in mineral oil (450 mg, 11.25 mmol, 1.13 equiv) was washed with dry hexane (3 × 10 mL), dried in vacuo, and suspended in THF (30 mL). The reaction vessel was cooled to 0 °C (ice/H_2O), and a solution of cinnamyl alcohol (1.342 g, 10.00 mmol) in THF (10 mL) was added dropwise via addition funnel over a 4-min period. The reaction mixture was allowed to warm to room temperature, stirred for 5 min, and recooled to 0 °C, and tetra-*n*-butylammonium iodide (100 mg, 0.27 mmol, 0.03 equiv) was added. A solution of benzyl bromide (1.25 mL, 10.51 mmol, 1.05 equiv) in THF (5 mL) was added dropwise via the addition funnel over a 15-min period. The reaction mixture was allowed to warm to room temperature, stirred for 5 h, poured into H_2O (50 mL), and extracted with TBME (3 × 75 mL). The extracts were washed once with brine (50 mL), dried (K_2CO_3), filtered through a pad of silica gel, and concentrated. The residue was purified by silica gel chromatography (hexane/EtOAc, 28/1) and bulb-to-bulb distillation to afford 2.171 g (97%) of the known[25] ether **4** as a clear, colorless liquid: bp 145–150 °C (0.15 Torr); ^{1}H NMR (300 MHz) 7.39–7.24 (m, 10 H, Ph), 6.62 (d, J = 16.0, 1 H, HC(1)), 6.32 (dt, J = 6.0, 16.0, 1 H, HC(2)), 4.56 (s, 2 H, OCH_2Ph), 4.18 (d, J = 6.0, 2 H, H_2C(3)); ^{13}C NMR (75.5 MHz) 138.19, 136.64, 132.41, 128.49, 128.36, 127.74, 127.60 (Ph), 126.41 (C(1)), 125.99 (C(2)), 72.08 (OCH_2Ph), 70.69 (C(3)); TLC R_f 0.55 (hexane/EtOAc, 4/1); GC:t_R 14.0 min (200 °C (5 min), 10 °C/min, 250 °C (10 min)).

2-(*trans*-2-Phenylethenyl)-1,3-dioxane (5). In a 100-mL flask fitted with a Dean–Stark trap, a solution of *trans*-cinnamaldehyde (3.00 mL, 23.8 mmol) in benzene (40 mL) was treated with ethylene glycol (2.70 mL, 48.4 mmol, 2.0 equiv) and *p*-toluenesulfonic acid monohydrate (5 mg). The reaction mixture was heated at 90 °C with azeotropic removal of H_2O for 1 h and allowed to cool to room temperature. The reaction mixture was poured into brine (75 mL) and extracted with TBME (3 × 100 mL). The combined organic layers were dried (K_2CO_3), filtered through a pad of Celite, and concentrated. Purification of the crude product by silica gel chromatography (hexane/EtOAc, 20/1) and bulb-to-bulb distillation to afford 3.86 g (92%) of a thick, clear oil, which solidified upon cooling. Recrystallization from cold pentane afforded 3.690 g (88%) of the known[26] acetal **5** as white plates: mp 33–34 °C (pentane); ^{1}H NMR (300 MHz) 7.35 (m, 5 H, Ph), 6.78 (d, J = 16.0, 1 H, HC(2′)), 6.18 (dd, J = 6.1, 16.0, 1 H, HC(1′)), 5.44 (d, J = 6.1, 1 H, HC(2)), 4.06, 3.97 (2 m, 4 H, H_2C(4)), H_2C(5)); TLC R_f 0.31 (hexane/EtOAc, 20/1); GC t_R 7.92 min (200 °C (5 min), 5 °C/min, 250 °C (5 min)).

(*R*,*S*)-1-(Benzyloxy)-2-cyclohexene (7). In a 200-mL, three-neck flask, a 60% suspension of NaH in mineral oil (600 mg, 15.0 mmol, 1.0 equiv) was washed with hexane (3 × 10 mL), dried in vacuo, and suspended in DME (40 mL). The reaction vessel was cooled to 0 °C (ice/H_2O), and 2-cyclohexen-1-ol (982 μL, 10.0 mmol) was added slowly via syringe. The reaction mixture was allowed to warm to room temperature, stirred for 10 min, and recooled to 0 °C, and tetra-*n*-butylammonium iodide (200 mg, 0.54 mmol, 0.05 equiv) was added. Benzyl bromide (1.43 mL, 12.0 mmol, 1.2 equiv) was added dropwise via syringe. The reaction mixture was allowed to slowly warm to room temperature and was stirred for 12 h. The reaction mixture was poured into ice water (70 mL) and extracted with TBME (3 × 100 mL). The extracts were washed with H_2O (1 × 75 mL) and brine (1 × 100 mL), combined, dried (K_2CO_3), filtered through a pad of Celite, and concentrated. Purification by silica gel chromatography (hexane/EtOAc, 30/1) and bulb-to-bulb distillation to afford 1.750 g (93%) of the known[27] ether **7**. Data for **7**: bp 165–170 °C (9 Torr); ^{1}H NMR (300 MHz) 7.32 (m, 5 H, Ph), 5.84 (m, 2 H, HC(2), HC(3)), 4.58 (AA′ q, J = 11.96, 2 H, H_2CO), 3.96 (br m, 1 H, HC(1)), 2.04 (m, 1 H), 1.99 (m, 1 H), 1.85–1.73 (m, 3 H), 1.57 (m, 1 H); TLC R_f 0.30 (hexane/EtOAc, 20/1); GC t_R 9.06 min (180 °C (5 min), 20 °C/min, 250 °C (5 min)).

Spectroscopic Data for (4*R*,5*R*)-4,5-Bis((2-methylethoxy)carbonyl)-2-(*trans*-2-phenylethenyl)-1,3-dioxolane (9). Although the preparation of **9** has been previously described,[10d] the ^{1}HMR spectral data are incomplete and the ^{13}C NMR data are not provided. Data for **9**: bp 210–220 °C (0.4 Torr); ^{1}H NMR (300 MHz) 7.45–7.27 (m, 5 H, Ph), 6.86 (d, J = 16.0, 1 H, HC(2′)), 6.27 (dd, J = 6.8, 16.0, 1 H, HC(1′)), 5.82 (d, J = 6.8, 1 H, HC(2)), 5.30–5.11 (m, 2 H, OCH(CH_3)$_2$), 4.80 (d, J = 3.8, 1 H, HC(4)), 4.71 (d, J = 3.8, 1 H, HC(5)), 1.34–1.26 (m, 12 H, CH_3's); ^{13}C NMR (75.5 MHz) 169.10 (*C*=O), 168.68 (*C*=O), 136.66 (C(2′)), 135.40 (ipso-Ph), 128.57, 128.52, 127.05 (Ph), 123.83 (C(1′)), 107.15 (C(2)), ~77.2* (C(4), C(5)), 69.80 (*C*H(CH_3)$_2$), 21.66 (CH_3) (*these signals were obscured by the $CDCl_3$ triplet); TLC R_f 0.24 (hexane/EtOAc, 8/1); GC t_R 22.54 min (240 °C, isothermal).

Bicyclo[8.1.0]undecane (10). In a 50-mL, three-neck flask, a solution of **1** (400 μL, 2.52 mmol) in DCE (12.5 mL) was cooled to 0 °C, and Et_2Zn (520 μL, 5.07 mmol, 2.00 equiv) was added via syringe. To this solution was added $ClCH_2I$ (730 μL, 10.02 mmol, 4.0 equiv) dropwise via syringe, and the reaction mixture was stirred for 20 min at 0 °C. Saturated NH_4Cl (20 mL) was carefully added via syringe, and the reaction was allowed to warm to room temperature, stirred vigorously for 10 min, and extracted with TBME (3 × 20 mL). The extracts were washed with H_2O (1 × 20 mL) and brine (1 × 20 mL), combined, dried (K_2CO_3), filtered through a pad of silica gel, and concentrated at aspirator pressure. Bulb-to-bulb distillation of the residue afforded 335 mg (87%) of analytically pure **10**: bp 110–115 °C (30 Torr); ^{1}H NMR (300 MHz) 2.0–1.1 (m, 16 H, H_2C(2), H_2C(3), H_2C(4), H_2C(5), H_2C(6), H_2C(7), H_2C(8), H_2C(9)), 0.63 (m, 3 H, HC(1), HC(10), HC(11)), −0.47 (m, 1 H, HC(11)); ^{13}C NMR (75.5 MHz) 29.00 (C(2), C(9)), 26.55 (C(3), C(8)), 25.19 (C(4), C(7)), 21.75 (C(5)), 16.68 (C(1), C(10)), 8.85 (C(11)); IR (CCl_4) 3854 (w), 3056 (m), 2913 (s), 2859 (s), 2691 (w), 1474 (s), 1447 (s), 1389 (w), 1354 (w), 1320 (w), 1285 (w), 1069 (w), 1026 (m), 992 (w), 945 (w); MS (70 eV) 152 (M^+, 7.0), 124 (9.1), 110 (10.2), 109 (18.2), 96 (42.9), 95 (40.8), 83 (15.4), 82 (65.3), 81 (59.5); GC t_R 6.68 min (150 °C (10 min), 10 °C/min, 200 °C (10 min)). Anal. Calcd for $C_{11}H_{20}$ (152.28): C, 86.76; H, 13.24. Found: C, 86.73; H, 13.19.

(*R*,*S*)-*trans*-2-Methyl-1-phenylcyclopropane (11). In a 25-mL, two-neck flask, a solution of **2** (260 μL, 2.00 mmol) in DCE (10 mL) was cooled to 0 °C, and Et_2Zn (1.03 mL, 10.0 mmol, 5.00 equiv) was added via syringe. To this solution was added $ClCH_2I$ (1.46 mL, 20.0 mmol, 10.0 equiv) dropwise via syringe. The solution was stirred for 20 min at 0 °C, allowed to warm to room temperature, and was stirred for 60 min. The reaction mixture was cooled to 0 °C, and saturated NH_4Cl (10 mL) was carefully added via syringe. Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (pentane/Et_2O, 99/1) and bulb-to-bulb distillation to afford 239 mg of a 92/8 mixture of 11/2 (84% yield, 9% recovered starting material): bp 90–95 °C (30 Torr); ^{1}H NMR (300 MHz) 7.15 (m, 5 H, Ph), 1.56 (m, 1 H, HC(1)), 1.18 (d, J = 5.78, 3 H, H_3C), 1.04 (m, 1 H, HC(2)), 0.88 (m, 1 H, HC(3)), 0.73 (m, 1 H, HC(3)); GC t_R 7.29 min (130 °C (5 min), 10 °C/min, 200 °C (10 min)). The spectral data matches that reported in the literature.[28]

(*R*,*S*)-*trans*-2-Phenyl-1-cyclopropanemethanol (12). In a 25-mL, two-neck flask, a solution of Et_2Zn (410 μL, 4.00 mmol, 2.00 equiv) in DCE (7 mL) was cooled to 0 °C, and $ClCH_2I$ (585 μL, 8.03 mmol, 4.0 equiv) was added via syringe. The solution was stirred for 5 min at 0 °C, and a solution of **3** (268 mg, 2.00 mmol) in DCE (3 mL) was added slowly via syringe. The reaction mixture was stirred for 20 min at 0 °C and then quenched with saturated NH_4Cl (20 mL). Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (hexane/EtOAc, 6/1) and bulb-to-bulb distillation to afford 275 mg (93%) of the known[28] cyclopropane **12** as a clear, colorless oil: bp 145–150 °C (2 Torr); ^{1}H NMR (300 MHz) 7.15 (m, 5 H, Ph), 3.60 (dd, J = 2.33, 6.71, 2 H, H_2C(1)), 1.81 (m, 1 H, HC(2′)), 1.78 (br s, 1 H, O*H*), 1.43 (m, 1 H, HC(1′)), 0.94 (m, 2 H, H_2C(3′)); ^{13}C NMR (75.5 MHz) 142.37, 128.30, 125.74, 125.58 (Ph), 66.48 (C(1)), 25.25 (C(2′)), 21.24 (C(1′)), 13.83 (C(3′)); TLC R_f 0.10 (hexane/EtOAc, 4/1); GC t_R 8.60 min (170 °C isothermal). Anal. Calcd for $C_{10}H_{12}O$ (148.21): C, 81.04; H, 8.16. Found: C, 80.99; H, 8.18.

(*R*,*S*)-*trans*-1-((Benzyloxy)methyl)-2-phenylcyclopropane (13). In a 25-mL, two-neck flask, a solution of **4** (224 mg, 1.00 mmol) in DCE (5 mL) was cooled to 0 °C, and Et_2Zn (205 μL, 2.00 mmol, 2.00 equiv) was added via syringe. To this solution

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was added $ClCH_2I$ (292 μL, 4.00 mmol, 4.00 equiv) dropwise via syringe. The reaction mixture was stirred for 20 min at 0 °C, and saturated NH_4Cl (3 mL) was carefully added via syringe. Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (hexane/EtOAc, 50/1) and bulb-to-bulb distillation to afford 236 mg (99%) of **13** as a clear, colorless oil: bp 125–130 °C (0.10 Torr); ^1H NMR (300 MHz) 7.18 (m, 10 H, Ph), 4.54 (s, 2 H, H_2CPh), 3.50 (m, 1 H, HC(1′)), 3.41 (m, 1 H, HC(1′)), 1.78 (m, 1 H, HC(2)), 1.44 (m, 1 H, HC(1)), 0.93 (m, 2 H, $H_2C(3)$); ^{13}C NMR (75.5 MHz) 142.53, 138.39, 128.32, 128.24, 127.60, 127.50, 125.76, 125.40 (Ph), 73.43 (CH_2Ph), 72.43 (C(1′)), 22.58 (C(2)), 21.40 (C(1)), 14.17 (C(3)); IR (CCl_4) 3067 (m), 3030, (m), 2855 (m), 2334 (w), 1943 (w), 1728 (w), 1605 (w), 1497 (m), 1455 (m), 1414 (w), 1360 (m), 1310 (w), 1252 (w), 1204 (w), 1167 (w), 1098 (s); MS (70 eV) 238 (M^+, 0.5), 147 (11), 130 (8), 129 (11), 117 (32), 92 (11), 91 (100); TLC R_f 0.55 (hexane/EtOAc, 4/1); GC t_R 11.02 min (240 °C isothermal). Anal. Calcd for $C_{17}H_{18}O$ (238.33): C, 85.67; H, 7.61. Found: C, 85.70; H, 7.60.

(*R*,*S*)-*trans*-2-(2-Phenyl-1-cyclopropyl)-1,3-dioxolane (14). In a 25-mL, two-neck flask, a solution of **5** (352 mg, 2.00 mmol) in DCE (10 mL) was cooled to −23 °C (CO_2/CCl_4), and Et_2Zn (620 μL, 6.05 mmol, 3.02 equiv) was added via syringe. To this solution was added $ClCH_2I$ (880 μL, 12.08 mmol, 6.04 equiv) dropwise via syringe. The reaction mixture was stirred for 90 min at −23 °C, and a 20% solution of KOH (10 mL) was carefully added via syringe. Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (hexane/EtOAc, 20/1) and bulb-to-bulb distillation to afford 345 mg (91%) of **14** as a clear, colorless oil. This material is highly labile, decomposing within hours at room temperature or 2–3 days at −20 °C: bp 145–150 °C (0.2 Torr); ^1H NMR (300 MHz) 7.16 (m, 5 H, Ph), 4.67 (d, J = 5.26, 1 H, HC(2)), 3.93, 3.81 (2 m, 4 H, $H_2C(4)$, $H_2C(5)$), 1.99 (m, 1 H, HC(2′)), 1.43 (m, 1 H, HC(1′)), 1.08, 0.95 (2 m, $H_2C(3')$); ^{13}C NMR: (75.5 MHz) 141.59, 128.07, 125.84, 125.52 (Ph), 105.49 (C(2)), 64.74 (C(4), C(5)), 24.54 (C(2′)), 19.14 (C(1′)), 11.36 (C(3′)); IR (CCl_4) 3030 (m), 2953 (m), 2882 (m), 1736 (w), 1607 (m), 1501 (m), 1466 (w), 1427 (m), 1379 (m), 1221 (m), 1190 (m), 1150 (m), 1111 (s), 1075 (m), 1038 (m); MS (eV) 190 (M+, 2), 117 (10), 115 (11), 104 (7), 99 (7), 91 (12), 86 (39), 77 (6), 73 (100); TLC R_f 0.25 (hexane/EtOAc, 20/1); GC t_R 9.82 min (180 °C (5 min), 10 °C/min, 250 °C (10 min)). Anal. Calcd for $C_{12}H_{14}O_2$ (190.24) C, 75.76; H, 7.42. Found: C, 75.61; H, 7.46.

(*R*,*S*)-(1*l*,2*u*,6*u*)-2-Hydroxybicyclo[4.1.0]heptane (15). In a 25-mL, two-neck flask, a solution of Et_2Zn (620 μL, 6.00 mmol, 2.00 equiv) in DCE (15 mL) was cooled to 0 °C, and $ClCH_2I$ (0.88 mL, 12.0 mmol, 4.0 equiv) was added via syringe. The reaction mixture was stirred for 5 min at 0 °C, and a solution of **6** in DCE (3 mL) was added slowly via syringe. The reaction mixture was stirred for 30 min at 0 °C and then quenched with saturated NH_4Cl (10 mL). Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (hexane/EtOAc, 6/1) and bulb-to-bulb distillation to afford 318 mg (95%) of the known[24] cyclopropane **15** as a single isomer as indicated by GC analysis: bp 120–125 °C (30 Torr); ^1H NMR (300 MHz) 4.22–4.15 (m, 1 H, HC(2)), 1.88–1.80 (m, 1 H), 1.64–1.58 (m, 1 H), 1.47–1.34 (m, 3 H), 1.24–1.13 (m, 3 H), 1.02–0.94 (m, 1 H), 0.60–0.53 (m, 1 H, HC(7)), 0.32–0.20 (m, HC(7)); TLC R_f 0.28 (hexane/EtOAc, 3/1); GC t_R 8.80 min (110 °C isothermal).

(*R*,*S*)-(1*l*,2*u*,6*u*)-2-(Benzyloxy)bicyclo[4.1.0]heptane (16). In a 25-mL, two-neck flask, a solution of **7** (188 mg, 1.00 mmol) in DCE (6 mL) was cooled to 0 °C, and Et_2Zn (205 μL, 2.00 mmol, 2.00 equiv) was added via syringe. To this solution was added CH_2I_2 (320 μL, 4.00 mmol, 4.00 equiv) dropwise via syringe. The reaction mixture was stirred for 20 min at 0 °C, and saturated NH_4Cl (4 mL) was carefully added via syringe. Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (hexane/EtOAc, 30/1) and bulb-to-bulb distillation to afford 200 mg (99%) of **16** as a single isomer as indicated by GC analysis: bp 110–115 °C (0.2 Torr); ^1H NMR (300 MHz) 7.32 (m, 5 H, Ph), 4.71 (d, J = 11.9, 1 H, HC(8)), 4.53 (d, J = 11.9, 1 H, HC(8)), 3.95 (m, 1 H, HC(2)), 1.80 (m, 1 H, HC(5)), 1.53 (m, 2 H, HC(3)), HC(5)), 1.38 (m, 1 H, HC(4)), 1.24–1.07 (m, 4 H, HC(1), HC(3), HC(4), HC(6)), 0.63 (m, 1 H, H_{endo} C(7)), 0.45 (m, 1 H, H_{exo}C(7)); ^{13}C NMR: (75.5 MHz) 139.24, 128.20, 127.61, 127.12 (Ph), 72.90 (C(2)), 69.22 (CH_2Ph), 27.64 (C(3)), 23.34 (C(5)), 19.58 (C(4)), 13.95 (C(1)), 12.29 (C(6)), 7.11 (C(7)); IR (CCl_4) 3067 (m), 3029 (m), 2986 (m), 2924 (m), 2859 (m), 2818 (m), 1605 (w), 1499 (m), 1462 (m), 1451 (m), 1412 (w), 1374 (w), 1250 (w), 1120 (m), 1159 (w), 1109 (s), 1032 (m), 974 (w), 942 (w), 916 (m); MS (10 eV) 202 (M^+, 5), 172 (19), 111 (81), 104 (22), 97 (12), 96 (38), 95 (62), 94 (12), 93 (16), 92 (41), 91 (100), 81 (20), 80 (21); TLC R_f 0.60 (hexane/EtOAc, 8/1); GC t_R 10.25 min (180 °C (5 min), 20 °C/min, 250 °C (3 min)). Anal. Calcd for $C_{14}H_{18}O$ (202.30): C, 83.12; H, 8.97. Found: C, 82.94; H, 8.89.

(*S*)-(1*l*,2*u*,4′*u*,5′*u*)-4′,5′-Diphenylspiro[bicyclo[4.1.0]heptane-2,2′-[1,3]dioxolane] (17). In a 25-mL, two-neck flask, a solution of **8** (58.5 mg, 0.20 mmol) in DCE (1 mL) was cooled to −23 °C (CO_2/CCl_4), and Et_2Zn (62 μL, 0.60 mmol, 3.0 equiv) was added via syringe. To this solution was added $ClCH_2I$ (88 μL, 1.20 mmol, 6.0 equiv) via syringe. The reaction mixture was stirred for 90 min at −23 °C, and a 20% solution of KOH (2 mL) was carefully added via syringe. Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (hexane/EtOAc, 20/1) to afford 54 mg (90%) of **17** as white plates. A diastereomeric ratio of 95/5 was indicated by analysis of the ^{13}C NMR spectrum (128.5 MHz) of the crude product:[10g] ^1H NMR (300 MHz) 7.37–7.24 (m, 10 H, Ph), 4.92 (d, J = 8.5, 1 H, HC(4′)), 4.78 (d, J = 8.5, 1 H, HC(5′)), 1.97 (m, 1 H), 1.87 (m, 1 H), 1.70 (m, 2 H), 1.53 (m, 3 H), 1.35 (m, 1 H), 0.86 (m, 1 H), 0.45 (q, J = 5.4, 1 H).

(91%*R*,9%*S*)-(4*l*,5*l*,1′*u*,2′*l*)-4,5-Bis((2-methylethoxy)carbonyl)-2-(*trans*-2-phenylcyclopropyl)-1,3-dioxolane (18). In a 25-mL, two-neck flask, a solution of **9** (70 mg, 0.20 mmol) in DCE (2 mL) was cooled to −23 °C (CO_2/CCl_4), and Et_2Zn (100 μL, 1.00 mmol, 5.0 equiv) was added via syringe. To this solution was added $ClCH_2I$ (150 μL, 2.0 mmol, 10.0 equiv) via syringe. The reaction mixture was stirred for 90 min at −23 °C, and saturated NH_4Cl (8 mL) was carefully added via syringe. Standard workup (see **10**) provided a crude product that was purified by silica gel chromatography (hexane/EtOAc, 8/1) and afforded 69 mg (95%) of **18** as a clear, colorless oil, which solidified on standing.[10d] A 91/9 mixture of diastereomers was indicated by inspection of the ^1H NMR (500 MHz, benzene-d_6) spectrum of the crude material. Although the signals for the two diastereomers were co-incident for spectra obtained in $CDCl_3$, the HC(2′) multiplet at 2.18 ppm in the ^1H NMR spectrum obtained in benzene-d_6 at 500 MHz was base-line resolved: ^1H NMR (500 MHz) 7.31–7.13 (m, 5 H, Ph), 5.20–5.06 (m, 3 H, HC(2), $HC(CH_3)_2$, $HC(CH_3)_2$), 4.76 (d, J = 4.0, 1 H, HC(4)), 4.65 (d, J = 4.0, 1 H, HC(5)), 2.18 (m, 1 H, HC(2′)), 1.64 (m, 1 H, HCC(1′)), 1.33 (m, 12 H, CH_3's), 1.30–0.99 (m, 2 H, $H_2C(3')$); TLC R_f 0.24 (hexane/EtOAc, 8/1); GC t_R 7.26 min (250 °C isothermal).

General Procedure for Calculation of Relative Response Factors. A stock solution of 1.00 M cyclododecane in DCE was prepared by weighing 16.83 g (100 mmol) of cyclododecane into a 100-mL volumetric flask and diluting to the mark with DCE. Carefully weighted pure samples of each of the compounds in Table III were separately mixed with an equimolar amount of the cyclododecane stock solution and diluted with an equal volume of DCE. The resulting solutions were then injected onto an HP-5 50-m GC column and the area of the cyclododecane peak was divided by the area of the olefin (or cyclopropane) peak. The injections were repeated in triplicate and averaged to give a response factor relative to cyclododecane for each of the compounds.

General Procedure for Cyclopropanation of 1, 2, 4, 5, and 7 (Analytical GC Runs). A magnetically stirred solution of the olefin (0.25 mmol) in dry DCE (1.25 mL) was cooled to 0 °C (room temperature for **2**, −23 °C for **5**), and Et_2Zn (x equiv) was added via syringe. (The stoichiometry used for each substrate is provided in Table III.) The dihalomethane ($2x$ equiv) was added via syringe, and the reaction mixture was stirred at the indicated temperature for the indicated time and quenched by the addition of saturated NH_4Cl (2 mL). The reaction mixture was allowed to warm to room temperature and stirred vigorously for 10 min, and a 1.00 M stock solution of cyclododecane in DCE (250 μL) was added. An aliquot of the reaction mixture was filtered through a pipette of silica gel with CH_2Cl_2 as the eluent and partially concentrated. Determination of the product ratios was accomplished by GC analysis using the programs indicated below. Final ratios and yields were calculated on the basis of independently obtained response factors as described above. GC programs: 1/10:

150 °C (10 min), 10 °C/min, 200 °C (5 min); 4/13: 180 °C (5 min), 10 °C/min, 240 °C (10 min); 7/16: 180 °C (5 min), 20 °C/min, 250 °C (5 min); 2/11: 130 °C (5 min), 10 °C/min, 200 °C (5 min); 5/14: 180 °C (5 min), 10 °C/min, 250 °C (5 min).

General Procedures for Cyclopropanation of 3 and 6 (Analytical GC Runs). A magnetically stirred solution of Et_2Zn (51 μL, 0.50 mmol, 2.00 equiv) in dry DCE (0.75 mL) was cooled to 0 °C, and the dihalomethane (1.00 mmol, 4.00 equiv) was added via syringe. The reaction mixture was stirred for 5 min at 0 °C, and a solution of the olefin (0.25 mmol) in DCE (0.50 mL) was added slowly via syringe. The reaction mixture was quenched by the addition of saturated NH_4Cl (2 mL), was allowed to warm to room temperature, and was stirred vigorously for 10 min. A 1.00 M stock solution of cyclododecane in DCE (250 μL) was then added. An aliquot of the reaction mixture was filtered through a pipette of silica gel with EtOAc as the eluent and partially concentrated. Determination of the product ratios was accomplished by GC analysis using the programs indicated as follows: 3/12, 160 °C isothermal; 6/15, 80 °C (3 min), 10 °C/min, 240 °C (3 min). Final ratios and yields were calculated on the basis of independently obtained response factors as described above.

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Registry No. 1, 935-31-9; 2, 873-66-5; 3, 4407-36-7; 4, 101306-31-4; 5, 83977-12-2; 6, 62860-38-2; 7, 102922-57-6; 8, 128820-14-4; 9, 99267-72-8; 10, 286-92-0; 11, 57637-49-7; 12, 79981-48-9; 13, 136616-39-2; 14, 136616-40-5; 15, 136616-41-6; 16, 136616-42-7; 17, 136658-31-6; 18 (isomer 1), 99267-80-8; 18 (isomer 2), 136658-32-7; DCE, 107-06-2; Et_2Zn, 557-20-0; $ClCH_2I$, 593-71-5; CH_2I_2, 75-11-6; *trans*-cinnamaldehyde, 14371-10-9.

One-Flask, Regiospecific Conversions of Allylic Alcohols into Two-Carbon-Extended, Conjugated Dienoate Esters. Use of a New Sulfinyl Orthoester

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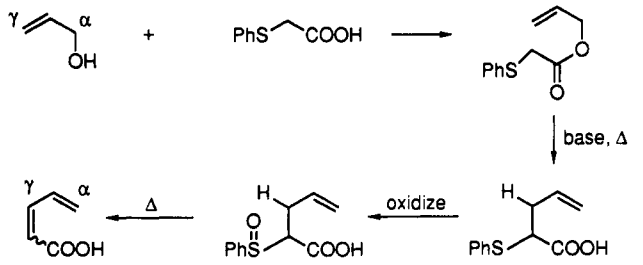
Sixteen differently substituted primary and secondary allylic alcohols are shown to react with sulfinyl orthoacetate 1 at 100 °C sequentially via a [3,3] sigmatropic rearrangement and then a β-elimination of benzenesulfenic acid to form conjugated dienoate esters 5–13 in 45–95% yields. This one-flask, intramolecular carbon–carbon bond-forming process represents a simple and convenient method for regiospecific γ-attachment of a two-carbon (ethoxycarbonyl)methylene unit via the synthetic equivalent of an S_N2' process. Two examples are given in which rationally designed dienoates 20 and 24, prepared via this one-flask process and carrying a pendant alkene unit, undergo intramolecular 2 + 4 cycloaddition producing bicyclic cyclohexenes 21 and 25.

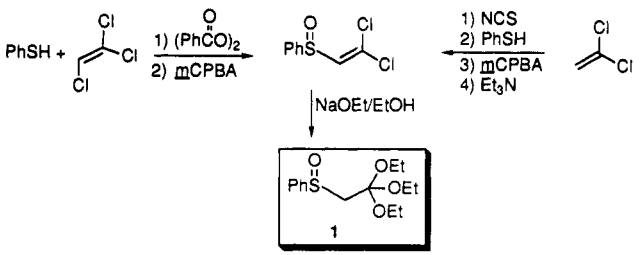
Introduction

In connection with a project on asymmetric total synthesis of hormonally active vitamin D_3 analogues, we required a simple and high-yield synthetic method for conversion of a cyclohexenyl allylic alcohol into the corresponding two-carbon-extended, conjugated dienoate ester.[1] Although the standard protocol of orthoester Claisen rearrangement to form a γ,δ-unsaturated ester[2] proceeded well, subsequent introduction of the requisite α,β-unsaturation under various conditions proceeded poorly.[1a] Likewise, Ireland ester enolate Claisen rearrangement[2g] of a cyclohexenyl allylic α-(phenylthio)acetate, although successful, was not high yielding, and it involved a linear sequence of steps including isolation of three intermediates on the path toward the 2,4-pentadienoic acid product (Scheme I). Based on our interest in sulfoxide chemistry,[3]

Scheme I



Scheme II



we have overcome this difficulty and have developed a streamlined process using an orthoester carrying a sulfinyl group designed to undergo spontaneous thermal β-elimination[4] under the same reaction conditions used for the

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