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Homologation Strategy for the Generation of 1-Chloroalkyl Radicals from Organoboranes

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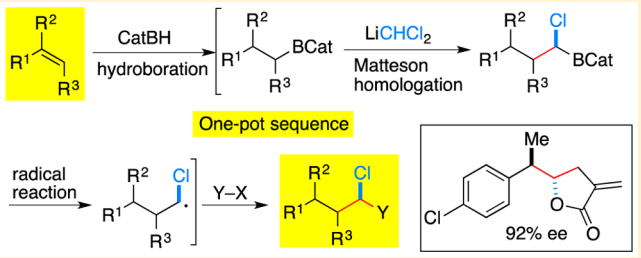
Supporting Information

ABSTRACT: The generation of 1-bromo and 1-chloroalkyl radicals from organoboranes has been investigated. The direct approach involving the hydroboration of halogenated alkenes is impeded by partial dehalogenation taking place during the hydroboration process. An indirect method involving the generation of *B*-(1-chloroalkyl)catecholborane by homologation of *B*-alkylcatecholborane with dichloromethyllithium was developed. A reaction sequence involving a hydroboration reaction, a Matteson homologation, and a radical allylation process has been performed as a one-pot process that takes advantage of three different reactivities of organoboron species. Starting from styrene derivatives, it was possible to prepare *B*-(1-chloro-2-arylpropyl)catecholboranes that are excellent precursors to 1-chloro-2-arylpropyl radicals. A concise approach for the synthesis of an optically active α-methylene-γ-lactone from *p*-chlorostyrene has been developed on the basis of a two-step sequence involving an enantioselective hydroboration−homologation−cyclization reaction followed by a hydrolysis−lactonization process.



INTRODUCTION

Chlorinated radicals are attractive intermediates for the preparation of functionalized molecules. The trichloromethyl radical can be easily generated from tetrachloromethane and bromotrichloromethane using transition-metal catalysts or radical initiators.[1−3] Polyhalogenated alkyl radicals are involved in many radical reactions. For example, Kharasch reported the free radical-mediated addition of polyhalogenated alkanes to alkenes.[4,5] This reaction, however, is restricted to substrates which contain more than two geminal halogen atoms or those that have other activating groups, such as −COOR and −CN.[6,7] Simple monohalogenated alkyl radicals are more difficult to generate. Only a few reactions involving 1-chloroalkyl radicals have been reported. The reaction of geminal dichlorides with lithium aluminum hydride is known to proceed mainly via a 1-chloroalkyl radical intermediate.[8] Miyano et al. reported the AIBN-initiated addition of iodochloromethane to terminal alkenes to synthesize 1-chloro-3-iodoheptane.[9] Zard and co-workers described the use of α-chloro trifluoromethyl xanthate as a radical precursor for the addition to olefins.[10] For the formation of 1-bromoalkyl radicals, there are only few approaches involving radiolysis of the corresponding organic bromides.[11,12]

During the past decade, organoboranes such as *B*-alkylcatecholboranes were shown to be very efficient precursors of alkyl radicals that can be used in a wide range of radical processes.[13−16] However, radicals generated from organoboranes are often not functionalized. In this paper, we report our attempts to use *B*-(1-haloalkyl)catecholboranes to generate 1-haloalkyl radicals.

RESULTS AND DISCUSSION

Hydroboration Approach. The most straightforward approach for the preparation of *B*-(1-haloalkyl)catecholboranes is the hydroboration of 1-haloalkenes. For instance, Elgendy disclosed two procedures for the hydroboration of 1-haloalkenes with catecholborane. He reported excellent regioselectivity for both the neat[17] and the rhodium-catalyzed[18] hydroboration of simple α-haloalkenes, although significant quantities of the dehalogenated products were observed when prolonged heating was employed.[19] Such dehalogenation side reactions were also observed by Maddaluno,[20] Brown,[21] and Pasto.[22−24] However, encouraged by Elgendy's results, the preparation of *B*-(1-halo-2-methylpropyl)catecholboranes by hydroboration of 1-bromo- and 1-chloro-2-methylpropene (**1a**, **1b**) was investigated under neat conditions. When a 1:1 mixture of catecholborane and 1 equiv of the haloalkene was heated at 70−90 °C for 16−20 h, a moderate conversion (<66%) and the corresponding *B*-(1-halo-2-methylpropyl)-catecholboranes **2a** and **2b** were formed together with the dehalogenated product **3**. Catalysis of the hydroboration using a rhodium catalyst was examined next.[18] By using 1.5 equiv of catecholborane, a good conversion could be achieved, but significant amounts of the dehalogenated product **3** were formed with both the bromide **1a** and the chloride **1b**. Attempts to optimize this reaction by modifying the degree of the oxidation of the ligand according to the work of Burgess did not afford a significant enhancement.[25] Although the *B*-1-

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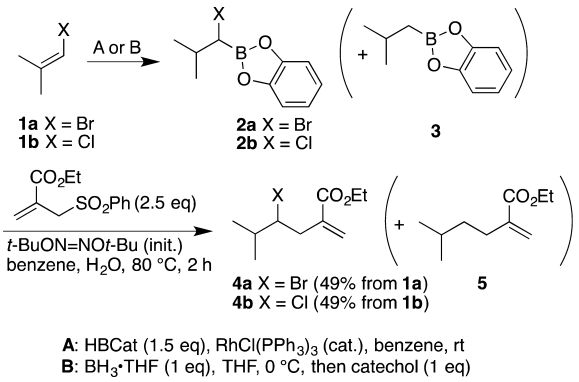
halogenoalkylcatecholboranes were generated as a mixture with the corresponding nonhalogenated *B*-alkylcatecholboranes, the conversion obtained by employing the rhodium-catalyzed hydroboration with alkene **1a** was sufficient for a preliminary investigation of the reactivity of the 1-halolalkyl radical generated from the corresponding organoboranes. The radical allylation with ethyl 2-((phenylsulfonyl)methyl)acrylate[15] was selected as benchmark reaction (Scheme 1). Addition of a small

Scheme 1. One-Pot Hydroboration−Radical Allylation of 1a and 1b



quantity of water during the radical step was beneficial to the reaction, improving the yield by about 10%. The overall yield for the bromide **4a** was moderate (49%). However, taking into account that the hydroboration was leading to the dehalogenated product **3**, the estimated yield for the radical reaction of **2a** to **4a** was very satisfactory (81%). For the reaction with the 1-chloro-2-methylpropene **1b**, the procedure of Brown, using a hydroboration with diborane in THF, gave somewhat better results than the rhodium-catalyzed hydroboration.[21] The intermediate monoalkylborane was treated with catechol to form *B*-(1-chloro-1-methylpropyl)catecholborane **2b**. This procedure allows minimization of the formation of the dehalogenated product, but the conversion remains low (55%). Radical allylation afforded the desired chlorinated alkene **4b** in 49% yield from **1b.**

Due to the limitation of the hydroboration of 1-haloalkenes with either catecholborane or BH_3·THF, it was necessary to develop another more efficient procedure to prepare the promising *B*-1-haloalkylcatecholboranes.

Matteson Homologation Approach. The well-established Matteson homologation procedure with dichloromethyllithium represents a very attractive approach for the synthesis of 1-chloroalkylboronic esters.[26,27] The homologation reaction proceeds through an ate complex that rearranges via 1,2-migration−chloride displacement to afford the corresponding 1-chloroalkylboronic ester. Most of the reported examples of Matteson homologation involve boronates derived from aliphatic diols such as *B*-alkylpinacolboranes. The homologation of *B*-alkylcatecholboranes (RBCat) with dichloromethyllithium ($LiCHCl_2$) was described by Matteson but did not lead to synthetic applications since under extended heating in THF the reaction was low yielding. Better results were achieved by using vacuum pyrolysis.[27] For these reasons, we decided to investigate further the $LiCHCl_2$-mediated homologation for *B*-alkylcatecholboranes and design a one-pot process involving a subsequent radical reaction.

Using the reaction conditions developed by Matteson and modified by Brown, an initial one-pot process was attempted.[27,28] Preliminary studies involved the homologation of *B*-cyclohexylcatecholborane with $LiCHCl_2$, leading to the putative 1-chloroalkylboronate ester. The organoborane was subsequently subjected to a radical allylation reaction[15] with the allyl phenyl sulfone. Monitoring of the reaction by gas chromatography showed that a small amount (<8%) of the desired homologated−allylated product was formed. This preliminary result demonstrated that such a one-pot process is feasible, but a more detailed investigation of the homologation step was necessary. A detailed ^{11}B NMR study of the homologation reaction was then conducted with *n*-octylcatecholborane **6** (Figure 1).[29] The metalation of dichloromethane was

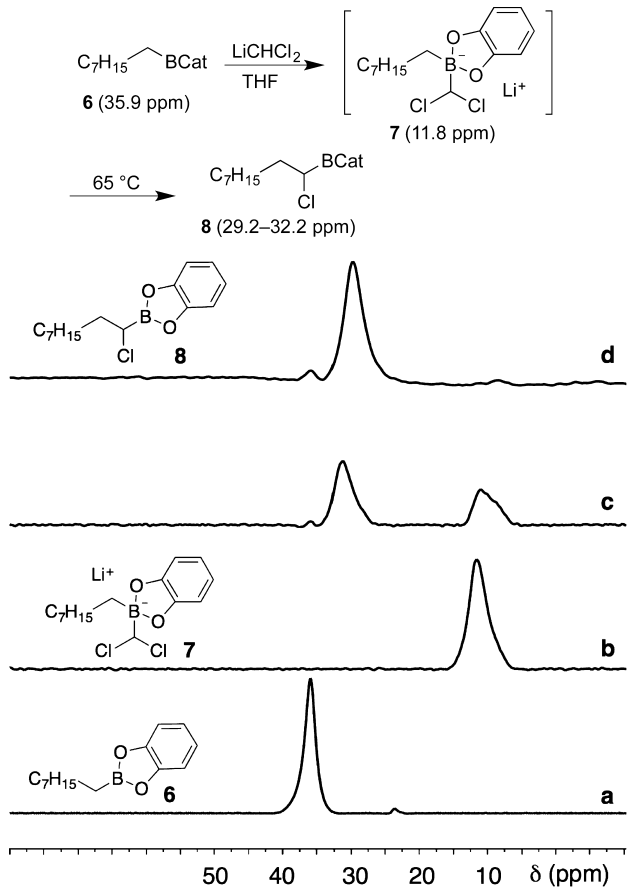


Figure 1. ^{11}B NMR study of the homologation of *B*-octylcatecholborane (**6**) to *B*-1-chlorononylcatecholborane (**8**). *n*-Octylcatecholborane **6** was treated with $LiCHCl_2$ (from *n*-BuLi and CH_2Cl_2) followed by heating at 65 °C. Aliquots of the reaction mixture were diluted in C_6D_6, and spectra were measured at 25 °C. (a) Alkylcatecholborane **6** at the outset of the reaction. (b) Boronate complex **7** just after treatment with $LiCHCl_2$ at −100 °C and warming to room temperature. (c) Rearrangement of **7** to **8** in refluxing THF after 2.5 h. (d) Rearrangement of **7** to **8** in refluxing THF after 8.5 h (reaction completed).

performed using either butyllithium or lithium diisopropylamide, and the migration was examined under thermal condition as well as in the presence of $ZnCl_2$.[27,28,30,31] The cleanest reaction was obtained by generating $LiCHCl_2$ with BuLi at −100 °C followed by addition of *n*-octylcatecholborane **6** (^{11}B NMR 35.9 ppm) to provide the boronate complex **7** (11.8 ppm).[28] Rearrangement of boronate **7** to 1-chlorononylboro-

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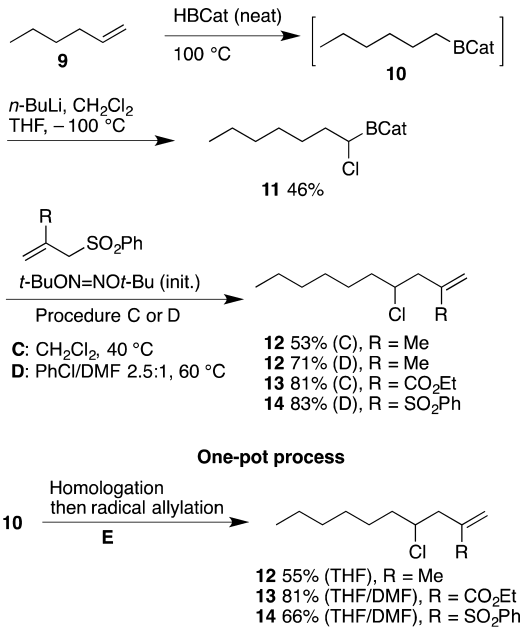
nate **8** (29.2−32.2 ppm)[32] required heating at reflux temperature for 8.5 h (see the ^{11}B NMR spectra in Figure 1).

After having established efficient procedures for the in situ generation of *B*-1-chloroalkylcatecholborane **8**, its utilization in a subsequent radical reaction was attempted. The radical allylation of **8** with 2-methylallyl phenyl sulfone was initiated with either di-*tert*-butyl hyponitrite[33] or air.[34] In order to probe further the use of *B*-1-chloroalkylcatecholboranes in radical reactions, the pure 1-chlorohexylcatecholborane **11** was isolated according to Matteson's procedure.[27] Neat hydroboration of 1-hexene **9** with HBCat afforded *B*-*n*-hexylcatecholborane (**10**) that was directly treated with $LiCHCl_2$ to afford, after vacuum distillation, 1-chlorohexylcatecholborane **11** with a 46% isolated yield for the two steps. The radical allylation reaction starting from isolated **11** with 2-methylallyl phenyl sulfone was then investigated (Scheme 2). Reactions were run under the radical

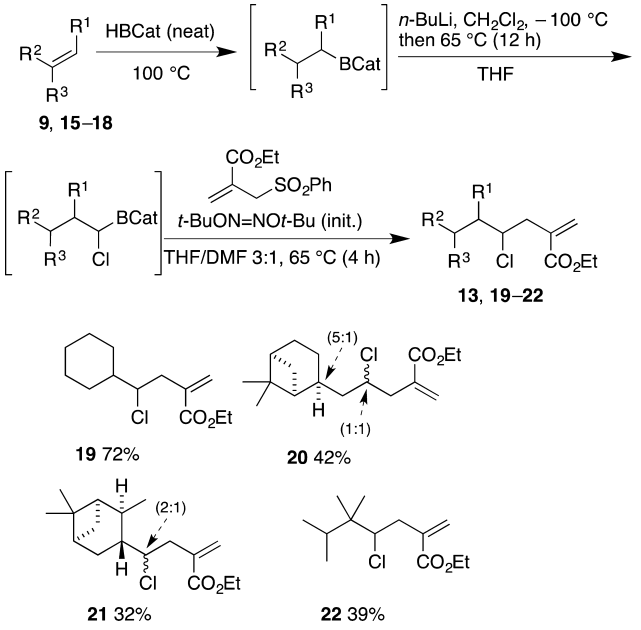
Scheme 2. Preparation and Allylation of the *B*-1-Chloroalkylcatecholborane 11



allylation conditions reported previously[15] (dichloromethane as solvent, 40 °C) or in a 1,2-dichloroethane or chlorobenzene/*N*,*N*-dimethylformamide 2.5:1 mixture at 60 °C. It was found that the polar cosolvent DMF was beneficial to the efficiency, although it was significantly slowing down the reaction at temperatures below 60 °C.[35] At 60 °C, the reaction afforded **12** in 71% yield in a 1,2-dichloroethane/*N*,*N*-dimethylformamide 2.5:1 mixture. A similar result was obtained when chlorobenzene was used instead of 1,2-dichloroethane. The reaction was also examined with the more reactive 2-ethoxycarbonylallyl and 2-phenylsulfonylallyl phenyl sulfones. They gave the allylated products **13** and **14** in 81 and 83% yields, respectively. The one-pot homologation−radical allylation sequence was examined next. The chlorinated radical precursor **11** was prepared by treatment of *B*-hexylcatecholborane **10** with $LiCHCl_2$ (from *n*-BuLi and CH_2Cl_2) at −100 °C in THF and subsequent heating at reflux overnight to ensure completion of the rearrangement. The radical allylation reaction was run directly in THF without evaporationof the solvent, affording **12** in 55%. Higher yields were obtained with 2-ethoxycarbonylallyl and 2-phenylsulfonylallyl phenyl sulfones. In that case, best results were obtained by adding DMF. Under these conditions, product **13** was isolated in 81% yield and **14** in 66% yield.

Finally, the scope and limitation of the one-pot reaction was examined with a variety of preformed or generated in situ *B*-alkylcatecholboranes. For this purpose, the ethoxycarbonylallyl phenyl sulfone was used as a trap. All results are reported in Scheme 3. The secondary alkyl radical generated from

Scheme 3. Scope and Limitations of the Hydroboration−Homologation−Allylation Process Involving Aliphatic Alkenes



cyclohexene (**15**) gave the allylated product **19** in 72% yield. Reaction of primary, secondary, and tertiary *B*-alkylcatecholboranes generated from (−)-*β*-pinene (**16**), (+)-*α*-pinene (**17**) and tetramethylethylene (**18**) gave also the desired products **20**−**22** in 32−42% yield. No attempt to further optimize this reaction was made. Even if the yields remain modest, they are remarkable considering that three different reactions of boron derivatives were exploited in this one-pot process (hydroboration, homologation, and radical reaction). The stereochemistry of the process involving (−)-*β*-pinene (**16**) and *α*-pinene (**17**) is in accord with expectations. The hydroboration of (+)-*α*-pinene (**17**) is highly stereoselective, and the anionotropic rearrangement reaction proceeds with retention of configuration. In the case of (−)-*β*-pinene (**16**), the hydroboration affords a 5:1 mixture of diastereoisomers. The formation of the last stereogenic center (*α* to the chlorine atom) takes place during the radical reaction, and it was not stereoselective in the case of (−)-*β*-pinene (product **20**). However, a modest stereocontrol (dr 2:1) was obtained in the case of (+)-*α*-pinene (product **21**).

Reactions Involving Homologation of Styrene Derivatives. Styrene derivatives are very attractive substrates for the homologation reaction since they are particularly suitable for the development of an asymmetric version by taking advantage of highly efficient enantioselective hydroboration reactions.[36] 4-Methoxystyrene (**23**) was selected as a model substrate for the optimization of the reaction conditions. It was hydroborated with 1.1 equiv of catecholborane (HBCat) in

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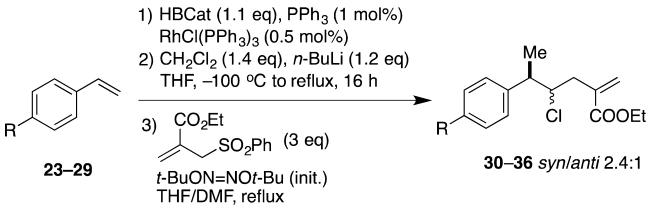
THF at room temperature using $RhCl(PPh_3)_3$ as the catalyst.[25,37] Under these conditions, modest yield and regioselectivity were obtained (Table 1, entry 1). Addition of

Table 1. One-Pot Hydroboration−Homologation−Allylation of Styrene Derivatives



entry	additive	product (R)	ratio[a]	yield[b,c] (%)
1		**30** (OMe)	86:14	49[b]
2	PPh_3	**30** (OMe)	>98:2	68[b] (63)[c]
3	PPh_3	**31** (H)	>98:2	73[b] (67)[c]
4	PPh_3	**32** (F)	>98:2	71[b]
5	PPh_3	**33** (CF_3)	>98:2	65[b]
6	PPh_3	**34** (Me)	>98:2	71[b]
7	PPh_3	**35** (Ph)	>98:2	65[b] (64)[c]
8	PPh_3	**36** (Cl)	>98:2	76[b] (63)[c]

[a]Ratio of Markovnikov/*anti*-Markovnikov products. [b]GC yield of the Markovnikov product. [c]Isolated yield.

triphenylphosphine[25] increased both the regioselectivity of hydroboration (≥98%) as well as the overall yield (Table 1, entry 2). The *B*-(1-arylethyl)catecholboranes were then added to a solution of dichloromethyllithium in THF at −100 °C. Heating under reflux for 16 h afforded the desired *B*-(1-chloro-2-arylpropyl)catecholboranes that were treated at 70 °C with ethyl 2-((phenylsulfonyl)methyl)acrylate and di-*tert*-butyl hyponitrite as a radical initiator and DMF as a cosolvent. The reactions afforded the desired products **30**−**36** in 65−76% yield and a modest diastereoselectivity (*syn*/*anti* 2.4:1) (Table 1, entries 2−8).

The relative *syn* configuration of the major diastereomer of **35** was determined by X-ray crystallographic analysis of the dinitrobenzoate **37**[38] (Figure 2) that was prepared from **35** (major diastereomer) via DIBALH reduction followed by esterification with 3,5-dinitrobenzoyl chloride. The stereochemical outcome of the radical process is rationalized by

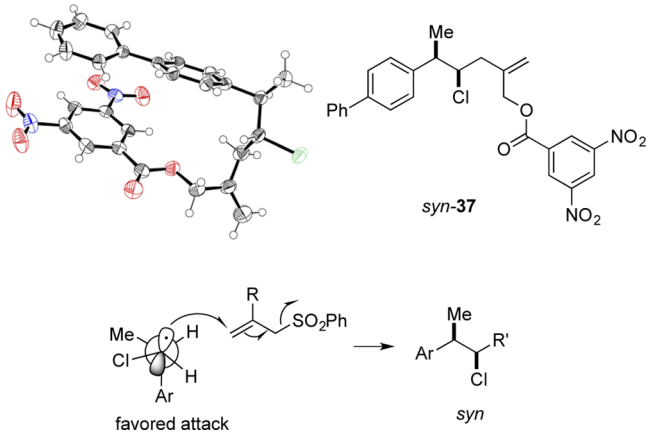
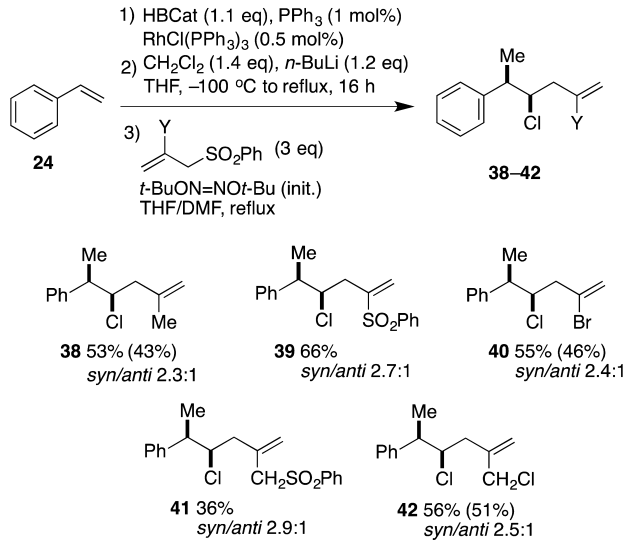


Figure 2. X-ray single-crystal structure of *syn*-**37** derived from the major diastereomer of **35** (50% probability ellipsoids). Felkin−Anh model rationalizing the formation of the *syn*-diastereomer.

considering a Felkin−Anh-type transition state similar to the one proposed for 1-silyloxy-substituted radicals and related radicals[39−42] (Figure 2).

The optimized one-pot procedure starting from styrene was next examined with different allyl sulfones (Scheme 4). 1-

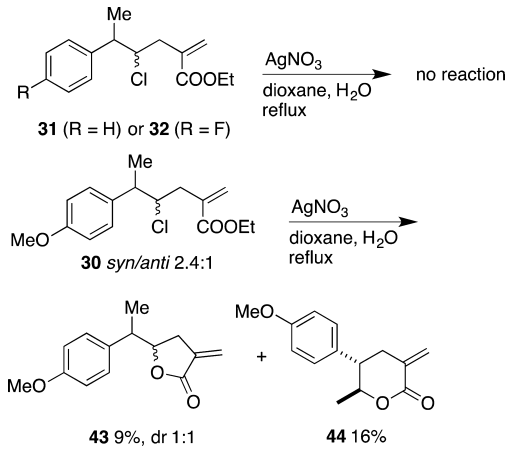
Scheme 4. Homologation−allylation of Styrene with Different Allyl Sulfones (Isolated Yields in Parentheses)



Chloro-2-arylpropyl radicals possess a reactivity very similar to simple alkyl radicals.[15] Sulfones bearing electron-withdrawing groups, such as a sulfonyl group (Y = $PhSO_2$) and an ester group (Y = CO_2Et), afforded the corresponding allylated products in good yields. The lower yield observed for **41** (36%) is due to double addition to the allylic bis-sulfone. The observed diastereoselectivities are similar to the one reported in Table 1 (*syn*/*anti* 2.3−2.9:1).

To illustrate the synthetic potential of the method, the conversion of the γ-chloro esters **30**−**32** to α-methylene-γ-lactones was investigated (Scheme 5).[43] Treatment of esters **31** and **32** with silver nitrate according to Carlson's procedure[44] did not afford any product, and the starting material was recovered unchanged. Ester **30** proved to be more reactive under these conditions, but the reaction afforded a mixture of

Scheme 5. Silver(I)-Mediated Lactonization of γ-Chloroesters 30−32



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the desired γ-lactone **43** (9%, 1:1 mixture of diastereomers) together with the δ-lactone **44** (16%).

The structure of **44** was confirmed by X-ray single-crystal structure analysis (Figure 3).[45] The formation of **44** may be

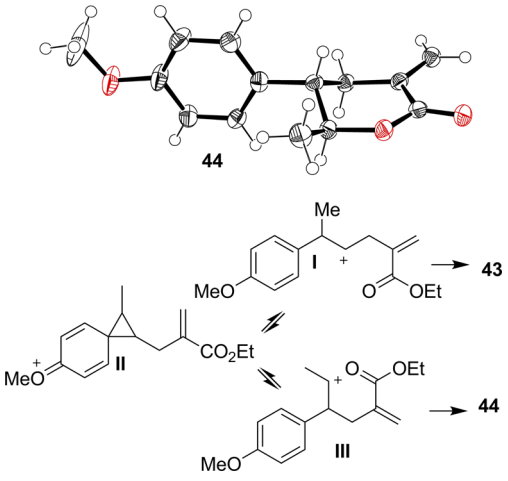
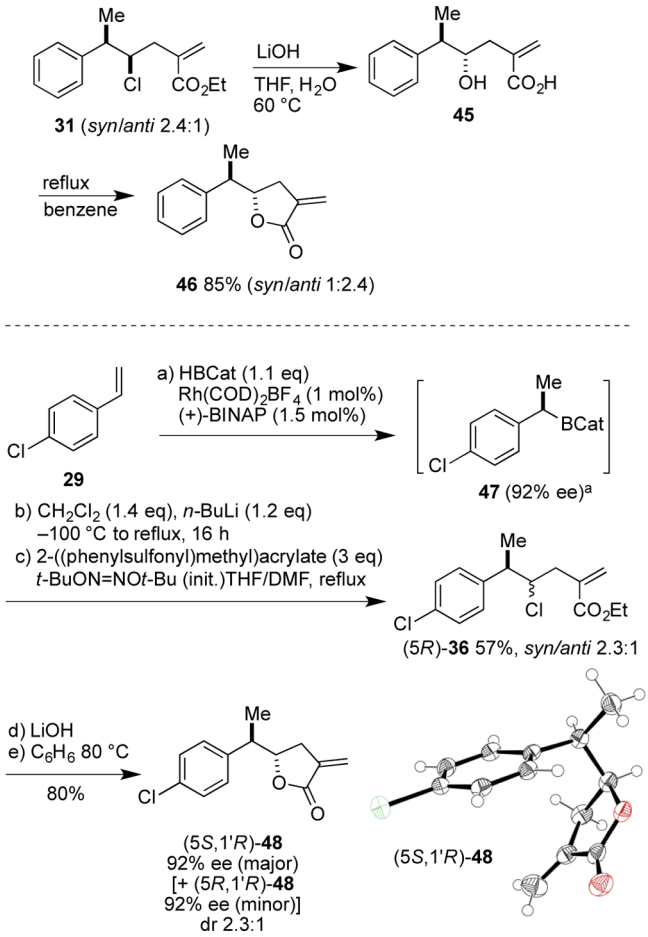


Figure 3. X-ray single-crystal structure of **44** and mechanistic rationalization for its formation (50% probability ellipsoids).

rationalized by the formation of a secondary carbocation intermediate **I** that isomerizes via an ethylenebenzenium intermediate **II** to a new secondary carbocation **III**. Cyclization of **I** is expected to be stereorandom since the chiral center is outside the γ-lactone ring. In contrast, cyclization of **III** should afford the δ-lactone **44** with a good *trans* stereocontrol since the stereogenic center is in the lactone ring.

In order to avoid a carbocationic pathway, the lactonization was performed via a two-step procedure. The γ-chloroester **31** (*syn*/*anti* 2.4:1) was treated with lithium hydroxide to afford the γ-hydroxy acid **45** that lactonized upon heating in benzene and azeotropic removal of water with a Dean−Stark apparatus (Scheme 6, top).[46] Inversion of the stereochemistry at the γ-center is taking place during this transformation (see below), and the lactone **46** was obtained in 85% yield as a *syn*/*anti* 1:2.4 mixture. On the basis of this successful lactonization procedure, the preparation of the optically active α-methylene-γ-lactone **48** involving a one-pot asymmetric hydroboration−homologation−radical allylation procedure was examined (Scheme 6, bottom). The enantioselective hydroboration of *p*-chlorostyrene **29** with catecholborane was performed according to Hayashi's procedure in the presence of a catalytic amount of $Rh(COD)_2BF_4$ and (+)-BINAP.[47] The desired chloroester **36** was obtained in 57% yield and moderate diastereoselectivity (*syn*/*anti* 2.3:1). The level of enantioselectivity and the absolute stereochemistry of the hydroboration step were determined by converting the intermediate boronate **47** into the known (*R*)-1-(4-chlorophenyl)ethanol[48] where the absolute configuration was determined by comparison of the sign of the optical rotation and analysis by GC on a chiral column. The measured ee (92% ee) is in good agreement with the reported value of 91% ee.[47] Treatment of the chloroester **36** with lithium hydroxide in THF/H_2O (5:1) at 60 °C gave the intermediate hydroxy acid that was used without purification for the lactonization step. Lactone **48** was obtained in 80% from **36**. The enantiomeric purity of the two diastereomers was determined to be 92% by GC analysis on a chiral column. The major diastereomer of **48** was recrystallized from a mixture

Scheme 6. Synthesis of α-Methylene-γ-lactones 46 and 48 and X-ray Crystal Structure of the Major Diastereomer (*S*)-5-((*R*)-1-(4-Chlorophenyl)ethyl)-3-methylenedihydrofuran-2(3*H*)-one (48) (50% Probability Ellipsoids)[a]



[a]ee was determined after conversion to the corresponding alcohol via treatment with H_2O_2/NaOH.

of dichloromethane and pentane. Its relative configuration was confirmed by X-ray crystallographic analysis (Scheme 6).[49]

Hydroboration−Homologation−Radical Reactions. To demonstrate further the synthetic potential of this method, the hydroboration−homologation reaction was coupled with a series of radical processes beyond the above-mentioned allylation reactions (Scheme 7). For instance, conjugate addition to methyl vinyl ketone (Brown−Negishi reaction) leading to **49** was examined. Using the one-pot procedure used for the above radical allylation, we observed a low yield (35%, dr 2.7:1) and partial polymerization of the trap. By modifying the reaction condition and using the optimized condition developed for the conjugate addition to vinyl ketone,[50] i.e., by initiating the radical reaction with oxygen in a CH_2Cl_2/H_2O/DMPU solvent mixture, a yield of 50% for the formation of **49** was obtained. Water was added to the reaction mixture in order to hydrolyze the excess of catecholborane as well as the boron enolate formed during the reaction. The presence of DMPU (= 1,3-dimethyl-3,4,5,6-tetrahydro-2-pyrimidinone) as an additive has a positive effect on the yield as already observed in other boron-based radical reactions.[50−52] Recently, our group reported a mild radical procedure for the protodeboronation of organoboranes with *tert*-butylcatechol (TBC).[53] Initial

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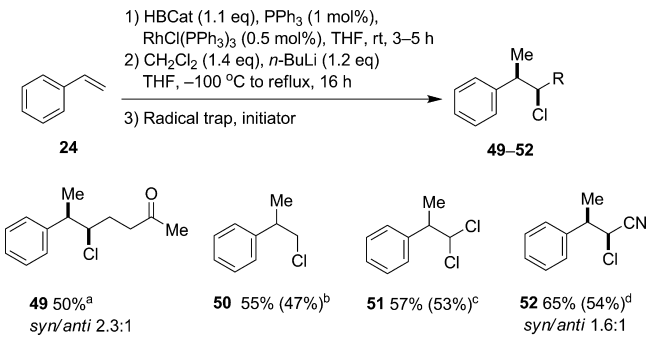
Scheme 7. Hydroboration−Homologation−Radical Reactions with Miscellaneous Radical Traps



[a]Methyl vinyl ketone (5 equiv), CH_2Cl_2, H_2O (3 equiv), DMPU (1 equiv), air, rt. [b]*tert*-Butylcatechol (2 equiv), 1,4-dithiane (20 mol%), $ClCH_2CH_2Cl$, reflux, air. [c]$PhSO_2Cl$ (5 equiv), *t*-BuN=NO-*t*-Bu (init), THF. [d]$TolSO_2CN$ (5 equiv), *t*-BuN=NO-*t*-Bu (init), THF.

attempts to apply this procedure for the protodeboronation of *B*-(1-chloro-2-phenylpropyl)catecholborane faced an unexpected problem. A rapid oxidation of the *tert*-butylcatechol to the corresponding *o*-quinone was observed. Since a possible activation of molecular oxygen by Wilkinson's catalyst was believed to be responsible for this oxidation, 1,4-dithiane was added to the reaction mixture before running the radical protodeboronation to poison the rhodium catalyst. The best yield was obtained when tetrahydrofuran was replaced by 1,2-dichloroethane for the radical process. Under these conditions, the desired product **50** was obtained in a 55% yield (Scheme 7). The whole process corresponds to a regioselective chloromethylation of styrene. The chlorination with benzenesulfonyl chloride was investigated next.[54] In tetrahydrofuran at refluxing temperature, the dichlorinated product **51** was obstained in 57% yield. Finally, the cyanation reaction with *p*-toluenesulfonyl cyanide was examined (Scheme 7).[55] The α-chloronitrile **52** was obtained in 65% when the reaction was run in tetrahydrofuran with 5 equiv of *p*-$TolSO_2CN$.[56,57]

CONCLUSIONS

The generation of 1-chlorinated alkyl radicals from organoboranes was investigated according to two different strategies: (a) the direct hydroboration of chlorinated alkenes was found to be unsuitable due to the partial dehalogenation taking place during the hydroboration process; (b) a Matteson type homologation strategy involving *B*-alkylcatecholboranes with lithiated dichloromethane proved to work efficiently for the generation of 1-chloroalkyl radicals. The generation of 1-chloro-2-arylpropyl radicals from styrene via a hydroboration−homologation−homolytic substitution at boron by heteroatom centered radicals was examined in more detail. Five different types of radical reactions, i.e., allylation, conjugate addition, cyanation, chlorination, and hydrogen atom transfer, have been successfully performed, demonstrating that 1-halogenoalkyl radicals behave very similarly to previously investigated alkyl radicals. These one-pot reaction sequences take advantage of three of the most important reactions reported for organoboranes, namely hydroboration, Matteson homologation, and finally radical reactions. Interestingly, an asymmetric version of this reaction is possible by incorporating an enantioselective hydroboration process as demonstrated by the short synthesis of an optically active α-methylenelactone.[43]

EXPERIMENTAL SECTION

General Information. All reactions were performed under a nitrogen atmosphere in oven-dried (170 °C) flasks and standard precautions against moisture were taken. Unless mentioned, commercial reagents were used as received. Catecholborane was distilled prior to use. Dichloromethane (CH_2Cl_2), benzene, diethyl ether (Et_2O), and tetrahydrofuran (THF) were filtered over a column of dried alumina under a positive pressure of argon. *N*,*N*-Dimethylformamide (DMF) was bought dry (over molecular sieves) from a commercial supplier and used as received. Dichloroethane (DCE) and chlorobenzene (PhCl) were distilled over CaH_2 under nitrogen atmosphere. Diisopropylamine was distilled over CaH_2 under nitrogen atmosphere and stored on KOH pellets. The commercial solution of *n*-butyllithium (hexane, 2.5 M) was titrated prior to use. Silica gel 60 Å (40−63 μm) was used for flash column chromatography (FC). Basic aluminum oxide was used for short filtrations. ^1H and ^{13}C NMR spectra were recorded on spectrometers operating at 300 MHz for ^1H and 75 MHz for ^{13}C at 25 °C. ^{11}B NMR spectra were recorded on a spectrometers operating at 128 or 160 MHz at 25 °C. Chemical shifts are reported in units of δ (ppm) using residual $CHCl_3$ (δ = 7.26 for ^1H NMR spectra and δ = 77.16 for ^{13}C NMR spectra), or C_6H_6 (δ = 7.16 for ^1H NMR spectra and δ = 128.06 for ^{13}C NMR spectra) as the internal standard. Chemical shifts of ^{11}B spectra are given relative to $BF_3{\cdot}OEt_2$. The following abbreviations were used to explain the multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, sept = septet, m = multiplet, br = broad. Infrared spectra were recorded neat or as film and are reported in wave numbers (cm^{-1}). Low-resolution mass spectra (LRMS) were recorded in EI mode at 70 eV or were taken from GC−MS (EI mode at 70 eV; GC column: Macherey−Nagel Optima Delta3, 20 m) analysis. High-resolution mass spectrometry using electrospray ionization (ESI-HRMS) or on a triple-stage quadrupole instrument equipped with a combined Atmospheric Pressure Ion (API) source. High-resolution mass spectrometry using electron ionization (EI-HRMS) were performed on a double-focusing magnetic sector mass spectrometer; mass spectra were measured in electron impact (EI) mode at 70 eV, with a source temperature of 200 °C, an acceleration voltage of 5 kV, and a resolution of 10'000; the instrument was scanned between *m*/*z* 30 and 900 at 2 scan min^{-1}; perfluorokerosene (PFK) served for calibration. GC analyses were measured on a Macherey−Nagel Optima Delta3 column (20 m) using a constant flow (1.4 mL/min) of helium as carrier gas. Melting points (uncorrected) were measured on a Büchi B-545 apparatus.

Hydroboration Approach. *Neat Hydroboration of **1a** and **1b**.* The reported procedure[17] was followed with slight modifications (stoichiometry) in various scales (1−30 mmol). A mixture of catecholborane and α-haloalkene was either heated to reflux temperature in an apparatus with cooling finger or with a conventional reflux condenser, or it was heated to 80 °C in a sealed tube under nitrogen atmosphere. The reaction was monitored by ^1H NMR and ^{11}B NMR. Characteristic peaks for α-halo alkylboronates **2a** and **2b** and for *B*-(2-methylpropyl)catecholborane **3** are in accordance with the literature.[17]

*Rhodium-Catalyzed Hydroboration of **1a** and **1b**.* The reported procedure[18] was followed with slight modifications (stoichiometry, catalyst loading, concentration). To a solution of $RhCl(PPh_3)_3$ in benzene were added the 1-haloalkene and catecholborane. The reaction was stirred at rt and monitored by ^1H NMR and ^{11}B NMR.

*Procedure A: Ethyl 4-Bromo-5-methyl-2-methylenehexanoate (**4a**) and Ethyl 5-Methyl-2-methylenehexanoate (**5**).* To a solution of $RhCl(PPh_3)_3$ (0.9 mg, 1 μmol) in dry benzene (340 μL) were added 1-bromo-2-methylpropene **1a** (200 μL, 2.0 mmol) and catecholborane (320 μL, 3.0 mmol). The mixture was stirred at rt for 36 h. The reaction was then diluted with benzene (1.66 mL), and an aliquot was taken by syringe for NMR analysis in C_6D_6. The reaction mixture was split into two (A and B), and each portion was added to a new reaction flask containing ethyl 2-((phenylsulfonyl)-methyl)acrylate (636 mg, 2.5 mmol). Di-*tert*-butyl hyponitrite (10 mg, 0.06 mmol) was added to both reaction mixtures, and water (200 μL)

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was added to only one of them (B). The reaction mixtures were heated to reflux for 1 h, and then a second portion of di-*tert*-butyl hyponitrite (10 mg, 0.06 mmol) was added, and the reaction was heated for 1 h before cooling to rt. The black reaction mixtures were directly loaded on a silica gel column for purification. FC (pentane/Et_2O 100:0−99:1) afforded a mixture of **4a** and **5** (146 mg for B and 125 mg for A) as a colorless (B) and brownish (A) liquid, respectively. The ratio of **4a**/**5** was determined by NMR, leading to calculated yields of **4a** (121 mg, 49%) and **5** (25 mg, 15%) for B and **4a** (100 mg, 40%) and **5** (25 mg, 15%) for A. Analytically pure samples of **4a** and **5** were obtained by partial separation from the mixture with a second FC (cyclohexane).

4a: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.30 (m, 1H), 5.69 (m, 1H), 4.26−4.18 (m, 3H), 2.91 (ddd, J = 14.6, 4.2, 0.9 Hz, 1H), 2.69 (dd, J = 14.6, 9.8 Hz, 1H), 1.90 (dsept, J = 6.6, 3.3 Hz, 1H), 1.31 (t, J = 7.1 Hz, 3H), 1.05 (d, J = 6.7 Hz, 3H), 1.01 (d, J = 6.7 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.8, 137.6, 128.1, 63.8, 61.0, 39.8, 34.5, 21.1, 18.0, 14.3; IR 2965, 1710, 1180, 1145 cm^{-1}; EI-MS (GC−MS) m/z (relative intensity) 235 (0.06) [M$^+$ − methyl], 233 (0.06) [M$^+$ − methyl], 205 (1.2), 203 (1.2), 195 (3.8), 193 (3.8), 169 (34), 123 (100), 95 (61), 81 (13), 67 (22), 55 (25); ESI-HRMS calcd for $C_{10}H_{18}O_2Br$ [M + H]$^+$ 249.0485, found 249.0486.

5: ^{1}H NMR (300 MHz, $CDCl_3$) δ = 6.08 (m, 1H), 5.47 (m, 1H), 4.23−4.14 (m, 2H), 2.29−2.24 (m, 2H), 1.55 (sept, J = 6.6 Hz, 1H), 1.36−1.24 (m, 2H), 1.27 (t, J = 7.1 Hz, 3H), 0.88 (d, J = 6.6 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 167.7, 141.5, 124.0, 60.6, 37.8, 29.9, 27.9, 22.6 (2C); EI-LRMS (GC−MS) m/z 170 (1) [M$^+$], 155 (3), 127 (13), 115 (100), 109 (25), 99 (22), 87 (41), 69 (38), 56 (61); ESI-HRMS calcd for $C_{10}H_{19}O_2$ [M + H]$^+$ 171.1380, found 171.1378.

*Procedure B: Ethyl 4-Chloro-5-methyl-2-methylenehexanoate (**4b**).* At 0 °C, a commercial solution of BH_3·THF (1 M in THF, 5 mL, 5 mmol) was added to a solution of **1b** (500 μL, 5.0 mmol) in THF (12 mL), and the mixture was stirred at 0 °C for 30 min. Then, a solution of catechol (550 mg, 5 mmol) in THF (5 mL) was added over a period of 5 min via cannula. A small flow of N_2 was maintained to remove H_2. It was stirred at 0 °C for 2 h until H_2 evolution stopped completely. This solution containing **2b** was divided in two equal parts and immediately used for the radical reaction. Half of the solution of **2b** was added to ethyl 2-((phenylsulfonyl)methyl)acrylate (1.59 g, 6.25 mmol). Di-*tert*-butyl hyponitrite (22 mg, 0.125 mmol) was added, and the mixture was heated under reflux. After 1 h, a second portion of di-*tert*-butyl hyponitrite (22 mg, 0.125 mmol) was added, the reaction mixture was heated for 1 h and cooled to rt, and the mixture was extracted with Et_2O and washed with water and brine. The organic layer was dried over Na_2SO_4 and filtered, and solvents were removed under reduced pressure. FC (pentane/Et_2O 98:2) afforded **4b** (250 mg, 49%) as a colorless liquid: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.29 (d, J = 1.2 Hz, 1H), 5.69 (m, 1H), 4.21 (dq, J = 7.1, 0.5 Hz, 2H), 4.07 (dt, J = 9.9, 3.7 Hz, 1H), 2.86 (ddd, J = 14.4, 3.7, 1.0 Hz, 1H), 2.52 (ddd, J = 14.4, 9.9, 0.7 Hz, 1H), 2.00 (dsept, J = 6.7, 3.7 Hz, 1H), 1.31 (t, J = 7.1 Hz, 3H), 1.05 (d, J = 6.7 Hz, 3H), 1.01 (d, J = 6.7 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.8, 137.1, 128.1, 67.9, 60.9, 38.9, 34.3, 20.0, 17.0, 14.3; IR 2967, 1712, 1200, 1149 cm^{-1}; EI-MS (GC−MS) m/z 205 (0.05) [M$^+$], 189 (0.6), 169 (84), 149 (31), 123 (100), 95 (54), 86 (30), 56 (63), 55 (53); ESI-HRMS calcd for $C_{10}H_{18}O_2Cl$ [M + H]$^+$ 205.0995, found 205.0990.

Homologation Approach. *B-n-Octylcatecholborane (**6**).* The mixture of 1-octene (6.3 mL, 40 mmol) and catecholborane (2.1 mL, 20 mmol) was stirred in a sealed tube at 100 °C for 16 h. The mixture was then added via cannula to a two-neck flask fitted with two inlet tabs. The excess of 1-octene was removed under high vacuum (0−35 °C over 5 h). The disappearance of the olefinic protons was monitored by ^{1}H NMR. The boronate **6** (colorless liquid) was stored under N_2 in the refrigerator and used without further purification: ^{1}H NMR (300 MHz, C_6D_6): δ 7.07−7.01 (m, 2H), 6.83−6.77 (m, 2H), 1.62−1.52 (m, 2H), 1.33−1.20 (m, 10H), 1.18−1.12 (m, 2H), 0.91−0.87 (m, 3H); ^{13}C NMR (75 MHz, C_6D_6) δ 148.9, 122.7, 112.5, 32.6, 32.3, 29.8, 29.6, 24.1, 23.1, 14.4, 11.0 (br, *C*-B); ^{11}B NMR (160 MHz, C_6Cl_6) δ 35.9.

Testing of Procedures for the Homologation of 6 Monitored by ^{1}H and ^{11}B NMR. All samples for NMR analysis were prepared as follows: an aliquot (50−100 μL) of the reaction mixture was taken by syringe and diluted in degassed C_6D_6 in a dried NMR tube with septum cap under N_2. Small variations in the chemical shift of the homologated product **8** were observed, which were attributed to complexation of the boron atom to the amine and/or $ZnCl_2$.

(a) A solution of dichloromethane (150 μL, 2.4 mmol) in THF (5 mL) was cooled to −100 °C. *n*-BuLi (2.1 M in hexane, 1 mL, 2.1 mmol) was added to this cold solution by syringe with precooling (the solution was allowed to run down the cold wall of the reaction flask). It was stirred for 5 min at −100 °C (EtOH cooling bath), and then a solution of octylcatecholborane **6** (464 mg, 2.0 mmol) in Et_2O (1.2 mL) was added. Precipitation of borate complex **7** occurred instantaneously. The bath was then warmed from −100 °C to about −60 °C over 15 min by addition of EtOH to the cooling bath until stirring was possible again. Then the bath was removed, and the white slurry was allowed to warm to rt while turning into a dark yellow solution. After being stirred at rt for 2 h, a first NMR spectrum was measured. The reaction mixture was then heated at 65 °C for 2.5 h, and another aliquot for NMR analysis was taken. It was further heated at 65 °C for 6 h and then analyzed again by NMR, revealing clean formation of **8** (29.7 ppm).

(b) To a solution of diisopropylamine (650 μL, 4.62 mmol) in THF (2 mL) at −78 °C was slowly added *n*-BuLi (2.3 M in hexane, 2.0 mL, 4.6 mmol). It was warmed to 0 °C and stirred for 10 min. After being cooled to −65 °C, the solution was added dropwise via cannula to a solution of dichloromethane (300 μL, 4.62 mmol) and octylcatecholborane **6** (894 mg, 3.85 mmol) in THF (4.6 mL) at −5 °C. The orange solution was then stirred at −5 °C for 30 min, and an aliquot was analyzed by NMR. The reaction mixture was heated at 65 °C for 1.5 h (NMR) and additionally for 3 h. At that time, NMR analysis showed almost clean formation of **8** (29.2 ppm).

(c) Same procedure as for procedure a above until warming to −60 °C, starting from **6** (464 mg, 2 mmol). At−60 °C a freshly prepared solution of $ZnCl_2$ (2 M in Et_2O, 700 μL, 1.4 mmol) was added and the mixture was allowed to warm overnight while stirring and a first aliquot was analyzed by NMR. The reaction mixture was then heated at 65 °C for 1 h (NMR) and additionally for 1.5 h. At that time, NMR analysis showed clean formation of **8** (31.8 ppm).

(d) Same procedure as procedure b above until stirring at −5 °C for 30 min, starting from **6** (894 mg, 3.85 mmol). The orange solution was then added via cannula to a suspension of dried and powdered $ZnCl_2$ in THF (1 mL) at −5 °C. The initially white mixture turned into a brown solution, which was stirred at rt overnight. An aliquot was analyzed by NMR and showed clean formation of **8** (32.2 ppm).

*B-n-Hexylcatecholborane (**10**).* Prepared by the same procedure as **6**, starting from 1-hexene **9** (7.5 mL, 60 mmol). The excess of 1-hexene was removed under vacuum. The resulting crude boronate **10** (7.04 g, 86%) was stored as a yellowish liquid under N_2 in the fridge: ^{1}H NMR (300 MHz, C_6D_6) δ 7.07−7.01 (m, 2H), 6.83−6.77 (m, 2H), 1.60−1.50 (m, 2H), 1.33−1.19 (m, 6H), 1.16−1.11 (m, 2H), 0.88−0.84 (m, 3H); ^{13}C NMR (75 MHz, C_6D_6) δ 148.9, 122.7, 112.5, 32.3, 32.0, 24.1, 23.0, 14.3, 11.0 (br, *C*-B).

*B-(1-Chloro-1-hexyl)catecholborane (**11**).* Prepared according to literature procedure[27] with minor modifications. In a two-neck flask with a distillation top part and an inlet tab, a solution of dichloromethane (1.22 mL, 19.1 mmol) in THF (35 mL) was cooled to −100 °C (EtOH cooling bath). *n*-BuLi (2.09 M in hexane, 8 mL, 16.7 mmol) was added to this cold solution by syringe with precooling (the solution was allowed to run down the cold wall of the reaction flask). The solution was stirred for 5 min at −100 °C (EtOH cooling bath), and then a solution of crude hexylcatecholborane **10** (3.25 g, 15.9 mmol) in THF (11 mL) was added. Precipitation of the borate complex occurred instantaneously. The reaction mixture was warmed from −100 °C to about −60 °C over 10 min to allow stirring. The cooling bath was removed, and the white slurry was allowed to warm to rt while turning into a brown solution. THF was evaporated by flushing the flask with a light flow of N_2. The brown solid residue was placed in a distillation apparatus under vacuum (10^{-2} mbar) and heated in an oil bath at 130 °C. Melting of the residue was observed. Distillation (bp 90 °C, 10^{-2} mbar) afforded the pure boronate **11**

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(2.13 g, 53%; 46% over two steps) that was stored in a glovebox: ^{1}H NMR (300 MHz, C_6D_6) δ 7.02−6.96 (m, 2H), 6.81−6.74 (m, 2H), 3.62 (t, J = 7.4 Hz, 1H), 1.93−1.79 (m, 2H), 1.49−1.26 (m, 2H), 1.23−1.07 (m, 6H), 0.86−0.82 (m, 3H); ^{13}C NMR (75 MHz, C_6D_6) δ 148.4, 123.4, 113.0, 42.2 (br), 34.4, 31.9, 29.1, 27.5, 22.9, 14.3; ^{11}B NMR (160 MHz, C_6Cl_6) δ 32.7.

*Procedure C and D. Radical Allylation of 1-Chloroboronate **11** with Various Allyl Sulfones.* A solution of boronate **11** (202 mg, 0.8 mmol) in solvent (800 μL; C: CH_2Cl_2; D: PhCl/DMF 2.5:1) was added via cannula to a solution of the sulfone (2.4 mmol) in solvent (800 μL; C: CH_2Cl_2; D: PhCl/DMF 2.5:1). Then di-*tert*-butyl hyponitrite (4.0 mg, 0.024 mmol) was added, and the reaction was heated for 2−4 h at 40 °C (C) or 60 °C (D). Every 1 h, a further portion of di-*tert*-butyl hyponitrite (4.0 mg, 0.024 mmol) was added. After being cooled to rt, the crude product was purified by FC.

*4-Chloro-2-methyldec-1-ene (**12**).* (a) According to procedure C, starting from **11** (202 mg, 0.80 mmol) in CH_2Cl_2 (800 μL) and (2-methylallylsulfonyl)benzene (471 mg, 2.4 mmol). The reaction was stopped after 2 h. FC (cyclohexane) afforded **12** (86 mg, 57%) as a colorless liquid containing traces of unknown impurities (53% estimated yield). Second FC (cyclohexane) gave analytically pure material for characterization and GC calibration: ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.85 (m, 1H), 4.79 (m, 1H), 4.03 (dtd, J = 8.5, 7.1, 4.1 Hz, 1H), 2.45 (d, J = 7.1 Hz, 2H), 1.80−1.26 (m, 10H), 1.75 (s, 3H), 0.91−0.87 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 141.9, 113.6, 61.3, 47.2, 38.3, 31.9, 29.0, 26.5, 22.7, 22.3, 14.2; IR ν (cm^{-1}) 2927, 2858, 1455, 893; EI-LRMS (GC−MS) m/z 188 (0.2) [M$^+$], 153 (6.4), 109 (6.6), 97 (17), 81 (24), 69 (53), 56 (100); EI-HRMS calcd for $C_{11}H_{21}Cl$ [M$^+$] 188.1332, found 188.1333.

*Ethyl 4-Chloro-2-methylenedecanoate (**13**).* (a) According to procedure C starting from **11** (202 mg, 0.80 mmol) in CH_2Cl_2 (800 μL) and 2-ethoxycarbonylallyl phenyl sulfone (610 mg, 2.4 mmol). The reaction was stopped after 2 h. FC (pentane to pentane/Et_2O 98:2) afforded **13** (160 mg, 81%) as a colorless liquid: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.29 (d, J = 1.3 Hz, 1H), 5.68 (m, 1H), 4.21 (dq, J = 7.1, 0.5 Hz, 2H), 4.14−4.05 (m, 1H, C*H*-Cl), 2.82 (ddd, J = 14.3, 4.4, 1.0 Hz, 1H), 2.56 (ddd, J = 14.3, 9.0, 0.6 Hz, 1H), 1.82−1.64 (m, 2H), 1.60−1.25 (m, 8H), 1.30 (t, J = 7.1 Hz, 3H), 0.90−0.85 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.8, 137.0, 128.3, 61.7, 61.0, 41.6, 38.5, 31.8, 28.9, 26.5, 22.7, 14.3, 14.2; IR 2928, 1713, 1195, 1146 cm^{-1}; EI-MS (GC−MS) m/z 247 (0.15) [M$^+$], 211 (53), 165 (23), 149 (41), 137 (100), 121 (31), 111 (36), 95 (67), 81 (87), 69 (69), 55 (99); ESI-HRMS calcd for $C_{13}H_{24}O_2Cl$ 247.1459 [M + H]$^+$, found 247.1463.

*[(3-Chloro-1-methylenenonyl)sulfonyl]benzene (**14**).* According to procedure D starting from **11** (177 mg, 0.7 mmol) in chlorobenzene (500 μL) and 2-phenylsulfonylallyl phenyl sulfone (677 mg, 2.1 mmol) in DMF (200 μL). The reaction was stopped after 4 h. FC (pentane/Et_2O = 85:15) afforded **14** (184 mg, 83%) contaminated by $PhSO_2SPh$ (14 mg) as a colorless liquid: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.89−7.86 (m, 2H), 7.67−7.61 (m, 1H), 7.58−7.52 (m, 2H), 6.48 (s, 1H), 5.95 (m, 1H), 4.01−3.93 (m, 1H), 2.72 (ddd, J = 15.8, 4.5, 1.0 Hz, 1H), 2.55 (dd, J = 15.8, 9.2 Hz, 1H), 1.74−1.55 (m, 2H), 1.50−1.18 (m, 8H), 0.90−0.85 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.6, 138.8, 133.8, 129.4, 128.4, 127.2, 60.1, 39.1, 38.3, 31.7, 28.7, 26.3, 22.6, 14.1; IR 2927, 2858, 1446, 1305, 1137, 1082, 746, 687 cm^{-1}; EI-MS (GC−MS) m/z 279 (10) [M$^+$ − Cl], 217 (11), 182 (11), 143 (100), 137 (64), 125 (96), 95 (46), 81 (52), 77 (59), 67 (40), 55 (64); ESI-HRMS calcd for $C_{16}H_{23}O_2ClNaS$ [M + Na]$^+$ 337.0999, found 337.1006.

Procedure E. One-Pot Hydroboration−Homologation−Radical Allylation Reaction. **Preparation of the *B*-Alkylcatecholborane.** A mixture of the alkene (2.0 mmol) and catecholborane (1.0 mmol) was stirred at 100 °C for 20 h. The mixture was cooled to rt and diluted with THF (0.5 mL). This solution was used as obtained for the homologation procedure. **Homologation Reaction.** A solution of dichloromethane (80 μL, 1.21 mmol) in THF (2 mL) was cooled to −100 °C (EtOH cooling bath). *n*-BuLi (2.36 M in hexane, 450 μL, 1.062 mmol) was slowly added by syringe with precooling (the solution was allowed to run down the cold wall of the reaction flask). The solution was stirred for 5 min at −100 °C, and then the solution of the *B*-alkylcatecholborane (1.0 mmol) in THF (0.5 mL) was added. Precipitation of borate complex occurred immediately. The cooling bath was removed, and the white slurry was allowed to warm to rt while turning into a yellow or brown solution. The solution was heated to reflux for 16 h (precipitation of LiCl) and cooled to rt. **Radical Allylation.** A solution of the allylsulfone (3.0 mmol) in THF or DMF (0.8 mL) was then added followed by di-*tert*-butyl hyponitrite (5.2 mg, 0.030 mmol). The reaction mixture was heated at 65 °C for 4 h. Every 1 h, di-*tert*-butyl hyponitrite (5.2 mg, 0.030 mmol) was added. The reaction mixture was cooled to rt, filtered over a pad of aluminum oxide, and washed with Et_2O. Solvents were removed under reduced pressure and the crude product was purified by FC.

*Ethyl 4-Chloro-4-cyclohexyl-2-methylenebutanoate (**19**).* According to procedure E starting from *B*-cyclohexylcatecholborane (200 mg, 0.99 mmol), using ethyl 2-((phenylsulfonyl)methyl)acrylate (770 mg, 3.03 mmol) in DMF (0.8 mL). FC (cyclohexane/EtOAc 98:2) afforded **19** (174 mg, 72%) as a colorless liquid: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.27 (d, J = 1.3 Hz, 1H), 5.66 (m, 1H), 4.19 (dq, J = 7.1, 0.5 Hz, 2H), 4.00 (dt, J = 10.1, 3.9 Hz, 1H), 2.86 (ddd, J = 14.4, 3.5, 1.0 Hz, 1H), 2.49 (dd, J = 14.4, 10.1 Hz, 1H), 1.84−1.57 (m, 6H), 1.32−1.09 (m, 5H), 1.29 (t, J = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.8, 137.2, 128.0, 67.1, 60.9 (OCH_2CH_3), 44.3, 38.6, 30.2, 28.0, 26.4, 26.3, 26.1, 14.3; IR 2926, 2854, 1710, 1197, 1135 cm^{-1}; EI-MS (GC−MS) m/z 244 (0.15) [M$^+$], 209 (60) [M$^+$-Cl], 163 (34), 135 (100), 95 (46), 81 (49), 67 (60), 55 (77); ESI-HRMS calcd for $C_{13}H_{21}O_2ClNa$ [M + Na]$^+$ 267.1122, found 267.1127.

*Ethyl 4-Chloro-5-((1S,5S)-6,6-dimethylbicyclo[3.1.1]hept-2-yl)-2-methylenepentanoate (**20**).* According to procedure E starting from (−)-β-pinene **16** (320 μL, 2.06 mmol), using ethyl 2-((phenylsulfonyl)methyl)acrylate (770 mg, 3.03 mmol) in DMF (0.8 mL). FC (cyclohexane/toluene) afforded **20** (129 mg, 42% dr 1:1.1:4.5:5.5) as a colorless liquid. Diastereoselectivity was determined by GC analysis of the crude reaction mixture. Retention time = 38.5 min (minor), 38.8 min (minor), 38.9 min (major), 39.0 min (major) (starting temperature 40 °C, hold: 0 min, rate: 4 °C/min): ^{1}H NMR (300 MHz, $CDCl_3$) all four diastereoisomers (overlapping multiplets) δ 6.29 (m, 1H), 5.67 (m, 1H), 4.28−4.09 (m, 3H), 2.88−2.76 (m, 1H), 2.60−2.48 (m, 1H), 2.41−2.24 (m, 2H), 2.06−1.62 (m, 7H), 1.52−1.35 (m, 1H), 1.33−1.28 (m, 3H), 1.19−1.17 (m, 3H), 0.97−0.83 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) two major diastereoisomers δ 166.8, 137.0, 128.3, 128.2, 60.9, 60.3, 60.0, 47.2, 46.6, 46.2, 45.1, 42.3, 41.7, 41.5, 41.5, 38.8, 38.2, 38.0, 33.8, 33.4, 28.3, 28.2, 26.5, 26.4, 23.42, 23.36, 22.7, 21.5, 14.4, 14.3; two minor diastereoisomers (visible peaks) δ 166.7, 136.9, 128.3, 60.9, 59.8, 59.4, 46.5, 45.6, 45.1, 44.7, 42.4, 41.7, 41.12, 41.05, 39.8, 39.5, 32.1, 31.9, 26.95, 26.89, 24.54, 24.47, 23.8, 22.4, 21.4, 20.25, 20.20; IR 2908, 1714, 1195, 1156 ν cm^{-1}; EI-MS (GC−MS) m/z 263 (3) [M$^+$ − Cl], 219 (14), 189 (13), 173 (25), 149 (40), 145 (56), 133 (49), 123 (42), 107 (44), 93 (52), 82 (85), 67 (99), 55 (89), 41 (100); ESI-HRMS calcd for $C_{17}H_{27}O_2Cl$ [M$^+$] 298.1700, found 298.1698.

*Ethyl 4-Chloro-4-((1R,2R,5S)-2,6,6-trimethylbicyclo[3.1.1]hept-3-yl)-2-methylenebutanoate (**21**).* According to procedure E starting from (+)-α-pinene **17** (330 μL, 2.06 mmol), using ethyl 2-((phenylsulfonyl)methyl)acrylate (770 mg, 3.03 mmol) in DMF (0.8 mL). FC (cyclohexane/toluene) afforded **21** (97 mg, 32%, dr 1:2.2) as a colorless liquid together with nonhomologated product (25 mg) and 4,4-dichloro-2-methylenebutanoate (7 mg). The diastereoselectivity was determined by GC analysis of the crude reaction mixture. Retention time = 38.1 min (major), 39.0 min (minor) (starting temperature 40 °C, 4 °C/min): ^{1}H NMR (300 MHz, $CDCl_3$) major diastereoisomer δ 6.29 (d, J = 1.3 Hz, 1H), 5.69 (m, 1H), 4.33−4.15 (m, 3H), 2.77 (ddd, J = 14.3, 5.2, 1.0 Hz, 1H), 2.66 (ddd, J = 14.3, 9.0, 0.8 Hz, 1H), 2.27−1.73 (m, 7H), 1.31 (t, J = 7.1 Hz, 3H), 1.21 (s, 3H), 1.15−1.08 (m, 1H), 1.03−0.99 (m, 6H); minor diastereoisomer (visible, characteristic peaks) 6.31 (m, 1H), 5.72 (m, 1H), 4.10 (ddd, J = 10.9, 5.1, 2.0 Hz, 1H), 3.05−3.00 (m, 1H), 2.47 (dd, J = 14.4, 10.9 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): major diastereoisomer δ 166.8, 137.3, 128.1, 66.9, 61.0, 47.6, 42.6, 41.3, 40.2, 39.6, 39.2, 32.3, 28.2, 27.8, 22.9, 21.4, 14.4; minor diastereoisomer δ 66.9, 137.1, 128.4, 68.5,

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61.0, 48.4, 43.5, 41.4, 39.1, 38.9, 38.7, 32.3, 31.4, 27.9, 23.2, 23.0, 14.3; IR 2902, 1713, 1196, 1140 cm^{-1}; EI-MS (GC−MS) *m/z* 298 (0.15) [M^+], 283 (0.2) [M^+ − (Me)], 263 (0.2) [M− -Cl], 255 (0.4), 219 (19), 173 (54), 145 (60), 133 (56), 105 (63), 93 (57), 83 (81), 69 (61), 55 (100), 41 (76); ESI-HRMS calcd for $C_{17}H_{27}O_2ClNa$ [M + Na]$^+$ 321.1592, found 321.1599.

*Ethyl 4-Chloro-5,5,6-trimethyl-2-methyleneheptanoate (**22**).* The mixture of 2,3-dimethyl-2-butene (175 μL, 1.46 mmol) and a borane−dimethyl sulfide complex (94%, 150 μL, 1.46 mmol) was stirred at 0 °C for 2.5 h. It was then diluted with CH_2Cl_2 (1.1 mL) and slowly added via cannula to a solution of catechol (161 mg, 1.46 mmol) in CH_2Cl_2 (2 mL) at 0 °C. The resulting solution was stirred at rt for 2 h. CH_2Cl_2 and dimethyl sulfide were evaporated by flushing N_2 at rt through the flask and then under vacuum at 0 °C to rt for about 2.5 h. The mixture was then diluted with THF (0.5 mL), and this solution was added to the $LiCHCl_2$ solution according to procedure E. FC (cyclohexane/EtOAc 98:2) afforded **22** (141 mg, 39%) as a colorless liquid together with the nonhomologated product (21 mg) and ethyl 4,4-dichloro-2-methylenebutanoate (13 mg): ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.28 (m, 1H), 5.67 (m, 1H), 4.21−4.12 (m, 3H), 2.99−2.95 (m, 1H), 2.32 (dd, *J* = 14.3, 11.2 Hz, 1H), 1.90 (sept, *J* = 6.9 Hz, 1H), 1.28 (t, *J* = 7.1 Hz, 3H), 0.92 (s, 3H), 0.90 (s, 3H), 0.88 (d, *J* = 6.9 Hz, 3H), 0.86 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.9, 137.5, 128.4, 70.2, 60.8, 40.9, 36.2, 33.9, 19.8, 19.0, 17.6, 17.2, 14.3; IR 2972, 1712, 1197, 1146 cm^{-1}; EI-MS (GC−MS) *m/z* 247 (0.03) [M^+], 211 (6) [M^+ − Cl], 203 (7), 167 (19), 139 (17), 126 (46), 98 (72), 85 (86), 55 (41), 43 (100); ESI-HRMS calcd for $C_{13}H_{23}O_2ClNa$ [M + Na]$^+$ 269.1279, found 269.1278.

Homologation of Styrene Derivative. *Procedure F. Hydroboration−Homologation−radical Reaction Involving Styrene Derivatives.* Styrene derivative (2.0 mmol) was added to a suspension of PPh_3 (6 mg, 1 mol %) and $RhCl(PPh_3)_3$ (10 mg, 0.5 mol %) in THF (1.6 mL) at rt under a N_2 atmosphere. The reaction mixture was stirred at rt for 30 min. Then catecholborane (0.24 mL, 2.2 mmol) was added dropwise, and the resulting solution was stirred at room temperature for 3−5 h. A $LiCHCl_2$ solution was prepared by adding *n*-BuLi (2.50 M in hexane, 0.96 mL 2.4 mmol) to a solution of CH_2Cl_2 (0.18 mL, 2.8 mmol) in THF (4 mL) at −100 °C (BuLi was allowed it to run down the cold glass wall of the reaction flask). After 20−30 min, the solution of the hydroborated styrene derivative was added in one portion. The reaction mixture was allowed to warm to rt slowly. After the mixture was heated at reflux overnight for 16 h, precipitation of LiCl was observed. The reaction mixture was cooled to rt, a solution of the radical trap (6 mmol) in DMF (1.6 mL) and hexadecane as internal standard were added followed by di-*tert*-butyl hyponitrite (10 mg, 3 mol %), and the mixture was heated to reflux. Every 1 h, a further portion of di-*tert*-butyl hyponitrite (10 mg, 3 mol %) was added. After being stirred at refluxing temperature for 3 h (the reaction was followed by GC), the mixture was cooled and filtered over Alox and purified by FC. GC yields were determined using the response factor method with hexadecane as internal standard.

*Ethyl 4-Chloro-5-(4-methoxyphenyl)-2-methylenehexanoate (**30**).* The reaction was performed according to procedure F starting from 1-methoxy-4-vinylbenzene **23** (323 mg, 2.41 mmol) and ethyl 2-(phenylsulfonylmethyl)acrylate[58] (1.82 g, 7.16 mmol) as the radical trap. Purification by FC (Et_2O/pentane 1:100 to 1:30) afforded **30** (449 mg, 63%) as a colorless oil (68% GC yield, dr 2.4:1): ^{1}H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.14−7.19 (m, 2H), 6.85−6.89 (m, 2H), 6.27 (d, *J* = 0.9 Hz, 1H), 5.64 (d, *J* = 0.6 Hz, 1H), 4.27 (ddd, *J* = 10.4, 6.9, 3.3 Hz, 1H), 4.13−4.23 (m, 2H), 3.79 (s, 3H), 2.91−3.05 (m, 1H), 2.78 (dd, *J* = 14.4, 2.5 Hz, 1H), 2.37 (dd, *J* = 14.6, 10.7 Hz, 1H), 1.44 (d, *J* = 7.0 Hz, 3H), 1.29 (t, *J* = 7.1 Hz, 3H); minor diastereomer δ 7.20−7.24 (m, 2H), 6.85−6.89 (m, 2H), 6.27 (d, *J* = 0.9 Hz, 1H), 5.61 (d, *J* = 0.6 Hz, 1H), 4.34 (ddd, *J* = 10.6, 4.8, 2.9 Hz, 1H), 4.13−4.23 (m, 2H), 3.80 (s, 3H), 3.11−3.20 (m, 1H), 2.86 (dd, *J* = 14.5, 2.0 Hz, 1H), 2.28 (dd, *J* = 14.5, 10.6 Hz, 1H), 1.44 (d, *J* = 7.0 Hz, 3H), 1.25 (t, *J* = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 166.7, 158.6, 137.1, 135.6, 128.8, 128.3, 114.0, 67.1, 60.9, 55.3, 46.1, 40.0, 18.2, 14.3; minor diastereomer δ 166.8, 158.6, 136.8, 134.0, 129.6, 128.4, 113.7, 66.5, 60.9, 55.3, 45.3, 38.8, 18.2, 14.3; IR (neat) 2979, 2934, 2907, 2837, 1710 (s), 1631, 1611, 1512, 1463, 1303, 1247, 1179, 1145, 1032, 950, 830, 809 cm^{-1}; EI-LRMS (GC−MS) *m/z* 260 (7), 231 (4), 187 (14), 135 (100), 105 (8), 91 (7), 77 (6); ESI-HRMS calcd for $C_{16}H_{22}O_3Cl$ [M + H]$^+$ 297.1252, found 297.1250.

*Ethyl 4-Chloro-2-methylene-5-phenylhexanoate (**31**).* The reaction was performed according to the procedure F starting from styrene **24** (214 mg, 2.05 mmol) and ethyl 2-(phenylsulfonylmethyl)acrylate[13] (1.52 g, 5.98 mmol) as the radical trap. Purification by FC (Et_2O/pentane 1:100) afforded **31** (365 mg, 67%) as a colorless oil (GC yield = 73%, dr 2.4:1): ^{1}H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.15−7.43 (m, 5H), 6.27 (s, 1H), 5.65 (s, 1H), 4.27−4.42 (m, 1H), 4.19 (qd, *J* = 7.1, 3.1 Hz, 2H), 2.99−3.08 (m, 1H), 2.78 (dd, *J* = 14.4, 2.7 Hz, 1H), 2.39 (dd, *J* = 14.4, 10.5 Hz, 1H), 1.47 (d, *J* = 7.0 Hz, 3H), 1.29 (t, *J* = 7.5 Hz, 3H); minor diastereomer δ 7.15−7.43 (m, 5H), 6.27 (s, 1H), 5.62 (s, 1H), 4.27−4.42 (m, 1H), 4.19 (qd, *J* = 7.1, 3.1 Hz, 2H), 3.13−3.27 (m, 1H), 2.89 (d, *J* = 13.7 Hz, 1H), 2.30 (dd, *J* = 14.5, 10.8 Hz, 1H), 1.47 (d, *J* = 7.0 Hz, 3H), 1.27 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 166.7, 143.6, 137.0, 128.6, 128.4, 128.3, 127.9, 127.0, 66.9, 60.9, 47.0, 40.1, 18.2, 14.3; minor diastereomer δ 166.8, 142.1, 136.8, 128.6, 128.5, 128.3, 127.9, 127.1, 66.2, 60.9, 46.2, 38.7, 18.0, 14.3; IR (neat) 3031, 2978, 2934, 1710, 1633, 1495, 1452, 1190, 1144, 1025, 949, 765, 699 cm^{-1}; EI-LRMS (GC−MS) *m/z* 230 (6), 215 (6), 184 (6), 157 (21), 156 (10), 141 (5), 115 (8), 105 (100), 79 (9), 77 (11); ESI-HRMS calcd for $C_{15}H_{20}O_2Cl$ [M + H]$^+$ 267.1146, found 267.1141.

*Ethyl 4-Chloro-5-(4-fluorophenyl)-2-methylenehexanoate (**32**).* The reaction was performed according to the procedure F starting from 1-fluoro-4-vinylbenzene **25** (259 mg, 2.12 mmol) and ethyl 2-(phenylsulfonylmethyl)acrylate[13] (1.55 g, 6.10 mmol) as the radical trap. Purification by FC (Et_2O/pentane 1:100) afforded **32** as a colorless oil (GC yield = 71%, dr 2.4:1): ^{1}H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.19−7.23 (m, 2H), 6.98−7.05 (m, 2H), 6.27 (s, 1H), 5.65 (s, 1H), 4.14−4.30 (m, 3H), 3.04 (p, *J* = 6.9 Hz, 1H), 2.76 (dd, *J* = 15.0, 3.2 Hz, 1H), 2.37 (dd, *J* = 14.3, 10.4 Hz, 1H), 1.43 (d, *J* = 6.9 Hz, 3H), 1.29 (t, *J* = 7.1 Hz, 3H); minor diastereomer δ 7.19−7.28 (m, 2H), 6.98−7.04 (m, 2H), 6.27 (s, 1H), 5.61 (s, 1H), 4.15−4.37 (m, 3H), 3.11−3.25 (m, 1H), 2.87 (dd, *J* = 14.4, 1.9 Hz, 1H), 2.26 (dd, *J* = 14.4, 10.6 Hz, 1H), 1.44 (d, *J* = 7.1 Hz, 3H), 1.27 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 166.5, 161.8 (d, $^1J_{CF}$ = 245.0 Hz, 139.1 (d, $^4J_{CF}$ = 3.3 Hz), 136.8, 129.3 (d, $^3J_{CF}$ = 7.9 Hz), 128.4, 115.3 (d, $^2J_{CF}$ = 21.2 Hz), 66.6, 60.8, 45.9, 39.9, 17.8, 14.2; minor diastereomer δ 166.6, 161.9 (d, $^1J_{CF}$ = 245.0 Hz), 137.6 (d, $^4J_{CF}$ = 3.2 Hz), 136.6, 130.0 (d, $^3J_{CF}$ = 7.8 Hz), 128.5, 115.0 (d, $^2J_{CF}$ = 21.3 Hz), 66.1, 60.9, 45.4, 38.9, 18.3, 14.2; IR (neat) 2979, 2934, 1710 (s), 1631, 1604, 1510, 1224, 1194, 1144, 1023, 949, 835 cm^{-1}; EI-LRMS (GC−MS) *m/z* 248 (10), 233(11), 219 (7), 202 (7), 175(38), 174 (19), 123(100), 103(28), 77(7); ESI-HRMS calcd for $C_{15}H_{19}O_2ClF$ [M + H]$^+$ 285.1052, found 285.1053.

*Ethyl 4-Chloro-2-methylene-5-(4-(trifluoromethyl)phenyl)-hexanoate (**33**).* The reaction was performed according to procedure F starting from 1-(trifluoromethyl)-4-vinylbenzene **26** (360 mg, 2.09 mmol) and ethyl 2-(phenylsulfonylmethyl)acrylate[13] (1.58 g, 6.21 mmol) as the radical trap. Purification by FC (Et_2O/pentane 1:100 to 1:50) afforded **33** as a colorless oil (65% GC yield, dr 2.4:1): ^{1}H NMR (300 MHz, $CDCl_3$), major diastereomer δ 7.59 (d, *J* = 8.1 Hz, 2H), 7.37 (d, *J* = 8.2 Hz, 2H), 6.29 (d, *J* = 0.9 Hz, 1H), 5.67 (d, *J* = 0.7 Hz, 1H), 4.33 (ddd, *J* = 10.0, 6.4, 3.4 Hz, 1H), 4.20 (q, *J* = 7.1 Hz, 2H), 3.12 (p, *J* = 6.8 Hz, 1H), 2.78 (dd, *J* = 13.9, 3.0 Hz, 1H), 2.41 (dd, *J* = 14.3, 10.3 Hz, 1H), 1.46 (d, *J* = 6.9 Hz, 3H), 1.29 (t, *J* = 7.1 Hz, 3H); minor diastereomer δ 7.58 (d, *J* = 8.2 Hz, 2H), 7.42 (d, *J* = 8.2 Hz, 2H), 6.28 (d, *J* = 0.8 Hz, 1H), 5.62 (d, *J* = 0.5 Hz, 1H), 4.37 (ddd, *J* = 10.6, 5.3, 2.9 Hz, 1H), 4.19 (q, *J* = 7.1 Hz, 2H), 3.14−3.34 (m, 1H), 2.91 (dd, *J* = 14.3, 2.0 Hz, 1H), 2.27 (dd, *J* = 14.3, 10.6 Hz, 1H), 1.47 (d, *J* = 7.0 Hz, 3H), 1.27 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 166.6, 147.6, 136.7, 129.4 (q, $^2J_{CF3}$ = 32.4 Hz), 128.7, 128.3, 125.6 (q, $^3J_{CF3}$ = 3.8 Hz), 124.3 (q, $^1J_{CF3}$ = 271.9 Hz), 66.1, 61.0, 46.5, 40.1, 17.4, 14.3; minor diastereomer δ 166.7, 146.2, 136.4, 129.4 (q, $^2J_{CF3}$ = 32.4 Hz), 129.0, 128.8, 125.3 (q, $^3J_{CF3}$ = 3.8 Hz), 124.4 (q, $^1J_{CF3}$ = 271.9 Hz), 65.5, 61.0, 46.2, 39.1, 18.4,

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14.2; IR (neat) 2983, 2938, 1710, 1619, 1323, 1193, 1163, 1118, 1068, 1016, 952, 841 cm^{-1}; EI-LRMS (GC−MS) *m/z* 298 (28), 283 (41), 253 (15), 225 (66), 224 (37), 209 (16), 173 (100), 153 (28), 133 (49), 97 (20); ESI-HRMS calcd for $C_{16}H_{19}ClF_3O_2$ $[M + H]^+$ 335.1020, found 335.1035.

*Ethyl 4-Chloro-2-methylene-5-(p-tolyl)hexanoate (**34**).* The reaction was performed according to procedure F starting from 1-methyl-4-vinylbenzene **27** (243 mg, 2.06 mmol) and ethyl 2-(phenylsulfonylmethyl)acrylate[13] (1.58 g, 6.21 mmol) as the radical trap. Purification by FC (Et_2O/pentane, 1:100 to 1:75) afforded **34** as a colorless oil (71% GC yield, dr 2.4:1): ^1H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.10−7.22 (m, 4H), 6.28 (s, 1H), 5.65 (s, 1H), 4.30 (ddd, *J* = 10.4, 7.1, 3.2 Hz, 1H), 4.14−4.25 (m, 2H), 3.01 (p, *J* = 6.9 Hz, 1H), 2.79 (dd, *J* = 14.4, 2.4 Hz, 1H), 2.26−2.42 (m, 1H), 2.34 (s, 3H), 1.46 (d, *J* = 6.9 Hz, 3H), 1.30 (t, *J* = 7.2 Hz, 3H); minor diastereomer δ 7.10−7.22 (m, 4H), 6.28 (s, 1H), 5.62 (s, 1H), 4.33−4.40 (m, 1H), 4.14−4.25 (m, 2H), 3.11−3.24 (m, 1H), 2.89 (dd, *J* = 14.4, 2.0 Hz, 1H), 2.26−2.42 (m, 1H), 2.35 (s, 3H), 1.46 (d, *J* = 6.9 Hz, 3H), 1.28 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 166.7, 140.5, 137.1, 136.5, 129.3, 128.5, 127.7, 67.0, 60.9, 46.6, 40.0, 21.1, 18.3, 14.3; minor diastereomer δ 166.8, 139.0, 136.8, 136.5, 129.0, 128.4, 128.3, 66.3, 60.9, 45.8, 38.7, 21.1, 18.1, 14.2; IR (neat) 2980, 2929, 1711 (s), 1631, 1515, 1191, 1144, 1024, 951, 817 cm^{-1}; EI-LRMS (GC−MS) *m/z* 209 (18), 171 (9), 144 (24), 141 (45), 125 (28), 119 (73), 113 (29), 91 (13), 85 (39), 77 (100), 68 (30), 51 (29); ESI-HRMS calcd for $C_{16}H_{22}O_2Cl$ $[M + H]^+$ 281.1303, found 281.1305.

*Ethyl 5-([1,1′-Biphenyl]-4-yl)-4-chloro-2-methylenehexanoate (**35**).* The reaction was performed according to procedure F starting from 4-vinyl-1,1′-biphenyl **28** (360 mg, 2.0 mmol) and ethyl 2-(phenylsulfonylmethyl)acrylate[13] (1.54 g, 6.06 mmol) as the radical trap. Purification by FC (Et_2O/pentane 1:100) afforded **35** as a colorless oil (436 mg, 64%) (65% GC yield, dr 2.4:1): ^1H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.53−7.64 (m, 4H), 7.41−7.50 (m, 2H), 7.30−7.39 (m, 3H), 6.30 (s, 1H), 5.67 (s, 1H), 4.37 (ddd, *J* = 10.3, 6.8, 3.3 Hz, 1H), 4.21 (qd, *J* = 7.1, 1.0 Hz, 2H), 3.10 (p, *J* = 6.9 Hz, 1H), 2.85 (dd, *J* = 14.0, 3.5 Hz, 1H), 2.44 (dd, *J* = 14.4, 10.4 Hz, 1H), 1.51 (d, *J* = 6.9 Hz, 3H), 1.31 (t, *J* = 7.1 Hz, 3H); minor diastereomer δ 7.54−7.66 (m, 4H), 7.30−7.51 (m, 5H), 6.30 (s, 1H), 5.65 (s, 1H), 4.33−4.47 (m, 1H), 4.15−4.27 (m, 2H), 3.19−3.34 (m, 1H), 2.95 (dd, *J* = 14.1, 2.1 Hz, 1H), 2.36 (dd, *J* = 14.6, 10.9 Hz, 1H), 1.52 (d, *J* = 7.0 Hz, 3H), 1.28 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 166.7, 142.6, 140.9, 139.9, 137.0, 128.9, 128.5, 128.3, 127.3, 127.1, 66.8, 60.9, 46.6, 40.1, 18.1, 14.3; minor diastereomer δ 166.8, 141.1, 140.9, 139.9, 136.7, 129.0, 128.9, 128.6, 127.1, 127.0, 66.2, 60.9, 45.9, 38.8, 18.1, 14.3; IR (neat) 2960, 2922, 2852, 1714, 1466, 1195, 1146, 949, 836, 766, 696 cm^{-1}; EI-LRMS (GC−MS) *m/z* 306 (20), 277 (11), 233 (51), 217 (12), 181 (100), 166 (29), 165 (33), 154 (16), 152 (12); ESI-HRMS calcd for $C_{21}H_{24}O_2Cl$ $[M + H]^+$ 343.1459, found 343.1451.

*Ethyl 4-Chloro-5-(4-chlorophenyl)-2-methylenehexanoate (**36**).* The reaction was performed according to procedure F starting from 1-chloro-4-vinylbenzene **29** (284 mg, 2.05 mmol) and ethyl 2-(phenylsulfonylmethyl)acrylate[13] (1.58 g, 6.21 mmol) as the radical trap. Purification by FC (Et_2O/pentane 1:100) afforded **36** as a colorless oil (389 mg, 63%) (76% GC yield, dr 2.4:1): ^1H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.27−7.33 (m, 2H), 7.15−7.25 (m, 2H), 6.27 (s, 1H), 5.65 (s, 1H), 4.27 (ddd, *J* = 10.2, 6.6, 3.4 Hz, 1H), 4.19 (qd, *J* = 7.1, 0.8 Hz, 2H), 3.02 (p, *J* = 6.8 Hz, 1H), 2.77 (dd, *J* = 14.3, 3.2 Hz, 1H), 2.37 (dd, *J* = 14.3, 10.4 Hz, 1H), 1.43 (d, *J* = 6.9 Hz, 3H), 1.29 (t, *J* = 7.1 Hz, 3H); minor diastereomer δ 7.27−7.33 (m, 2H), 7.15−7.25 (m, 2H), 6.27 (s, 1H), 5.61 (s, 1H), 4.30−4.37 (m, 1H), 4.19 (qd, *J* = 7.1, 0.8 Hz, 2H), 3.10 (m, 1H), 2.86 (dd, *J* = 14.3, 2.7 Hz, 1H), 2.25 (dd, *J* = 14.3, 10.5 Hz, 1H), 1.43 (d, *J* = 6.9 Hz, 3H), 1.28 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$), major diastereomer δ 166.6, 142.0, 136.8, 132.8, 129.3, 128.8, 128.6, 66.5, 61.0, 46.1, 40.0, 17.7, 14.3; minor diastereomer δ 166.7, 140.5, 136.6, 132.9, 130.0, 128.6, 128.5, 65.9, 61.0, 45.7, 39.0, 18.4, 14.3; IR (neat) 2981, 2938, 2907, 1710 (s), 1634, 1493, 1191, 1144, 1092, 1013, 951, 827, 699 cm^{-1}; EI-LRMS (GC−MS) *m/z* 264 (15), 249 (14), 235 (8), 219 (9), 191 (42), 155 (9), 141 (38), 139 (100), 115 (13), 103 (37), 77 (15); ESI-HRMS calcd for $C_{15}H_{19}O_2Cl_2$ $[M + H]^+$ 301.0762, found 301.0757.

*5-([1,1′-Biphenyl]-4-yl)-4-chloro-2-methylenehexyl 3,5-Dinitrobenzoate (**37**).* A solution of diisobutylaluminum hydride (DIBALH) (3.0 mL, 3.0 mmol, 1 M) was added dropwise to a solution of **35** (413 mg, 1.2 mmol) in dry dichloromethane (6 mL) at −78 °C over a period of 30 min. After being stirred for 3 h, the reaction mixture was treated with a saturated solution of ammonium chloride and then warmed to rt. The white precipitate was filtered off, the layers were separated, and the aqueous phase was extracted with CH_2Cl_2. The combined organic extracts were dried over Na_2SO_4, and the solvent was removed under reduced pressure. The crude product was purified by FC (Et_2O/pentane 1:4 to 1:2) to afford 5-([1,1′-biphenyl]-4-yl)-4-chloro-2-methylenehexan-1-ol (221 mg, 61%) as a colorless oil: ^1H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.53−7.66 (m, 4H), 7.43−7.48 (m, 2H), 7.29−7.40 (m, 3H), 5.18 (s, 1H), 5.00 (s, 1H), 4.30 (ddd, *J* = 10.4, 6.7, 3.9 Hz, 1H), 4.11 (s, 2H), 3.11(p, *J* = 6.9 Hz, 1H), 2.58 (dd, *J* = 14.7, 3.6 Hz, 1H), 2.39 (dd, *J* = 15.0, 10.1 Hz, 1H), 1.62 (s, 1H), 1.50 (d, *J* = 7.0 Hz, 3H); minor diastereomer δ 7.53−7.66 (m, 4H), 7.43−7.48 (m, 2H), 7.29−7.41 (m, 3H), 5.18 (s, 1H), 4.99 (s, 1H), 4.38 (ddd, *J* = 10.4, 4.6, 3.6 Hz, 1H), 4.11 (s, 2H), 3.19−3.32 (m, 1H), 2.63 (dd, *J* = 14.7, 3.3 Hz, 1H), 2.30 (dd, *J* = 15.2, 10.5 Hz, 1H), 1.62 (s, 1H), 1.50 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 145.3, 142.8, 140.9, 139.9, 128.9, 127.4, 127.1, 113.5, 67.0, 66.0, 46.1, 40.7, 17.7; minor diastereomer δ 145.1, 141.0, 140.9, 139.9, 129.0, 128.2, 127.0, 113.6, 66.2, 66.0, 45.7, 39.1, 17.9; IR (neat) 3354 (br), 3031, 2972, 2934, 2876, 1486, 1029, 904, 837, 766 (s), 737, 696 (s), 669 cm^{-1}; EI-LRMS (GC−MS) *m/z* 254 (2), 182 (4), 148 (2), 135 (100), 105 (10), 77 (10); ESI-HRMS calcd for $C_{19}H_{22}OCl$ $[M + H]^+$ 301.1354, found 301.1355.

Et_3N (81 mg, 0.80 mmol) was added to a solution of the alcohol (160 mg, 0.53 mmol) and 3,5-dinitrobenzoyl chloride (184 mg, 0.80 mmol) in CH_2Cl_2 (3 mL) at 0 °C. The mixture was slowly warmed to room temperature and stirred for 4 h. H_2O (5 mL) was added, and the solution was extracted with CH_2Cl_2 (2 × 5 mL). The combined organic layer was washed with a satd NaCl soln. (2 × 5 mL) and dried over $MgSO_4$. The solvent was evaporated, and the residue was purified by FC (pentane/Et_2O 20:1) to give **37** as a white solid. The major diastereomer was isolated and recrystallized from CH_2Cl_2/pentane. Its relative configuration was confirmed by X-ray crystallographic analysis.

syn-**37** (major diastereomer): mp 104.6−106.1 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.94 (d, *J* = 2.1 Hz, 2H), 8.88 (t, *J* = 2.1 Hz, 1H), 7.30−7.42 (m, 7H), 7.21−7.24 (m, 2H), 5.32 (s, 1H), 5.23 (s, 1H), 5.06 (d, *J* = 12.8 Hz, 1H), 4.68 (d, *J* = 12.8 Hz, 1H), 4.14 (ddd, *J* = 11.4, 8.7, 2.9 Hz, 1H), 3.02 (dq, *J* = 13.9, 6.9 Hz, 1H), 2.53 (d, *J* = 13.0 Hz, 1H), 2.37 (dd, *J* = 15.1, 10.4 Hz, 1H), 1.51 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 162.2, 148.5, 142.7, 139.9, 139.4, 139.2, 133.4, 129.3, 129.0, 128.1, 127.7, 127.1, 126.4, 122.4, 118.9, 68.4, 65.9, 47.0, 40.6, 19.2; IR (neat) 3099, 2926, 1734, 1721, 1540, 1342, 1273, 1164, 919, 842, 768, 730, 717, 692, 675, 668 cm^{-1}; EI-LRMS (GC−MS) *m/z* 318 (2), 182 (15), 181 (100), 166 (16), 165 (16), 152 (7), 115 (3), 91 (2), 77 (4); ESI-HRMS calcd for $C_{26}H_{24}ClN_2O_6$ $[M + H]^+$ 495.1322, found 495.1317.

*(3-Chloro-5-methylhex-5-en-2-yl)benzene (**38**).* The reaction was performed according to procedure F starting from styrene **24** (227 mg, 2.18 mmol) and ((2-methylallyl)sulfonyl)benzene[59] (1.30 g, 6.62 mmol) as the radical trap. This radical allylation reaction proceeded slowly and required refluxing overnight after the addition of di-*tert*-butyl hyponitrite. Purification by FC (pentane) afforded **38** as a colorless oil (194 mg, 43%) (53% GC yield, dr 2.3:1): ^1H NMR (300 MHz, $CDCl_3$/TMS) major diastereomer δ 7.18−7.37 (m, 5H), 4.85 (s, 1H), 4.78 (s, 1H), 4.18 (ddd, *J* = 9.1, 6.3, 5.3 Hz, 1H), 3.02 (p, *J* = 6.8 Hz, 1H), 2.21−2.47 (m, 2H), 1.71 (s, 3H), 1.44 (d, *J* = 6.9 Hz, 3H); minor diastereomer, δ 7.17−7.38 (m, 5H), 4.85 (s, 1H), 4.75 (s, 1H), 4.28 (dt, *J* = 9.9, 4.3 Hz, 1H), 3.12−3.24 (m, 1H), 2.16−2.49 (m, 2H), 1.71 (s, 3H), 1.44 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 144.0, 141.9, 128.6, 127.8, 127.0, 113.6, 66.6, 46.0, 45.3, 22.0, 17.3; minor diastereomer δ 142.1, 141.8, 128.7, 128.3, 127.0, 113.5, 65.8, 45.8, 43.4, 22.1, 17.8; IR (neat) 3083, 3031,

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2968, 2934, 1495, 1452, 1377, 888, 763, 698 (s) cm^{-1}; EI *m/z* 208 (29), 152 (29), 105.0 (100), 91 (7), 77 (6); EI-HRMS calcd for $C_{13}H_{17}Cl$ $[M]^+$ 208.1016, found 208.1013.

*(3-Chloro-5-(phenylsulfonyl)hex-5-en-2-yl)benzene (**39**).* The reaction was performed according to procedure F starting from styrene **24** (204 mg, 1.96 mmol) and (prop-2-ene-1,2-diyldisulfonyl)-dibenzene[15] (1.93 g, 5.99 mmol) as the radical trap. Purification by FC (TBME/cyclohexane, 1:4) afforded **39** as a white solid (GC yield = 66%, dr 2.7:1). The major diastereomer was recrystallized from CH_2Cl_2/pentane.

Major diastereomer: mp 88.6−90.6 °C; ^{1}H NMR (300 MHz, $CDCl_3$), δ 7.51−7.60 (m, 3H), 7.24−7.45 (m, 5H), 7.13−7.22 (m, 2H), 6.47 (s, 1H), 5.91 (s, 1H), 4.22−4.40 (m, 1H), 2.89 (dq, *J* = 14.1, 6.9 Hz, 1H), 2.52 (ddd, *J* = 15.6, 2.7, 1.0 Hz, 1H), 2.32 (dd, *J* = 15.6, 10.5 Hz, 1H), 1.44 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$), δ 146.2, 143.1, 138.5, 133.6, 129.2, 128.8, 128.3, 127.9, 127.8, 127.2, 65.6, 47.3, 37.8, 19.0; IR (neat) 3079, 3031, 2982, 2903, 1582, 1492, 1445, 1314, 1285, 1148, 1132, 1082, 957, 746, 703, 689, 682, 662, 613 cm^{-1}; EI-LRMS (GC−MS) *m/z* 157 (18), 156 (100), 141 (80), 129 (13), 115 (16), 105 (69), 91 (10), 77 (19); ESI-HRMS calcd for $C_{18}H_{20}O_2ClS$ $[M + H]^+$ 335.0867, found 335.0864.

*(5-Bromo-3-chlorohex-5-en-2-yl)benzene (**40**).* The reaction was performed according to procedure F starting from styrene **24** (216 mg, 2.07 mmol) and ((2-bromoallyl)sulfonyl)benzene[15] (1.60 g, 6.13 mmol) as the radical trap. Purification by FC (pentane) afforded **40** as a colorless oil (263 mg, 46%). The two diastereomers were isolated by careful separation (55% GC yield, dr 2.4:1): ^{1}H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.23−7.41 (m, 5H), 5.71 (s, 1H),), 5.55 (d, *J* = 1.5 Hz, 1H), 4.38 (ddd, *J* = 9.0, 6.9, 4.7 Hz, 1H), 3.08 (p, *J* = 6.9 Hz, 1H), 2.51−2.81 (m, 2H), 1.49 (d, *J* = 6.9 Hz, 3H); minor diastereomer δ 7.23−7.41 (m, 5H), 5.66 (s, 1H), 5.55 (d, *J* = 1.5 Hz, 1H), 4.43−4.52 (m, 1H), 3.22 (qd, *J* = 7.0, 4.6 Hz, 1H), 2.51−2.81 (m, 2H), 1.50 (d, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 143.2, 130.1, 128.8, 127.8, 127.2, 65.5, 48.4, 45.8, 17.8; minor diastereomer δ 141.4, 130.1, 128.7, 128.4, 127.3, 64.8, 47.3, 45.1, 18.2; IR (neat) 3060, 3031, 2971, 2934, 2872, 1631, 1495, 1452, 1200, 891, 764, 699 (s) cm^{-1}; EI *m/z* 274 (20), 272 (15), 234 (31), 218 (25), 209 (15), 157 (15), 152 (11), 105 (100), 106 (9), 91 (5), 79 (5), 77 (7); EI-HRMS calcd for $C_{12}H_{14}{}^{79}Br^{35}Cl$ $[M]^+$ 271.9962, found 271.9963.

*((4-Chloro-2-methylene-5-phenylhexyl)sulfonyl)benzene (**41**).* The reaction was performed according to procedure F starting from styrene **24** (212 mg, 2.04 mmol) and (2-methylenepropane-1,3-diyldisulfonyl)dibenzene (2.02 g, 6.00 mmol) as the radical trap. This radical allylation reaction proceeded slowly and was allowed to stir at reflux for another 3 h. Purification by FC (CH_2Cl_2/Et_2O/pentane 1:1:10) afforded **41** as a colorless oil (36% GC yield, dr 2.9:1): ^{1}H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.80−7.90 (m, 2H), 7.62−7.72 (m, 1H), 7.50−7.62 (m, 2H), 7.23−7.43 (m, 5H), 5.14 (s, 1H), 4.92 (s, 1H), 4.19−4.26 (m, 1H), 3.86 (s, 2H), 3.06 (p, *J* = 6.9 Hz, 1H), 2.61−2.72 (m, 1H), 2.42 (dd, *J* = 15.4, 10.7 Hz, 1H), 1.48 (d, *J* = 6.9 Hz, 3H); minor diastereomer δ 7.80−7.90 (m, 2H), 7.62−7.72 (m, 1H), 7.50−7.62 (m, 2H), 7.23−7.43 (m, 5H), 5.14 (s, 1H), 4.92 (s, 1H), 4.29 (ddd, *J* = 10.9, 5.1, 2.8 Hz, 1H), 3.85 (s, 2H), 3.13−3.26 (m, 1H), 2.82 (d, *J* = 15.4 Hz, 1H), 2.30 (dd, *J* = 15.4, 11.0 Hz, 1H), 1.48 (d, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 143.2, 138.2, 134.0, 133.8, 129.1, 128.7, 128.5, 127.8, 127.1, 123.1, 66.7, 62.7, 46.7, 42.3, 18.0; minor diastereomer δ 141.9, 138.3, 134.0, 133.8, 129.1, 128.5, 128.4, 128.3, 127.1, 123.2, 65.9, 62.6, 46.1, 41.0, 17.7; IR (neat) 3056, 3031, 2973, 2934, 1495, 1446, 1307, 1150, 1127, 1084, 752, 725, 701 (s), 687 (s) cm^{-1}; EI-LRMS (GC−MS) *m/z* 172 (13), 171 (78), 155 (11), 143 (15), 129 (22), 115 (17), 105 (100), 91 (35), 77 (20); ESI-HRMS calcd for $C_{19}H_{21}O_2ClNaS$ $[M + Na]^+$ 371.0843, found 371.0842.

*(3-Chloro-5-(chloromethyl)hex-5-en-2-yl)benzene (**42**).* The reaction was performed according to procedure F starting from styrene **24** (211 mg, 2.03 mmol) and ((2-(chloromethyl)allyl)sulfonyl)benzene[59] (1.39 g, 6.02 mmol) as the radical trap. Purification by FC (pentane) afforded **42** as a colorless oil (254 mg, 51%) (56% GC yield, dr 2.5:1): ^{1}H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.01−7.28 (m, 5H), 5.09 (s, 1H), 4.90 (s, 1H), 4.07 (ddd, *J* = 10.5, 7.0, 3.5 Hz, 1H), 3.89−3.98 (m, 2H), 2.90 (p, *J* = 6.9 Hz, 1H), 2.44−2.54 (m, 1H), 2.24 (dd, *J* = 15.2, 10.5 Hz, 1H), 1.33 (d, *J* = 6.9 Hz, 3H); minor diastereomer δ 7.01−7.28 (m, 5H), 5.09 (s, 1H), 4.89 (s, 1H), 4.15 (ddd, *J* = 10.8, 5.0, 3.2 Hz, 1H), 3.86−3.98 (m, 2H), 3.00−3.11 (m, 1H), 2.55−2.64 (m, 1H), 2.06−2.21 (m, 1H), 1.33 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 143.5, 141.7, 128.7, 127.8, 127.1, 117.8, 66.2, 47.9, 46.8, 40.5, 18.1; minor diastereomer δ 141.9, 141.5, 128.5, 128.4, 127.1, 117.9, 65.5, 48.0, 46.1, 38.9, 17.8; IR (neat) 3083, 3060, 3030, 2971, 2934, 1644, 1600, 1495, 1452, 1256, 909, 747, 699 (s) cm^{-1}; EI-LRMS (GC−MS) *m/z* 206 (1), 152 (7), 115 (5), 105 (100), 91 (7), 77 (6); EI-HRMS calcd for $C_{13}H_{16}Cl_2$ $[M]^+$ 242.0629, found 242.0626. Anal. Calcd for $C_{13}H_{16}Cl_2$: C, 64.21; H, 6.63. Found: C, 64.35; H, 6.45.

Silver(I)-Mediated Lactonization. Silver nitrate ($AgNO_3$) (342 mg, 2.02 mmol) was dissolved in 5 mL of water and 9 mL of dioxane and heated to reflux. Ester **30** (300 mg, 1.01 mmol) dissolved in 2 mL of dioxane was then added, and the resulting mixture was maintained at reflux for 2 h. After cooling, the mixture was filtered and concentrated. Water was added, and the mixture was extracted with CH_2Cl_2. The combined organic extracts were washed twice with brine and dried over $MgSO_4$. Evaporation of the solvents gave the crude product which was purified by FC (Et_2O/pentane, 1:2) to yield compound **43** (21 mg, 9%) and **44** (37 mg, 16%) as a white solid. Compound **44** was recrystallized from CH_2Cl_2/pentane. The relative configuration of **44** was confirmed by X-ray crystallographic analysis.

*5-(1-(4-Methoxyphenyl)ethyl)-3-methylenedihydrofuran-2(3H)-one (**43**):* ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.08−7.16 (m, 2H), 6.83−6.90 (m, 2H), 6.15 (t, *J* = 2.9 Hz, 1H), 5.50 (t, *J* = 2.5 Hz, 1H), 4.54 (td, *J* = 7.8, 6.4 Hz, 1H), 3.80 (s, 3H), 2.80−2.91 (m, 1H), 2.74 (ddt, *J* = 17.4, 7.6, 2.5 Hz, 1H), 2.54 (ddt, *J* = 17.4, 6.0, 2.9 Hz, 1H), 1.39 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.5, 158.9, 134.8, 133.5, 129.0, 121.9, 114.3, 81.5, 55.4, 44.8, 32.0, 18.2; IR (neat) 2955, 2923, 2853, 1752 (s), 1514, 1283, 1241, 1177, 1027, 1001, 960, 837, 632, 612 cm^{-1}; EI-LRMS (GC−MS) *m/z* 232 (10), 135 (100), 105 (15), 77(5); ESI-HRMS calcd for $C_{14}H_{17}O_3$ $[M + H]^+$: 233.1172, found 233.1169.

*5-(4-Methoxyphenyl)-6-methyl-3-methylenetetrahydro-2H-pyran-2-one (**44**):* ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.05−7.15 (m, 2H), 6.82−6.93 (m, 2H), 6.42−6.48 (m, 1H), 5.55−5.61 (m, 1H), 4.47−4.61 (m, 1H), 3.80 (s, 3H), 2.69−2.88 (m, 3H), 1.18 (d, *J* = 6.3 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.6, 159.1, 134.2, 132.0, 128.6, 128.1, 114.5, 81.6, 55.4, 46.6, 36.4, 20.2; IR (neat) 2981, 2934, 2836, 1703 (s), 1613, 1515 (s), 1444, 1302, 1256, 1174, 1136, 1077, 1030 (s), 962, 834, 825, 820, 811,785 cm^{-1}; EI-LRMS (GC−MS) *m/z* 232 (25), 188 (100), 159 (40), 134 (75), 129 (30), 115 (25), 91(15), 77(5); ESI-HRMS calcd for $C_{14}H_{17}O_3$ $[M + H]^+$ 233.1172, found 233.1173.

*4-Hydroxy-2-methylene-5-phenylhexanoic Acid (**45**).*[60] The ester **31** (dr 7:3, 290 mg, 1.09 mmol) was suspended in 10 mL of tetrahydrofuran in a 25 mL round-bottomed flask. LiOH·H_2O (185 mg, 4.41 mmol) in 2 mL of water was added, and the mixture was heated at 60 °C for 24 h. The mixture was cooled to rt, and HCl (1 M, 5 mL) was added followed by 10 mL of a satd aq NaCl solution, the mixture was extracted with Et_2O (4×), and the combined organic layers were dried over anhydrous Na_2SO_4 and then concentrated. The residue was used for the next step without purification. The corresponding pure hydroxy ester **45** was isolated by FC (pentane/Et_2O 1:1) as a white powder: ^{1}H NMR (300 MHz, acetone-d_6) major diastereomer δ 7.22−7.35 (m, 4H), 7.13−7.21 (m, 1H), 6.14−6.19 (m, 1H), 5.60−5.65 (m, 1H), 3.93 (ddd, *J* = 9.3, 5.1, 3.1 Hz, 1H), 2.78−3.28 (m, 3H), 2.53 (ddd, *J* = 14.1, 3.0, 1.0 Hz, 1H), 2.08−2.18 (m, 1H), 1.32 (d, *J* = 7.2 Hz, 3H); minor diastereomer δ 7.22−7.35 (m, 4H), 7.13−7.21 (m, 1H), 6.14−6.19 (m, 1H), 5.60−5.65 (m, 1H), 3.84−3.91 (m, 1H), 2.68−3.28 (m, 3H), 2.42 (dd, *J* = 14.6, 2.7 Hz, 1H), 2.13−2.21 (m, 1H), 1.32 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (75 MHz, acetone-d_6) major diastereomer δ 168.9, 144.9, 139.5, 129.4, 128.8, 127.3, 126.9, 74.7, 46.7, 38.5, 18.5; minor diastereomer δ 168.9, 146.3, 139.5, 129.1, 128.7, 127.3, 126.9, 75.0, 47.3, 39.1, 17.7; IR (neat) 3366 (br), 3025, 2964, 2918, 1699 (s), 1631, 1306, 1217, 1027,

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951, 761, 699 (s) cm^{-1}; EI-LRMS (GC−MS) *m*/*z* 202 (6), 157 (2), 115 (5), 105 (100), 97 (92), 77 (12), 69 (20).

*3-Methylene-5-(1-phenylethyl)dihydrofuran-2(3H)-one (**46**).*[61] The lactone **46** was obtained by heating **45** under reflux in benzene using a Dean−Stark apparatus with continuous removal of water for 24 h. The mixture was then cooled, and concentrated under reduced pressure. The crude product was purified by FC (Et_2O/pentane 1:3) to afford **46** (188 mg, 85%, dr 7:3) as a sticky oil: ^1H NMR (300 MHz, $CDCl_3$/TMS) major diastereomer δ 7.16−7.37 (m, 5H), 6.07 (t, *J* = 2.9 Hz, 1H), 5.48 (t, *J* = 2.5 Hz, 1H), 4.68 (dt, *J* = 7.7, 6.2 Hz, 1H), 2.61−3.06 (m, 3H), 1.37 (d, *J* = 7.2 Hz, 3H); minor diastereomer δ 7.16−7.37 (m, 5H), 6.15 (t, *J* = 2.9 Hz, 1H), 5.50 (t, *J* = 2.5 Hz, 1H), 4.58 (td, *J* = 7.9, 6.3 Hz, 1H), 2.49−2.96 (m, 3H), 1.42 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 170.3, 140.6, 134.6, 128.6, 128.4, 127.1, 121.6, 80.7, 44.2, 31.0, 16.3; minor diastereomer δ 170.3, 141.5, 134.7, 128.9, 127.9, 127.3, 121.9, 81.3, 45.7, 32.1, 18.0; IR (neat) 3025, 2968, 2930, 1755 (s), 1495, 1452, 1186, 1121, 994, 762, 698 (s) cm^{-1}; EI-LRMS (GC−MS) *m*/*z* 202 (6), 157 (2), 115 (5), 105 (97), 97 (100), 77 (15), 69 (22); ESI-HRMS calcd for $C_{13}H_{15}O_2$ $[M + H]^+$ 203.1067, found 203.1070.

(R)-1-(4-Chlorophenyl)ethanol. A mixture of $[Rh(COD)_2]^+BF_4^-$ (8 mg, 1 mol %, 0.02 mmol) and (+)-BINAP (18 mg, 1.5 mol %, 0.03 mmol) in 1,2-dimethoxyethane (2 mL) was stirred under N_2 at rt for 30 min, and 4-chlorostyrene **29** (278 mg, 2.0 mmol) was added followed at −78 °C by catecholborane (0.24 mL, 2.2 mmol). The reaction mixture was stirred at −78 °C for 2 h and then allowed to warm to rt overnight. The mixture was treated with EtOH (2 mL). To this mixture were added 3 M NaOH (2 mL) and 30% H_2O_2 (2 mL), and the resulting solution was stirred at rt for 3 h. Extraction with Et_2O followed by FC on silica gel (pentane/diethyl ether 2:1) gave (*R*)-1-(4-chlorophenyl)ethanol (300 mg (96% yield). This compound has been previously reported, and spectra data match those described:[48] ^1H NMR (300 MHz, $CDCl_3$) δ 7.27−7.36 (m, 4H), 4.87 (q, *J* = 6.4 Hz, 1H), 1.93 (br, 1H), 1.47 (d, *J* = 6.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 144.4 (C), 133.2 (CH), 128.7 (CH), 126.9 (CH), 69.9 (CH), 25.4 (CH_3); IR (neat) 3342, 2972, 2930, 1598, 1492, 1451, 1406, 1370, 1294, 1200, 1085, 1012, 895, 825, 777, 719 cm^{-1}; $[\alpha]_D^{22}$ = +47.2 (*c* = 1.0 in Et_2O) for an enantiomerically enriched sample of 92.4% ee (*R*) (lit.[47] $[\alpha]_D^{21}$ = +46.1 (*c* = 0.9 in Et_2O) for an enantiomerically enriched sample of 91% ee (*R*)).

*(4R,5R)-Ethyl 4-Chloro-5-(4-chlorophenyl)-2-methylenehexanoate (**36**).* A mixture of $[Rh(COD)_2]^+BF_4^-$ (8 mg, 1 mol %, 0.02 mmol) and (+)-BINAP (18 mg, 1.5 mol %, 0.03 mmol) in 1,2-dimethoxyethane (2 mL) was stirred under N_2 at rt for 30 min, and 4-chlorostyrene **29** (310 mg, 2.24 mmol) was added followed by catecholborane (0.26 mL, 2.44 mmol) at −78 °C. The reaction mixture was stirred at −78 °C for 2 h and then allowed to warm to rt overnight. The organoborane was then treated according to procedure F. FC (Et_2O/pentane 1:100) afforded the ester **36** a colorless oil (385 mg, 57%, dr = 2.3:1). The two diastereomers can be separated at this stage by FC. Spectral data fit the data of racemic **36**.

*Synthesis of the Enantiomerically Enriched α-Methylene Lactone **48**.* The enantiomerically enriched ester **36** (343 mg, 1.14 mmol, dr 2.3:1) was dissolved in THF (30 mL) in a 100 mL round-bottomed flask. LiOH·H_2O (240 mg, 5.72 mmol) in water (6 mL) was added, and the reaction mixture was heated at 60 °C for 24 h. After being cooled to rt, 1 M HCl (10 mL) was added followed by a satd aq NaCl solution (10 mL). The mixture was extracted Et_2O (4 × 20 mL), and the combined organic layers were dried over anhydrous $MgSO_4$ and concentrated. The crude hydroxyester was used for next step without purification. It was dissolved in benzene (200 mL) and heated under reflux in a Dean−Stark apparatus for 24 h (TLC monitoring). The reaction mixture was then cooled and concentrated under reduced pressure. The crude product was purified by FC (AcOEt/pentane 1:3) to afford lactone **48** (216 mg, 80%, dr 2.3:1) as a colorless oil. The two diastereomers (white solids) were separated by FC. The major diastereomer was recrystallized from CH_2Cl_2/pentane, and its relative configuration was confirmed by X-ray crystallographic analysis: EI-LRMS (GC−MS) *m*/*z* 236 (3), 141 (23), 139 (63), 103 (31), 97 (100), 96.3 (39), 77 (17), 69 (25); ESI-HRMS calcd for $C_{13}H_{14}ClO_2$ $[M + H]^+$ 237.0677, found 237.0681.

*(S)-5-((R)-1-(4-Chlorophenyl)ethyl)-3-methylenedihydrofuran-2(3H)-one (**48**) (major diastereomer):* mp 82.7−84.5 °C; ^1H NMR (300 MHz, $CDCl_3$), δ 7.27−7.32 (m, 2H), 7.12−7.21 (m, 2H), 6.11 (t, *J* = 2.8 Hz, 1H), 5.52 (t, *J* = 2.5 Hz, 1H), 4.64 (dt, *J* = 7.5, 6.2 Hz, 1H), 2.86−3.05 (m, 2H), 2.63 (ddt, *J* = 17.2, 6.1, 2.9 Hz, 1H), 1.36 (d, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$), δ 170.2, 139.2, 134.4, 133.1, 129.8, 128.9, 122.1, 80.5, 44.0, 31.3, 16.7; IR (neat) 2972, 2935, 2872, 1753, 1661, 1488, 1432, 1400, 1275, 1254, 1115, 1092, 1079, 1009, 982, 948, 934, 847, 839, 808, 796, 744, 720, 657, 615 cm^{-1}; $[\alpha]_D^{21}$ = +48.4 (*c* = 0.82, CH_2Cl_2) for an enantiomerically enriched sample of 92.7% ee.

*(R)-5-((R)-1-(4-Chlorophenyl)ethyl)-3-methylenedihydrofuran-2(3H)-one (**48**) (minor diastereomer):* mp 98.2−100.0 °C; ^1H NMR (300 MHz, $CDCl_3$), δ 7.27−7.35 (m, 2H), 7.12−7.21 (m, 2H), 6.18 (t, *J* = 2.9 Hz, 1H), 5.54 (t, *J* = 2.5 Hz, 1H), 4.56 (td, *J* = 7.7, 6.4 Hz, 1H), 2.90 (p, *J* = 7.1 Hz, 1H), 2.78 (ddt, *J* = 17.3, 7.7, 2.5 Hz, 1H), 2.53 (ddt, *J* = 17.4, 6.1, 2.9 Hz, 1H), 1.40 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$), δ 170.2, 140.0, 134.4, 133.2, 129.4, 129.1, 122.2, 80.9, 45.0, 31.9, 17.7; IR (neat) 2977, 2922, 2890, 1747, 1668, 1486, 1342, 1279, 1250, 1175, 1150, 1118, 1092, 1079, 1004, 985, 949, 931, 840, 811, 774, 727, 627, 607 cm^{-1}; $[\alpha]_D^{20}$ = −8.0 (*c* = 0.47, CH_2Cl_2) for an enantiomerically enriched sample of 92.7% ee.

*5-Chloro-6-phenylheptan-2-one (**49**).* The hydroboration−homologation reaction was performed according to procedure F starting from styrene **24** (202 mg, 1.94 mmol). The resulting mixture was cooled to rt, and the solvent was removed under vacuum. Then CH_2Cl_2 (7 mL), H_2O (0.1 mL), DMPU (256 mg, 2.00 mmol, 1.0 equiv), and the 3-buten-2-one (710 mg, 10.13 mmol) were added under N_2. Finally, air was introduced through a needle placed just above the reaction surface. After 2 h of stirring at room temperature, the reaction mixture was filtered over Alox, and purified by FC (pentane/Et_2O 3:1) to give **49** as a colorless oil (50% GC yield, dr 2.3:1): ^1H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.12−7.38 (m, 5H), 4.06 (ddd, *J* = 10.3, 7.5, 2.7 Hz, 1H), 2.99 (p, *J* = 7.0 Hz, 1H), 2.49−2.74 (m, 2H), 2.11 (s, 3H), 1.93−2.13 (m, 1H), 1.65−1.78 (m, 1H), 1.44 (d, *J* = 6.9 Hz, 3H); minor diastereomer δ 7.16−7.36 (m, 5H), 4.11 (ddd, *J* = 10.9, 5.5, 2.6 Hz, 1H), 3.05−3.20 (m, 1H), 2.49−2.78 (m, 2H), 2.13 (s, 3H), 2.07−2.19 (m, 1H), 1.62−1.75 (m, 1H), 1.42 (d, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 207.9, 143.5, 128.7, 127.8, 127.1, 68.8, 47.2, 40.7, 30.6, 30.1, 18.7; minor diastereomer δ 208.0, 142.4, 128.5, 128.4, 127.0, 68.2, 46.6, 40.8, 30.2, 29.1, 17.8; IR (neat) 3031, 2968, 2929, 1713 (s), 1604, 1495, 1452, 1357, 1162, 910, 764, 699 (s) cm^{-1}; EI-LRMS (GC−MS) *m*/*z* 188 (7), 170 (7), 145 (6), 131 (8), 115 (7), 105 (100), 91 (10), 77 (7); ESI-HRMS calcd for $C_{13}H_{17}OClNa$ $[M + Na]^+$ 247.0860, found 247.0867.

*2-Phenyl-1-chloropropane (**50**).* The hydroboration-homologation reaction was performed according to procedure F starting from styrene **24** (208 mg, 2.00 mmol). The resulting mixture was cooled to rt, and the solvent was removed under vacuum. $ClCH_2CH_2Cl$ (8 mL), 1,4-dithiane (48 mg, 20 mol %), hexadecane as internal standard, and 4-*tert*-butylcatechol (665 mg, 4.00 mmol) were added under N_2. The resulting solution was stirred for 8 h at 83 °C open to air. The black reaction mixture was cooled and filtered over Alox and purified by FC (pentane) to afford **50** as a colorless oil (145 mg, 47%) (55% GC yield). Spectral data were in accordance with literature data:[62] ^1H NMR (300 MHz, $CDCl_3$) δ 7.24−7.39 (m, 5H), 3.72 (dd, *J* = 10.7, 6.2 Hz, 1H), 3.56−3.66 (m, 1H), 3.06−3.21 (m, 1H), 1.43 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 143.5, 128.7, 127.3, 127.1, 50.9, 42.5, 19.1; IR (neat) 3065, 3031, 2967, 2872, 1603, 1494, 1452, 1014, 909, 760, 717, 696 (s) cm^{-1}; EI-LRMS (GC−MS) *m*/*z* 154 (7), 105 (100), 79 (10), 77 (10).

*(1,1-Dichloro-2-propyl)benzene (**51**).* The hydroboration−homologation reaction was performed according to procedure F starting from styrene **24** (214 mg, 2.05 mmol). The resulting mixture was cooled to rt, $PhSO_2Cl$ (1.80 g, 10.19 mmol, 5.0 equiv), hexadecane as internal standard, and di-*tert*-butyl hyponitrite (10 mg, 3 mol %) were added, and the mixture was heated at reflux. Every 1 h, a further

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portion of di-*tert*-butyl hyponitrite (10 mg, 3 mol %) was added. After 2 h, the mixture was cooled and filtered over Alox. Purification by FC (pentane) afforded **51** as a colorless oil (205 mg, 53%) (57% GC yield). Spectral data were in accordance with literature data:[63,64] ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.28−7.43 (m, 5H), 5.91 (d, J = 5.0 Hz, 1H), 3.47 (qd, J = 6.9, 5.1 Hz, 1H), 1.58 (d, J = 7.0 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 140.6, 128.6, 128.4, 127.8, 78.3, 50.4, 16.0. IR (neat) 3065, 3031, 2984, 2938, 1496, 1452, 1379, 1216, 797, 748, 725, 695 (s) cm^{-1}; EI-LRMS (GC−MS) m/z 188 (5), 115 (9), 105 (100), 79 (11), 77 (9).

*2-Chloro-3-phenylbutanenitrile (**52**).* The hydroboration−homologation reaction was performed according to procedure F starting from styrene **24** (214 mg, 2.05 mmol). The resulting mixture was cooled to rt, *p*-TolSO$_2$CN (1.86 g, 10.26 mmol), hexadecane as internal standard, and di-*tert*-butyl hyponitrite (10 mg, 3 mol %) were added, and the mixture was heated at reflux. Every 1 h, a further portion of di-*tert*-butyl hyponitrite (10 mg, 3 mol %) was added. After 2 h, the mixture was cooled and filtered over Alox. Purification by FC (pentane) afforded **52** as a colorless oil (198 mg, 54%) (65% GC yield, dr 1.6:1). Spectral data were in accordance with literature data:[65] ^{1}H NMR (300 MHz, $CDCl_3$) major diastereomer δ 7.29−7.44 (m, 5H), 4.54 (d, J = 7.2 Hz, 1H), 3.28−3.41 (m, 1H), 1.57 (d, J = 7.0 Hz, 3H); minor diastereomer δ 7.29−7.44 (m, 5H), 4.57 (d, J = 5.9 Hz, 1H), 3.28−3.41 (m, 1H), 1.62 (d, J = 7.0 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 139.1, 129.0, 128.0, 127.8, 116.4, 48.9, 44.9, 17.3; minor diastereomer δ 139.2, 129.1, 128.4, 127.8, 116.0, 48.6, 45.2, 16.3; IR (neat) 3065, 3031, 2975, 2943, 2876, 1496, 1453, 1382, 734, 697 (s) cm^{-1}; EI-LRMS (GC−MS) m/z 179 (2), 144 (1), 115 (3), 105 (100), 91 (2), 77 (10). EI-HRMS calcd for $C_{10}H_{10}ClN$ $[M]^+$ 179.0502, found 179.0499.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02610.

NMR spectra of all compounds (PDF)
X-ray crystallographic data for **37** (CIF)
X-ray crystallographic data for **44** (CIF)
X-ray crystallographic data for **48** (CIF)

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Notes

The authors declare no competing financial interest.

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