Cobalt-Catalyzed Cross-Coupling Reactions of Alkyl Halides with Allylic and Benzylic Grignard Reagents and Their Application to Tandem Radical Cyclization/Cross-Coupling Reactions

Hirohisa Ohmiya, Takashi Tsuji, Hideki Yorimitsu, and Koichiro Oshima*[a]

Abstract: Details of cobalt-catalyzed cross-coupling reactions of alkyl halides with allylic Grignard reagents are disclosed. A combination of cobalt(II) chloride and 1,2-bis(diphenylphosphino)ethane (DPPE) or 1,3-bis(diphenylphosphino)propane (DPPP) is suitable as a precatalyst and allows secondary and tertiary alkyl halides—as well as primary ones—to be employed as coupling partners for allyl Grignard reagents. The reaction offers a facile synthesis of quaternary carbon centers, which has practically never been possible with palladium, nickel, and copper catalysts. Benzyl, methallyl, and crotyl Grignard reagents can all couple with alkyl halides. The benzylation definitely requires DPPE or DPPP as a ligand. The reaction mechanism should include the generation of an alkyl radical from the parent alkyl halide. The mechanism can be interpreted in terms of a tandem radical cyclization/cross-coupling reaction. In addition, serendipitous tandem radical cyclization/cyclopropanation/carbonyl allylation of 5-alkoxy-6-halo-4-oxa-1-hexene derivatives is also described. The intermediacy of a carbon-centered radical results in the loss of the original stereochemistry of the parent alkyl halides, creating the potential for asymmetric cross-coupling of racemic alkyl halides.

Keywords: allylation · benzylation · cobalt · cross-coupling reaction · radical reaction

Introduction

Palladium- and nickel-catalyzed cross-coupling reactions are among the most powerful methods for carbon–carbon bond formation.[1] Their significance has been demonstrated in the syntheses not only of biologically active compounds, but also in those of high-performance organic materials. With regard to their scope, one of the most apparent limitations in the cross-coupling reactions had been the lack of capability to couple alkyl halides possessing β hydrogens. Recently, however, several groups have overcome the difficulty of β-hydride elimination.[2–6] Palladium- and nickel-catalyzed cross-coupling reactions have already moved on to the next stage and continue to develop.

Cross-coupling reactions can also be catalyzed by transition metals other than palladium and nickel. More than half a century ago, Kharasch and co-workers investigated the effect of transition metal salts such as iron and cobalt in reactions between organic halides and Grignard reagents.[7] The reaction was identified as a mixture of homo-coupling, disproportionation, and cross-coupling of alkyl groups from the combination of the alkyl Grignard reagent and the alkyl halide. Since the cross-coupling product was produced though the coupling of two radicals, one formed by the prior homolysis of the alkylmetal species and the other formed by single-electron transfer to organic halide, the cross-coupling reaction was virtually uncontrollable. Later, Kochi and co-workers reported selective cross-coupling reactions under copper and iron catalysis conditions.[8] Aside from the progress in copper-catalyzed cross-coupling reactions,[9] little attention had been paid to other transition metals such as iron and cobalt since Kochi's findings. Very recently though, a renaissance in the base metal-catalyzed coupling reaction has commenced.[10] Fürstner and co-workers have reported that ligandless iron salts function as catalysts in cross-coupling reactions between aryl chlorides and alkyl Grignard reagents,[11] and Nakamura and co-workers[12] and Hayashi and Nagano[13] have also developed cross-coupling reactions with iron catalysis, in which primary and secondary alkyl halides are usable as coupling partners for aryl Grignard reagents. These iron catalyst systems are superior to palladium or nickel catalyst systems in terms of the efficiency of the reaction, including the yields of the products and the speed of the synthesis, the ready availability of secondary alkyl halides under quite simple reaction conditions, and the use of inexpensive and toxicologically benign iron salts. Such iron-catalyzed reactions have thus attracted increasing attention.

[a] H. Ohmiya, T. Tsuji, Dr. H. Yorimitsu, Prof. K. Oshima
Department of Material Chemistry, Graduate School of Engineering
Kyoto University
Kyoto-daigaku Katsura, Nishikyo-ku, Kyoto 615-8510 (Japan)
Fax: (+81) 75-383-2438
E-mail: oshima@orgrxn.mbox.media.kyoto-u.ac.jp

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We have been interested in cobalt-catalyzed carbon–carbon bond-formation reactions.[14] Most of these reactions offer unprecedented coupling potential, generally impossible with palladium, nickel, copper, or even iron catalysts. Among them, cobalt-catalyzed coupling between alkyl halides and allyl Grignard reagents allows tertiary alkyl halides to be employed, resulting in facile formation of quaternary carbons.[15,16] Our cobalt catalyst system does not suffer from the difficulties of oxidative addition to alkyl halides and rapid β-hydride elimination, both of which are usually problematic in palladium-catalyzed reactions. Motivated by our early success, we have continued to explore the generality of cobalt-catalyzed allylation reactions. Here we report full details of the reaction, including its scope, the curious effects of the ligand and solvent, and couplings of alkyl halides with benzyl Grignard reagents.

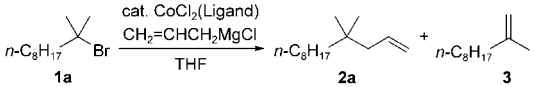
Abstract in Japanese:

塩化コバルト 1,3-ビス（ジフェニルホスフィノ）プロパン錯体存在下，ハロゲン化アルキルに対してアリルグリニャール反応剤を作用させたところ，対応する交差カップリング体が収率良く得られた．ハロゲン化アルキルとしては第一級，第二級のハロゲン化アルキルだけでなく第三級のハロゲン化アルキルも利用することができ，第四級炭素の簡便な合成法を開発できた．同様の触媒条件下クロチル，メタリル，ならびにベンジルグリニャール反応剤を用いたカップリング反応も進行することが明らかとなった．反応は電子豊富なコバルト錯体からハロゲン化アルキルへの一電子移動とそれに引き続く炭素ラジカルの生成により始まると考えられる．このメカニズムは連続的ラジカル環化・カップリング反応を行うことにより確認した．また炭素ラジカルの生成を利用すれば，ラセミ体のハロゲン化アルキルを用いた不斉交差カップリング反応が可能であることを明らかにした．さらにはこれらの研究の途上で偶然に見いだした連続的ラジカル環化・シクロプロパン化・アリル化反応についても述べる．

Results and Discussion

Cross-coupling between alkyl halides and allyl Grignard reagents: As a model reaction, the allylation of 2-bromo-2-methyldecane (**1a**) with allylmagnesium chloride was investigated first (Table 1). Allylmagnesium chloride (3 equiv) was added to a solution of **1a** in THF in the presence of [$CoCl_2$(dppp)] (0.1 equiv; dppp = 1,3-bis(diphenylphosphino)propane) at 0 °C. After the resulting mixture had been stirred for 2 h at 0 °C, conventional workup followed by silica gel column purification afforded **2a** in 80% yield, along with 2-methyl-1-decene (**3**, 18% yield, entry 3). The use of several bidentate ligands to restrain the formation of **3** was surveyed. Use of DPPE instead of DPPP increased the **2a**/**3** ratio up to 91:9, but a proportion of **1a** remained unchanged (entry 2). Significant amounts of **3** were obtained when DPPM and DPPB were employed (entries 1, 4). Reactions at lower temperatures might have allowed the formation of dehydrobromination product **3** to be avoided (Table 1, entries 5–8). Alkene **3** may be produced by conventional base-induced E2 dehydrobromination or through β-hydride elimination from the corresponding *tert*-alkylcobalt complex (vide infra). While [$CoCl_2$(dppe)] did not function as a precatalyst at −20 °C, the reaction at −20 °C in the presence of [$CoCl_2$(dppp)] provided **2** in excellent yield with the highest selectivity. Use of triphenylphosphine resulted in low **2a**/**3** selectivity. The choice of bidentate ligand and reaction temperature proved to be crucial for achieving high yields of the coupling product. THF was the best solvent, while the reaction in diethyl ether or 1,2-dimethoxyethane also yielded **2** in broadly comparable but slightly lower yields. No **2** was obtained when the cobalt catalyst was omitted. The amount of the Grignard reagent used has considerable influence: treatment with 1.5 equivalents of the Grignard reagent afforded **2a** in 60% yield (Table 1, entry 9).

Table 1. Effects of ligand and reaction temperature.[a]



Entry	Ligand[b]	Temp [°C]	Yield of **2a** [%]	**2a**/**3**
1	DPPM	0	39	46:54
2	DPPE	0	73	91:9
3	DPPP	0	80	82:18
4	DPPB	0	41	50:50
5	DPPE	−20	N.R.[c]	–
6	DPPP	−20	90	92:8
7	DPPP	−30	64	86:14
8	DPPP	−40	N.R.[c]	–
9	DPPP	−20	60[d]	93/7

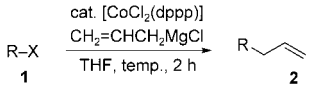
[a] **1a**/Grignard reagent/cobalt cat. = 1:3:0.1 [b] Ligands DPPM–DPPB denote $Ph_2P(CH_2)_nPPh_2$, n = 1, DPPM; n = 2, DPPE; n = 3, DPPP; n = 4, DPPB. [c] No reaction proceeded. [d] 1.5 equivalents of the Grignard reagent.

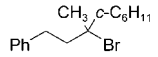
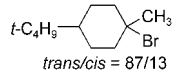
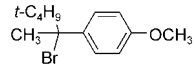
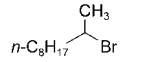
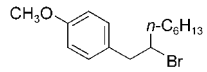
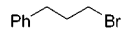
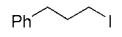
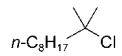
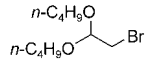
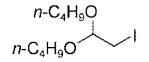
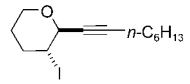
Allylation of a variety of alkyl halides proceeded smoothly, as shown in Table 2.[17] Benzylic allylation of **1d** required DPPE in place of DPPP for a satisfactory result to be attained. Secondary bromides were also subjected to allylation to afford the corresponding coupling products (Table 2, entries 4, 5), while a primary alkyl bromide was less reactive (Table 2, entry 6). Instead, use of alkyl iodides such as **1h** gave high yields at −40 °C. Use of the tertiary alkyl chloride **1i** resulted in low conversion even at higher temperatures. It is worth noting that haloacetaldehyde dibutyl acetals **1j** and **1k**, which have butoxy groups at the β-position to the halide atom, participated in the allylation.

Attempts to transform iodoarenes met with much more limited success (Scheme 1), the highest yield (32%) of **2j** being obtained in the presence of [$CoCl_2(PPh_3)_2$] at 20 °C under reaction conditions otherwise the same as above. Interestingly, highly selective conversion of sp^3 C–Br over sp^2 C–Br was achieved, **2a** being selectively produced and **1n** completely recovered when a mixture of **1n** and **1a** was subjected to the allylation. Unfortunately, amide, ester, and carbonate functionalities could not survive under the reaction conditions. Attacks on the carbonyl groups of compounds **1o**, **1p**, and **1q** took place even at −78 °C, with none of the desired products being obtained.

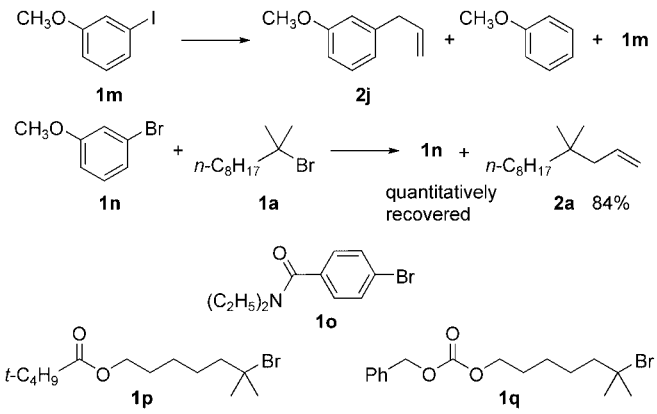
Cross-coupling reaction with methallyl, crotyl, prenyl, and benzyl Grignard reagents: Methallylation of **1a** and **1h**

Table 2. Allylation of various alkyl halides.



Entry	Substrate	1	Temp. [°C]	2	Yield [%]
1		**1b**	−20	**2b**	83
2	 *trans/cis* = 87/13	**1c**	0	**2c**	76[a]
3		**1d**	−20	**2d**	73[b]
4		**1e**	0	**2e**	57
5		**1f**	−20	**2f**	84
6		**1g**	0	**2g**	30
7		**1h**	−40	**2g**	82
8		**1i**	20	**2a**	31
9		**1j**	0	**2h**	49
10		**1k**	−40	**2h**	82
11		**1l**	−40	**2i**	76[c]

[a] *trans*/*cis* = 82:18 for **2c**. [b] DPPE was used instead of DPPP. [c] *trans*/*cis* = 86:14 for **2i**.

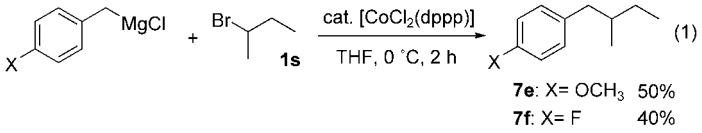


Scheme 1. Other transformations.

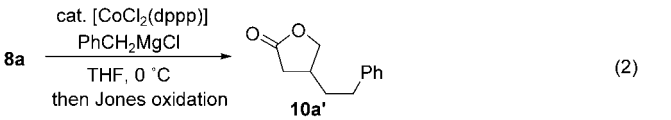
yielded **4a** and **4b** in 50 and 68% yields, respectively (Table 3, entries 1, 2). Treatment of **1a** with crotylmagnesium chloride predominantly afforded methyl-branched product **5a** in modest yield along with linear **5a′** (Table 3, entry 3). Excellent regioselectivity was observed upon treatment of **1h** with crotylmagnesium chloride (Table 3, entry 4). Similar couplings with prenylmagnesium chloride gave moderate to poor yields (Table 3, entries 5, 6). The regioselectivities were far from satisfactory. In all the reactions, the substrates were completely consumed, with allylbenzene or 2-methyl-1-decene and 2-methyl-2-decene being produced as the only by-product in each experiment.

A variety of phosphine ligands were screened for benzylation of alkyl halides, to reveal that DPPE or DPPP was again the best ligand (Table 4). It is noteworthy that 1,2-bis-(dimethylphosphino)ethane, a highly electron-donating bidentate ligand, acted as an effective ligand, while no reaction occurred with DPPM and DPPB. The number of methylene units between the two phosphorus atoms seems to be important. In contrast, 1,2-bis(diphenylphosphino)ethylene, a conformationally restricted ligand, interfered with the benzylation, indicating that a spacer of some flexibility is required. None of the monodentate ligands tested—such as PPh_3 and P(2-furyl)$_3$—served as a ligand for the benzylation, no conversion being observed. Unlike in the allylation reaction, solvent and reaction temperature are not significant variables in the benzylation reaction. Use of ether or dioxane did not affect the yield of **7a** (with DPPP, 45% and 53% yields, respectively). Benzylation reactions either at −10°C or at reflux gave no significant effects (with DPPP, 47%, 15 h and 50%, 5 min, respectively). Unlike in the allylation, use of a lower temperature (below −20°C) completely blocked the benzylation.

Use of 1.5 equivalents of benzylmagnesium chloride was sufficient for satisfactory yields of products to be attained. Several alkyl halides were subjected to the benzylation reaction (Table 5). Secondary alkyl halides underwent the benzylation in good to modest yields, while coupling with a tertiary alkyl group encountered difficulty.[18] *p*-Methoxybenzyl and *p*-fluorobenzyl Grignard reagents participated in the reaction given in Equation (1).

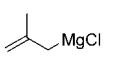
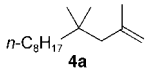
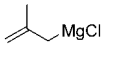
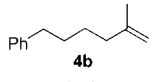
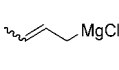
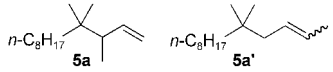
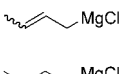
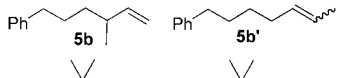
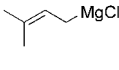
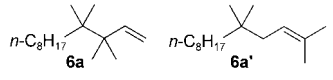
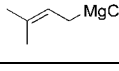
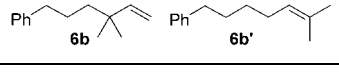


Tandem cyclization/cross-coupling reaction: clue to reaction mechanism: Substrates possessing carbon–carbon double bonds themselves such as **8** were then subjected to the reaction conditions (Scheme 2). Consequently, tandem cyclization/cross-coupling occurred, thereby affording 3-butenyl-substituted lactones after Jones oxidation of the cyclic acetal. For instance, iodoacetal **8c** was converted into lactone **10c** bearing a quaternary carbon center. Cyclization of **8d** exclusively provided the *trans* isomer **10d**. A cyclization/benzylation sequence was also established in the reaction of **8a**, but afforded the product only in 26% yield [Eq. (2)].



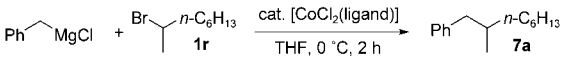
Interestingly, treatment of **8e** with allylmagnesium chloride in the presence of [$CoCl_2$(dppp)] furnished the ring-opened product **10e** (Scheme 3). Given that intramolecular carbocobaltation proceeds to yield cyclopropylmethylcobalt, β-carbon elimination could provide a route to **10e**. However,

Table 3. Methallylation, crotylation, and prenylation of alkyl halides **1a** and **1h**.

Entry	1	RMgCl	Product	Yield [%]
1[a]	**1a**		 **4a**	50
2[b]	**1h**		 **4b**	68
3[a]	**1a**		 **5a** **5a'**	60 (**5a**), 12 (**5a′**)
4[b]	**1h**		 **5b** **5b'**	93 (**5b**), 1 (**5b′**)
5[a]	**1a**		 **6a** **6a'**	11 (**6a**), 29 (**6a′**)
6[b]	**1h**		 **6b** **6b'**	10 (**6b**), 9(**6b′**)

[a] Performed at −20 °C. [b] Performed at −40 °C.

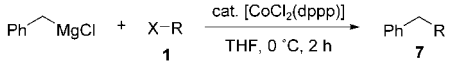
Table 4. Screening of ligands for benzylation.[a]

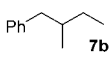
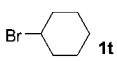
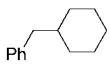
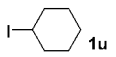
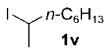
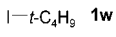
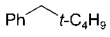


Entry	Ligand	Yield [%]
1	DPPM	N.R.
2	DPPE	46
3	DPPP	51
4	DPPB	N.R.
5	DPPH[b]	N.R.
6	$Me_2PCH_2CH_2PMe_2$	29
7	*cis*-$Ph_2PCH{=}CHPPh_2$	N.R.
8	(*R*)-BINAP	N.R.

[a] **1r**/Grignard reagent/cobalt cat. = 1:3.0:0.1. [b] 1,6-Bis(diphenylphosphino)hexane.

Table 5. Cobalt-catalyzed benzylation reaction.[a]

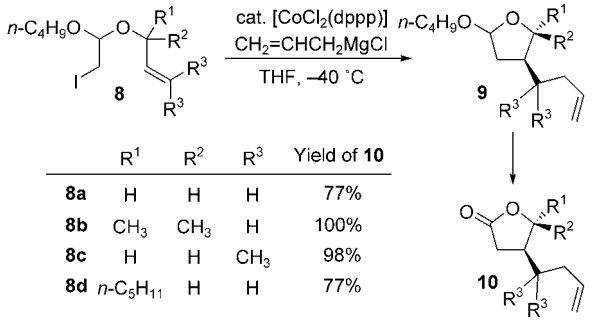


Entry	Substrate	Product	Yield [%]
1	 **1s**	 **7b**	70
2	 **1t**	 **7c**	40
3	 **1u**	**7c**	61[b]
4	 **1v**	**7a**	62
5	 **1w**	 **7d**	37

[a] **1**/Grignard reagent/cobalt cat. = 1:1.5:0.1. [b] Three equivalents of the Grignard reagent.

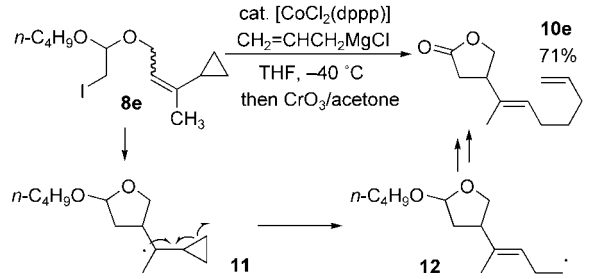
β-carbon elimination seems unlikely, since β-hydride and β-alkoxy eliminations were minor processes in the reactions of **1**. Alternatively, the ring-opening may be accounted for by the existence of radical intermediates **11** and **12**.[19] Taking all the experimental facts into consideration, we believe that the reaction mechanism should involve oxidative addition of alkyl halide by a radical mechanism.[20] Namely, the oxidative addition proceeds through a single-electron transfer from an electron-rich allyl- or benzylcobalt complex to the alkyl halide.

An unexpected tandem radical cyclization/cyclopropanation/allylation affording allyl cyclopropylmethyl ketone: During the course of our study of the solvent and ligand effects on the tandem cyclization/cross-coupling reactions of 5-alkoxy-6-halo-4-oxa-1-hexene derivatives **8**, we serendipitously observed the formation of cyclopropane



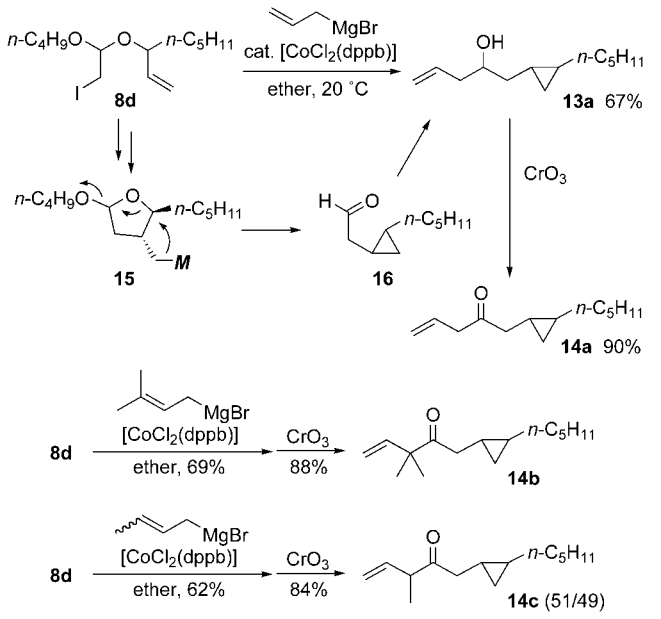
	R^1	R^2	R^3	Yield of **10**
8a	H	H	H	77%
8b	CH_3	CH_3	H	100%
8c	H	H	CH_3	98%
8d	n-C_5H_{11}	H	H	77%

Scheme 2. Tandem cyclization/cross-coupling reactions with substrates **8** possessing carbon–carbon double bonds.



Scheme 3. Reaction between **8e** and allylmagnesium chloride, furnishing the ring-opened product **10e**.

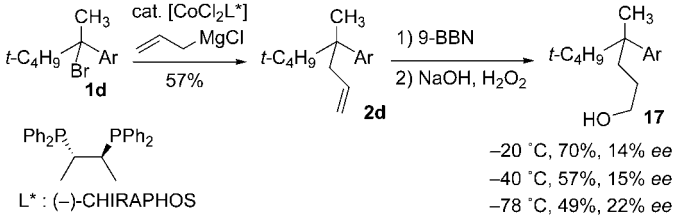
ring in a crude reaction mixture. After further investigation, we found that treatment of **8d** with allyl Grignard reagent in diethyl ether at 20 °C in the presence of [$CoCl_2$(dppb)] afforded cyclopropane **13a** in 67% yield (Scheme 4). Oxidation of the alcohol **13a** yielded allyl cyclopropylmethyl ketone **14a** as a single isomer. A plausible reaction mechanism is as follows. Single-electron transfer to **8d**, followed by loss of the bromide, could result in the formation of the corresponding radical. Sequential 5-*exo* radical cyclization and recombination of a cobalt complex would then afford (4-butoxy-3-oxacyclopentyl)methylcobalt. The cobalt species and/or the corresponding magnesium species **15** that would



Scheme 4. Formation of the cyclopropanated products.

be formed by transmetalation would be converted, in diethyl ether, into the corresponding cyclopropane **16**. In THF these species did not participate in intramolecular cyclopropanation (vide supra). The reaction in the less strongly coordinating diethyl ether could enhance the coordination of the oxygen atom(s) of **15** to Lewis acidic magnesium. The resulting aldehyde **16** would undergo carbonyl allylation to afford **13a**. The bromo analogue of **8d** would also undergo a similar conversion to afford **13a** in 59% yield. γ-Adducts **14b** and **14c** were similarly formed exclusively upon corresponding treatment of prenyl- and crotylmagnesium bromides.

Potential for asymmetric cross-coupling of racemic alkyl halides with allylmagnesium chloride: The intermediacy of a carbon-centered radical results in the loss of the original stereochemistry of the parent alkyl halides, and so the cobalt-catalyzed cross-coupling reaction offers potential for asymmetric cross-coupling of racemic alkyl halides. Treatment of racemic **1d** with allylmagnesium chloride in the presence of [$CoCl_2$\{(−)-chiraphos\}] at −20 °C afforded **2d** (Scheme 5). Hydroboration of **2d** followed by conventional oxidation provided **17** in 70% yield and 14% *ee*, while use of a lower temperature (−78 °C) increased the enantiomeric



Scheme 5. Asymmetric allylation of racemic **1d**. Ar = C_6H_4-4-OCH_3.

excess to 22%. Unfortunately, use of (−)-DIOP (DIOP = [(2,2-dimethyl-1,3-dioxolane-4,5-diyl)bis(methylene)]bis(diphenylphosphine)) or (*R*)-BINAP (BINAP = [1,1′-binaphthalene]-2,2′-diylbis(diphenylphosphine)) resulted in the exclusive formation of the corresponding dehydrobromination product. The cobalt-catalyzed asymmetric allylation thus represents a new aspect of transition metal-catalyzed radical reactions.[21,22]

Conclusion

We have found that the cobalt complexes [$CoCl_2$(dppe)] and [$CoCl_2$(dppp)] effected allylation of secondary and tertiary alkyl bromides and iodides with allyl Grignard reagents. The introduced allyl moiety could undergo a number of transformations, so this reaction should greatly increase the utility of cross-coupling reactions. The reaction is highly reliable, so far unique to cobalt complexes, and superior to the palladium- and nickel-catalyzed versions with respect to the availability of tertiary alkyl halides. The benzylation is also useful to install a benzyl unit on an alkyl chain. In both of the reactions, the specificity of DPPE and DPPP as ligands is curious and deserves further investigation. The accessibility of the coupling between sp^3 carbon atoms is thanks to facile oxidative addition through a single-electron transfer mechanism and fast reductive elimination of the product from cobalt(alkyl)allyl without suffering from β-elimination. The electron transfer mechanism was verified by the tandem radical cyclization/cross-coupling reaction, which resulted in the efficient synthesis of 3-butenyl- or 2-phenylethyl-substituted lactones. The cobalt-catalyzed cross-coupling reaction may be extended to highly enantioselective asymmetric coupling of racemic alkyl halides with organometallic reagents.

Experimental Section

^{1}H NMR (300 MHz) and ^{13}C NMR (75.3 MHz) spectra were taken on a Varian GEMINI 300 spectrometer in $CDCl_3$ as a solvent, and chemical shifts are given as δ values with tetramethylsilane as an internal standard. IR spectra were determined on a JASCO IR-810 spectrometer. TLC analyses were performed on commercial glass plates with 0.25 mm layers of Merck silica gel ($60F_{254}$). Wakogel silica gel (200 mesh) was used for column chromatography. Mass spectra (EI unless otherwise noted) were determined on a JEOL Mstation 700 spectrometer. The elemental analyses were carried out at the Elemental Analysis Center of Kyoto University.

Unless otherwise noted, materials obtained from commercial suppliers were used without further purification. Phosphine ligands were purchased from Tokyo Kasei Kogyo. Anhydrous $CoCl_2$ was purchased from Wako Pure Chemicals and was used after removal of water. Commercially available anhydrous $CoCl_2$ may contain some water. The completely anhydrous salt is clear blue, whereas purchased $CoCl_2$ is somewhat reddish-blue. Handling of $CoCl_2$ under air as usual also caused a low yield. Hence, in each experiment, $CoCl_2$ was carefully dried under reduced pressure (0.5 Torr) by heating with a hair dryer for 2 min in a reaction flask immediately before use.

A typical procedure for cobalt-catalyzed allylation of alkyl halide: Anhydrous cobalt(II) chloride (6.5 mg, 0.050 mmol) was placed in a 20 mL flask and heated in vacuo with a hair dryer for 2 min. After the color of the cobalt salt had changed to blue, dppp (25 mg, 0.060 mmol) and anhydrous THF (1.0 mL) were sequentially added under argon. The mixture

was stirred for about 10 min at room temperature. 2-Bromo-2-methyldecane (**1a**, 0.12 g, 0.50 mmol) and allylmagnesium chloride (1.0 M THF solution, 1.5 mL, 1.5 mmol) were successively added dropwise to the reaction mixture at −20 °C. While the Grignard reagent was being added, the mixture turned reddish-brown. After having been stirred at −20 °C for 2 h, the reaction mixture was poured into saturated ammonium chloride solution. The products were extracted with ethyl acetate (20 mL × 2). The combined organic layers were dried over Na_2SO_4 and concentrated. Silica gel column purification (hexane) of the crude product provided 4,4-dimethyl-1-dodecene (**2a**) and 2-methyl-1-decene (**3a**) (94 mg, 90 % and 8 % yields, respectively, as judged by ^{1}H NMR spectra).

A typical procedure for cobalt-catalyzed benzylation of alkyl halide: Cobalt(II) chloride (13 mg, 0.10 mmol) was placed in a 20 mL flask and heated in vacuo with a hair dryer for 2 min. DPPP (50 mg, 0.12 mmol) and anhydrous THF (3.0 mL) were then added under argon. After the mixture had been stirred at room temperature for about 10 min, 2-bromooctane (**1r**, 0.19 g, 1.0 mmol) and benzylmagnesium chloride (1.06 M THF solution, 2.83 mL, 3.00 mmol) were sequentially added dropwise at 0 °C. While the Grignard reagent was being added, the mixture turned brown. After having been stirred at 0 °C for 2 h, the reaction mixture was quenched with saturated ammonium chloride solution. The products were extracted with ethyl acetate (20 mL × 2). The combined organic layers were dried over Na_2SO_4 and concentrated. Purification of the crude oil by silica gel column chromatography (hexane) provided the corresponding benzylated product **7a** in 51 % yield (104 mg, 0.51 mmol).

Tandem cyclization/cross-coupling reaction: Anhydrous cobalt(II) chloride (6.5 mg, 0.050 mmol) was placed in a 20 mL flask and dried. DPPP (25 mg, 0.060 mmol) and anhydrous THF (1.0 mL) were added under argon. The mixture was stirred for about 10 min at room temperature. Iodoacetal (**8c**, 0.18 g, 0.50 mmol) and allylmagnesium chloride (0.91 M THF solution, 1.7 mL, 1.5 mmol) were successively added to the reaction mixture at −40 °C. While the Grignard reagent was being added, the mixture turned reddish-brown. After having been stirred at −40 °C for 2 h, the reaction mixture was poured into saturated ammonium chloride solution. The products were extracted with ethyl acetate (20 mL × 2). The combined organic layers were dried over Na_2SO_4 and concentrated. The crude oil was passed through a pad of silica gel with hexane/ethyl acetate 5:1 as eluent. The appropriate fractions were collected and concentrated, and the residue mainly containing **9c** was dissolved in acetone (10 mL). Jones oxidant was added dropwise until the reaction mixture had turned greenish red. After the mixture had been stirred for 1 h, the reaction was quenched with isopropyl alcohol. Extraction with ether and silica gel column purification (hexane/ethyl acetate 20:1) provided **10c** (76 mg, 0.49 mmol) in 98 % yield.

Tandem radical cyclization/cyclopropanation/allylation affording allyl cyclopropylmethyl ketone: Cobalt(II) chloride (6.5 mg, 0.050 mmol, reddish-blue) was placed in a 20 mL flask and was heated with a hair dryer in vacuo for 2 min. DPPB (26 mg, 0.060 mmol) and anhydrous diethyl ether (1 mL) were sequentially added under argon. The mixture was stirred for about 30 min. A bright blue mixture was obtained. Iodoacetal **8d** (177 mg, 0.50 mmol) and allylmagnesium bromide (0.90 M ether solution, 2.2 mL, 2.0 mmol) were successively added dropwise to the reaction mixture at 0 °C. While the Grignard reagent was being added, the mixture turned brown. After having been stirred at 20 °C for 5 h, the reaction mixture was poured into a saturated NH_4Cl solution. The products were extracted with ethyl acetate (3 × 20 mL), and the combined organic layers were dried over Na_2SO_4 and concentrated. Silica gel column purification (hexane/ethyl acetate 10:1) yielded **13a** (65.6 mg, 0.33 mmol) in 67 % yield, and Jones oxidation of **13a** (0.33 mmol) in acetone (10 mL) at room temperature followed by conventional workup and purification provided the ketone-substituted cyclopropane **14a** (58.4 mg, 0.30 mmol) in 90 % yield.

Asymmetric cross-coupling of racemic alkyl halides with allylmagnesium chloride: Anhydrous cobalt(II) chloride (13 mg, 0.10 mmol) was placed in a 20 mL flask, which was filled with argon. (−)-CHIRAPHOS (51 mg, 0.12 mmol) and anhydrous THF (2.0 mL) were sequentially added under argon, and the mixture was stirred for about 10 min at room temperature. Bromide **1d** (0.27 g, 1.0 mmol) and allylmagnesium chloride (1.0 M THF solution, 3.0 mL, 3.0 mmol) were successively added dropwise to the reaction mixture at −40 °C. After having been stirred for 4 h at −40 °C, the reaction mixture was poured into saturated ammonium chloride solution. The products were extracted with ethyl acetate, and the combined organic layers were dried and concentrated. Silica gel column purification (hexane/ethyl acetate 40:1) provided **2d** (0.13 g, 0.57 mmol) in 57 % yield, in addition to 0.17 mmol of the corresponding dehydrobromination product and 0.10 mmol of the corresponding protodebromination product. The allylated product **2d**, dissolved in THF (2 mL), was added at 0 °C to 9-borabicyclo[3.3.1]nonane (0.5 M THF solution, 4.6 mL, 2.3 mmol). The mixture was stirred at 20 °C for 15 h. Sodium hydroxide (6 M aqueous solution, 2.0 mL) and hydrogen peroxide (30 % aqueous solution, 2.0 mL) were sequentially added dropwise at 0 °C. After having been stirred for 1 h at 20 °C, the reaction mixture was diluted with water (50 mL), and a saturated aqueous solution of sodium thiosulfate was added. Extraction followed by silica gel column purification (hexane/ethyl acetate 3:1) yielded the corresponding alcohol **17** quantitatively. HPLC analysis of **17** (CHIRALCEL® OD column 4.6 mm × 250 mm Daicel Chemical Industries, hexane/2-propanol 90:10, 1.0 mL min^{-1}, 20 °C, and RI detector) showed that the ratio of the two enantiomers (retention time = 6.2 and 8.6 min) was 42.5:57.5.

Characterization data: Tertiary bromides **1a**–**1d** were prepared from the corresponding alcohols by treatment with PBr_3 in ether at −10 °C. Secondary bromides **1e** and **1f** were prepared in a similar fashion at −14 °C. Chloride **1i** was obtained from the corresponding alcohol by treatment with conc. HCl at room temperature. Haloacetals **1j**, **1k**, and **8** were prepared according to the literature.[23] Bromides **1p** and **1q** were prepared by sequential nucleophilic dimethylation of ε-caprolactone, selective esterification, and bromination. Bromide **1c** and iodide **1l** were found in the literature.[24,25] Products **7a**—**7e**[26–30] and **10a**'[31] were identical with the corresponding authentic samples.

2-Bromo-2-methyldecane (1a): ^{1}H NMR ($CDCl_3$): δ = 0.89 (t, J = 6.6 Hz, 3H), 1.24–1.36 (m, 12H), 1.44–1.56 (m, 2H), 1.75 ppm (s, 6H); ^{13}C NMR ($CDCl_3$): δ = 13.99, 22.55, 26.19, 29.17, 29.40, 29.52, 31.78, 34.15, 47.56, 68.75 ppm; IR (neat): $\tilde{\nu}$ = 1101, 1138, 1369, 1387, 1466, 2341, 2361, 2856, 2928 cm^{-1}; elemental analysis calcd (%) for $C_{11}H_{23}Br$: C 56.17, H 9.86; found: C 56.35, H 10.09.

2-Bromo-2-cyclohexyl-4-phenylbutane (1b): ^{1}H NMR ($CDCl_3$): δ = 1.10–1.32 (m, 6H), 1.60–1.74 (m, 4H), 1.76 (s, 3H), 2.04–2.26 (m, 3H), 2.78–2.90 (m, 2H), 7.17–7.23 (m, 3H), 7.26–7.33 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 26.27, 26.52, 26.80, 28.53, 28.59, 29.08, 30.09, 32.09, 45.53, 79.05, 126.02, 128.51, 128.54, 141.99 ppm; IR (neat): $\tilde{\nu}$ = 698, 746, 895, 1049, 1379, 1450, 1497, 1603, 2853, 2928, 3026 cm^{-1}.

2-Bromo-2-(4-methoxyphenyl)-3,3-dimethylbutane (1d): ^{1}H NMR ($CDCl_3$): δ = 1.07 (s, 9H), 2.77 (s, 3H), 3.81 (s, 3H), 6.80 (d, J = 9.0 Hz, 2H), 7.51 ppm (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 27.08, 29.52, 41.17, 55.23, 82.99, 112.01, 130.67, 135.99, 158.34 ppm; IR (Nujol): $\tilde{\nu}$ = 696, 741, 831, 1040, 1051, 1186, 1256, 1298, 1512, 1611, 2343, 2360 cm^{-1}; elemental analysis calcd (%) for $C_{13}H_{19}BrO$: C 57.57, H 7.06; found: C 57.29, H 6.88.

2-Bromo-1-(4-methoxyphenyl)octane (1f): ^{1}H NMR ($CDCl_3$): δ = 1.88 (t, J = 6.9 Hz, 3H), 1.18–1.40 (brs, 8H), 1.70–1.85 (m, 2H), 3.11 (dd, J = 7.2, 3.6 Hz, 2H), 3.71 (s, 3H), 4.12–4.21 (m, 1H), 6.85 (d, J = 8.4 Hz, 2H), 7.12 ppm (d, J = 8.4 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 13.92, 22.45, 27.44, 28.53, 31.56, 37.97, 44.77, 55.16, 58.40, 113.81, 130.28, 130.84, 158.53 ppm; IR (neat): $\tilde{\nu}$ = 818, 1038, 1178, 1250, 1302, 1441, 1466, 1512, 1012, 2856, 2930 cm^{-1}; HRMS found 298.0932 $[M]^+$; $C_{15}H_{23}{}^{79}BrO$ calcd 298.0938.

2-Chloro-2-methyldecane (1i): ^{1}H NMR ($CDCl_3$): δ = 0.89 (t, J = 9.6 Hz, 3H), 1.22–1.39 (m, 10H), 1.40–1.54 (m, 2H), 1.57 (s, 6H), 1.68–1.78 (m, 2H) ppm; ^{13}C NMR ($CDCl_3$): δ = 13.97, 22.55, 25.04, 29.17, 29.43, 29.66, 31.79, 32.33, 46.08, 71.29 ppm; IR (neat): $\tilde{\nu}$ = 1107, 1138, 1369, 1386, 1468, 2341, 2856, 2928 cm^{-1}; elemental analysis calcd (%) for $C_{11}H_{23}Cl$: C 69.26, H 12.15; found: C 69.40, H 12.37.

6-Bromo-6-methylheptyl pivalate (1p): ^{1}H NMR ($CDCl_3$): δ = 1.19 (s, 9H), 1.32–1.43 (m, 2H), 1.52–1.85 (m, 6H), 1.75 (s, 6H), 4.06 ppm (t, J = 6.6 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 26.2 (2C), 27.4, 28.8, 34.5, 47.6, 64.4, 64.5, 68.3, 178.5 ppm; IR (neat): $\tilde{\nu}$ = 1155, 1284, 1369, 1458, 1481, 1730, 2869, 2937, 3438 cm^{-1}; HRMS found 293.1115 (FAB, $[M+H^+]$); $C_{13}H_{26}{}^{79}BrO_2$ calcd 293.1116.

Benzyl 6-bromo-6-methylheptyl carbonate (1q): ^{1}H NMR ($CDCl_3$): δ = 1.35–1.47 (m, 2H), 1.45–1.60 (m, 2H), 1.65–1.85 (m, 4H), 1.74 (s, 6H), 4.16 (t, J = 6.6 Hz, 2H), 5.16 (s, 2H), 7.32–7.40 ppm (m, 5H); ^{13}C NMR

($CDCl_3$): δ = 25.7, 26.0, 28.6, 34.3, 47.3, 68.0, 68.1, 69.5, 128.2, 128.3, 128.4, 135.1, 155.0 ppm; IR (neat): $\tilde{\nu}$ = 696, 910, 952, 1255, 1369, 1398, 1498, 1745, 2862, 2941 cm^{-1}; HRMS found 343.0905 (FAB, $[M+H^+]$); $C_{16}H_{24}{}^{79}BrO_3$ calcd 343.0909.

4,4-Dimethyl-1-dodecene (2a): ^1H NMR ($CDCl_3$): δ = 0.84 (s, 6H), 0.88 (t, J = 6.6 Hz, 3H), 1.10–1.40 (brs, 14H), 1.94 (d, J = 7.2 Hz, 2H), 4.94–5.04 (m, 2H), 5.81 ppm (ddt, J = 16.8, 10.5, 7.2 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 13.98, 22.59, 23.87, 26.91, 29.28, 29.60, 30.52, 31.51, 31.85, 41.95, 46.44, 116.45, 136.12 ppm; IR (neat): $\tilde{\nu}$ = 912, 995, 1366, 1468, 1639, 2855, 2928, 3076 cm^{-1}; elemental analysis calcd (%) for $C_{14}H_{28}$: C 85.63, H 14.37; found C 85.61, H 14.63.

4-Cyclohexyl-4-methyl-6-phenyl-1-hexene (2b): ^1H NMR ($CDCl_3$): δ = 0.86 (s, 3H), 0.90–1.32 (m, 5H), 1.47–1.58 (m, 2H), 1.58–1.84 (m, 6H), 2.03–2.18 (m, 2H), 2.15 (t, J = 9.0 Hz, 2H), 5.03–5.10 (m, 2H), 5.85 (ddt, J = 16.5, 11.1, 7.2 Hz, 1H), 7.12–7.21 (m, 3H), 7.21–7.30 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 21.78, 26.76, 26.92, 27.20, 29.92, 37.74, 39.48, 41.45, 44.59, 116.71, 125.61, 128.39, 128.40, 135.90, 143.80 ppm; IR (neat): $\tilde{\nu}$ = 698, 741, 910, 995, 1377, 1450, 1497, 1600, 1638, 2341, 2361, 2853, 2928, 3026, 3063 cm^{-1}; elemental analysis calcd (%) for $C_{19}H_{28}$: C 88.99, H 11.01; found: C 88.98, H 11.10.

***cis*-4-*tert*-Butyl-1-methyl-1-(2-propenyl)cyclohexane (2c)**: ^1H NMR ($CDCl_3$): δ = 0.82 (s, 3H), 0.85 (s, 9H), 1.03–1.22 (m, 5H), 1.49–1.57 (m, 4H), 2.02 (s, 1H), 2.04 (s, 1H), 4.95 (m, 2H), 5.79 (ddt, J = 15.9, 10.8, 7.5 Hz, 1H) ppm; ^{13}C NMR ($CDCl_3$): δ = 22.48, 27.25, 27.60, 29.46, 32.48, 38.30, 40.03, 47.99, 116.39, 135.78 ppm; IR (neat): $\tilde{\nu}$ = 910, 997, 1366, 1452, 1639, 2844, 2868, 2941, 3074 cm^{-1}; elemental analysis calcd (%) for $C_{14}H_{26}$: C 86.52, H 13.48; found: C 86.46, H 13.51. The stereochemistry of **1c** and **2c** was determined by ^{13}C NMR experiments according to the literature.[32]

4-(4-Methoxyphenyl)-4,5,5-trimethyl-1-hexene (2d): ^1H NMR ($CDCl_3$): δ = 0.83 (s, 9H), 1.27 (s, 3H), 2.24 (dd, J = 14.1, 8.4 Hz, 1H), 3.00 (dd, J = 14.1, 3.6 Hz, 1H), 3.80 (s, 3H), 4.88 (d, J = 10.2 Hz, 1H), 5.01 (d, J = 17.1 Hz, 1H), 5.42–5.55 (m, 1H), 6.81 (d, J = 9.0 Hz, 2H), 7.20 ppm (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 21.26, 26.26, 36.51, 39.47, 45.22, 55.08, 112.15, 116.43, 130.12, 136.33, 136.85, 157.11 ppm; IR (neat): $\tilde{\nu}$ = 831, 910, 1038, 1188, 1252, 1294, 1375, 1464, 1514, 1611, 2361, 2955 cm^{-1}; HRMS found 232.1828 $[M]^+$; $C_{16}H_{24}O$ calcd 232.1831.

4-(4-Methoxybenzyl)-1-decene (2f): ^1H NMR ($CDCl_3$): δ = 0.87 (t, J = 6.6 Hz, 3H), 1.16–1.38 (brs, 10H), 1.60–1.70 (m, 1H), 2.01 (dd, J = 7.8, 7.2 Hz, 2H), 2.48 (d, J = 7.2 Hz, 2H), 3.79 (s, 3H), 4.97–5.03 (m, 2H), 5.72–5.85 (m, 1H), 6.82 (d, J = 9.0 Hz, 2H), 7.06 ppm (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 13.96, 22.55, 26.54, 29.49, 31.78, 32.81, 37.39, 39.14, 39.68, 55.18, 113.62, 116.03, 129.31, 130.16, 137.35, 147.81 ppm; IR (neat): $\tilde{\nu}$ = 804, 910, 1040, 1177, 1246, 1300, 1466, 1512, 1612, 2854, 2926 cm^{-1}; elemental analysis calcd (%) for $C_{18}H_{28}O$: C 83.02, H 10.84; found: C 83.02, H 11.03.

4-Pentenal dibutyl acetal (2h): ^1H NMR ($CDCl_3$): δ = 0.92 (t, J = 7.2 Hz, 6H), 1.38 (m, 4H), 1.56 (m, 4H), 1.70 (m, 2H), 2.11 (m, 2H), 3.41 (dt, J = 6.6, 9.3 Hz, 2H), 3.58 (dt, J = 6.6, 9.6 Hz, 2H), 4.48 (t, J = 5.7 Hz, 1H), 4.94–5.06 (m, 2H), 5.82 ppm (ddt, J = 17.1, 10.5, 6.6 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 13.77, 19.34, 28.94, 31.93, 32.59, 65.32, 102.62, 114.69, 138.27 ppm; IR (neat): $\tilde{\nu}$ = 912, 1049, 1074, 1128, 1261, 1350, 1379, 1458, 1641, 2933, 2959 cm^{-1}; elemental analysis calcd (%) for $C_{13}H_{26}O_2$: C 72.84, H 12.23; found: C 72.72, H 12.11.

***cis*-2-(1-Octynyl)-3-(2-propenyl)-1-oxacyclohexane (*cis*-2i)**: ^1H NMR ($CDCl_3$): δ = 0.90 (t, J = 6.9 Hz, 3H), 1.22–1.36 (m, 4H), 1.36–1.48 (m, 2H), 1.48–1.66 (m, 6H), 1.72–1.86 (m, 1H), 1.93–2.03 (m, 1H), 2.07–2.16 (m, 1H), 2.26 (dt, J = 1.8, 7.2 Hz, 2H), 3.59–3.70 (m, 1H), 3.85–3.95 (m, 1H), 4.54 (brs, 1H), 4.99–5.09 (m, 2H), 5.75 (ddt, J = 16.8, 10.2, 7.2 Hz, 1H) ppm; ^{13}C NMR ($CDCl_3$): δ = 13.90, 18.64, 22.47, 25.28, 25.37, 28.46, 28.70, 31.23, 36.71, 39.19, 62.71, 69.60, 75.84, 89.00, 116.30, 136.28 ppm; IR (neat): $\tilde{\nu}$ = 1078, 1350, 1439, 1641, 2239, 2341, 2858, 2932, 3076 cm^{-1}; HRMS found 234.1984 $[M]^+$; $C_{16}H_{26}O$ calcd 234.1979.

***trans*-2-(1-Octynyl)-3-(2-propenyl)-1-oxacyclohexane (*trans*-2i)**: ^1H NMR ($CDCl_3$): δ = 0.88 (t, J = 6.9 Hz, 3H), 1.08–1.45 (m, 7H), 1.45–1.70 (m, 5H), 1.84–1.98 (m, 2H), 2.24 (m, 2H), 2.40–2.49 (m, 1H), 3.39 (m, 1H), 3.80 (dt, J = 9.0, 2.7 Hz, 1H), 3.98 (dt, J = 11.1, 2.7 Hz, 1H), 5.03 (d, J = 8.7 Hz, 1H), 5.05 (d, J = 17.4 Hz, 1H), 5.79 ppm (ddt, J = 17.4, 8.7, 1.8 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 13.89, 18.62, 22.41, 25.29, 27.93, 28.46, 28.49, 31.21, 36.71, 41.07, 67.64, 72.65, 78.42, 86.61, 116.57, 135.97 ppm; IR (neat): $\tilde{\nu}$ = 1084, 1333, 1439, 1641, 2858, 2932, 3076 cm^{-1}; HRMS found 234.1984 $[M]^+$; $C_{16}H_{26}O$ calcd 234.1976.

2,4,4-Trimethyl-1-dodecene (4a): ^1H NMR ($CDCl_3$): δ = 0.85–0.90 (m, 9H), 1.20–1.27 (brs, 14H), 1.76 (s, 3H), 1.93 (m, 2H), 4.62 (brs, 1H), 4.82 ppm (brs, 1H); ^{13}C NMR ($CDCl_3$): δ = 14.4, 23.0, 24.4, 25.7, 27.8, 29.7, 30.0, 30.9, 32.2, 34.0, 43.0, 49.8, 113.9, 144.0 ppm; IR (neat): $\tilde{\nu}$ = 891, 1363, 1467, 1641, 2854, 2927, 2958, 3074, 3398 cm^{-1}; HRMS found 210.2352 $[M]^+$; $C_{15}H_{30}$ calcd 210.2348.

2-Methyl-6-phenyl-1-hexene (4b): ^1H NMR ($CDCl_3$): δ = 1.44–1.55 (m, 2H), 1.58–1.69 (m, 2H), 1.71 (s, 3H), 2.05 (t, J = 7.2 Hz, 2H), 2.64 (t, J = 7.2 Hz, 2H), 4.68 (s, 1H), 4.71 (s, 1H), 7.16–7.21 (m, 3H), 7.26–7.32 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 22.22, 27.13, 30.98, 35.75, 37.55, 109.87, 125.69, 128.32, 128.48, 142.84, 146.03 ppm; IR (neat): $\tilde{\nu}$ = 698, 746, 885, 1030, 1373, 1454, 1497, 1605, 1649, 2345, 2858, 2934, 3026, 3072 cm^{-1}; elemental analysis calcd (%) for $C_{13}H_{18}$: C 89.59, H 10.41; found C 89.30, H 10.27.

3,4,4-Trimethyl-1-dodecene (5a): ^1H NMR ($CDCl_3$): δ = 0.79 (brs, 9H), 0.90 (t, J = 6.6 Hz, 3H), 1.12–1.37 (brs, 14H), 1.97 (m, 1H), 4.90–5.15 (m, 2H), 5.77 ppm (ddd, J = 18.6, 9.0, 8.7 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 14.4, 15.1, 22.9, 23.0, 23.9, 24.6, 24.9, 29.7, 30.0, 31.0, 32.2, 40.9, 46.4, 113.8, 142.1 ppm; IR (neat): $\tilde{\nu}$ = 721, 887, 910, 997, 1365, 1467, 1637, 2854, 2925, 2958, 3074 cm^{-1}; HRMS found 210.2342 $[M]^+$; $C_{15}H_{30}$ calcd 210.2348.

3-Methyl-6-phenyl-1-hexene (5b): ^1H NMR ($CDCl_3$): δ = 0.98 (d, J = 6.6 Hz, 3H), 1.30–1.37 (m, 2H), 1.55–1.67 (m, 2H), 2.09–2.19 (m, 1H), 2.59 (t, J = 7.8 Hz, 2H), 4.88–4.98 (m, 2H), 5.68 (ddd, J = 17.6, 9.9, 7.5 Hz, 1H), 7.15–7.22 (m, 3H), 7.24–7.32 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 20.09, 29.06, 35.97, 36.20, 37.62, 112.54, 125.68, 128.32, 128.48, 142.88, 144.81 ppm; IR (neat): $\tilde{\nu}$ = 698, 746, 910, 995, 1373, 1419, 1454, 1497, 1605, 1639, 2858, 2932, 3028, 3065 cm^{-1}; elemental analysis calcd (%) for $C_{13}H_{18}$: C 89.59, H 10.41; found: C 89.66, H 10.57.

1-(4-Fluorophenyl)-2-methylbutane (7f): ^1H NMR ($CDCl_3$): δ = 0.83 (d, J = 6.6 Hz, 3H), 0.9 (t, J = 9.2 Hz, 3H), 1.04–1.41 (m, 2H), 1.62 (m, 1H), 2.35 (dd, J = 13.5, 8.1 Hz, 1H), 2.60 (dd, J = 13.5, 6.3 Hz, 1H), 6.90–6.99 (m, 2H), 7.04–7.13 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 11.8, 19.1, 29.3, 37.0, 42.7, 114.7, 114.9, 130.4, 130.5, 137.2, 137.3 ppm; IR (neat): $\tilde{\nu}$ = 837, 1157, 1222, 1379, 1461, 1510, 1600, 2856, 2875, 2925, 2962 cm^{-1}; HRMS found 166.1159 $[M]^+$; $C_{11}H_{15}F$ calcd 166.1158.

4-(3-Butenyl)-4,5-dihydro-2(3*H*)-furanone (10a): ^1H NMR ($CDCl_3$): δ = 1.56–1.63 (m, 2H), 2.06–2.25 (m, 3H), 2.53–2.68 (m, 2H), 3.94 (dd, J = 9.0, 7.5 Hz, 1H), 4.43 (dd, J = 9.0, 7.8 Hz, 1H), 5.00–5.09 (m, 2H), 5.78 ppm (ddt, J = 19.8, 7.2, 6.6 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 31.31, 32.02, 34.24, 34.96, 73.12, 115.65, 137.18, 177.14 ppm; IR (neat): $\tilde{\nu}$ = 839, 814, 1001, 1173, 1379, 1420, 1641, 1778, 2856, 2924, 3078 cm^{-1}; elemental analysis calcd (%) for $C_8H_{12}O_2$: C 68.54, H 8.63; found: C 68.45, H 8.45.

4-(3-Butenyl)-5,5-dimethyl-4,5-dihydro-2(3*H*)-furanone (10b): ^1H NMR ($CDCl_3$): δ = 1.25 (s, 3H), 1.43 (s, 3H), 1.38–1.46 (m, 1H), 1.51–1.65 (m, 1H), 1.95–2.32 (m, 4H), 2.59–2.69 (m, 1H), 4.98–5.10 (m, 2H), 5.77 ppm (ddt, J = 16.8, 10.5, 6.9 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 21.79, 27.35, 28.77, 32.26, 34.49, 45.08, 86.64, 115.70, 137.39, 175.67 ppm; IR (neat): $\tilde{\nu}$ = 918, 959, 1096, 1128, 1217, 1258, 1375, 1389, 1641, 1771, 2934, 2978 cm^{-1}; elemental analysis calcd (%) for $C_{10}H_{16}O_2$: C 71.39, H 9.59; found: C 71.36, H 9.78.

4-(1,1-Dimethyl-3-butenyl)-4,5-dihydro-2(3*H*)-furanone (10c): ^1H NMR ($CDCl_3$): δ = 0.90 (s, 3H), 0.91 (s, 3H), 1.98 (d, J = 7.5 Hz, 2H), 2.31–2.58 (m, 3H), 4.11 (dd, J = 9.0, 8.1 Hz, 1H), 4.32 (dd, J = 9.6, 8.1 Hz, 1H), 5.03–5.12 (m, 1H), 5.72–5.86 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 23.38, 23.67, 29.63, 34.22, 44.00, 45.29, 69.37, 118.32, 133.87, 177.37 ppm; IR (neat): $\tilde{\nu}$ = 918, 1003, 1026, 1175, 1470, 1639, 1780, 2964, 3076 cm^{-1}; elemental analysis calcd (%) for $C_{10}H_{16}O_2$: C 71.39, H 9.59; found: C 71.11, H 9.74.

***trans*-4-(3-Butenyl)-5-pentyl-4,5-dihydro-2(3*H*)-furanone (10d)**: ^1H NMR ($CDCl_3$): δ = 0.89 (t, J = 6.3 Hz, 3H), 1.24–1.72 (m, 10H), 1.98–2.25 (m, 4H), 2.71 (m, 1H), 4.10 (ddd, J = 7.8, 7.2, 4.2 Hz, 1H), 4.99–5.07 (m, 2H), 5.77 ppm (dddd, J = 16.8, 10.5, 6.9, 6.6 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 14.2, 22.7, 25.6, 31.8, 31.9, 32.4, 34.8, 35.4, 40.8, 86.0, 115.7, 137.2, 176.4 ppm; IR (neat): $\tilde{\nu}$ = 912, 945, 995, 1172, 1261, 1421, 1454, 1641, 1778, 2860, 2931 cm^{-1}; HRMS found 210.1619 $[M]^+$; $C_{13}H_{22}O_2$ calcd 210.1620.

4-(1-Methyl-1,6-heptadienyl)-4,5-dihydro-2(3*H*)-furanone (10e, *E* isomer): ^{1}H NMR ($CDCl_3$): δ = 1.45 (tt, J = 7.2, 7.2 Hz, 2H), 1.63 (s, 3H), 2.00–2.09 (m, 4H), 2.46 (dd, J = 17.7, 8.7 Hz, 1H), 2.60 (dd, J = 17.7, 8.7 Hz, 1H), 3.18 (tt, J = 8.1, 8.1 Hz, 1H), 4.08 (dd, J = 8.7, 7.5 Hz, 1H), 4.41 (dd, J = 8.7, 7.5 Hz, 1H), 4.94–5.05 (m, 2H), 5.28 (t, J = 7.2 Hz, 1H), 5.80 ppm (ddt, J = 17.1, 10.2, 6.9 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 13.50, 27.09, 28.52, 32.80, 33.19, 43.81, 71.77, 114.74, 127.20, 132.02, 138.61, 177.04 ppm; IR (neat): $\tilde{\nu}$ = 847, 910, 1013, 1171, 1439, 1639, 1782, 2341, 2361, 2858, 2926 cm^{-1}; elemental analysis calcd (%) for $C_{12}H_{18}O_2$: C 74.19, H 9.34; found: C 73.93, H 9.57. The stereochemistry was assigned by NOE.

1-(2-Pentylcyclopropyl)-4-penten-2-one (14a): ^{1}H NMR ($CDCl_3$): δ = 0.25 (ddd, J = 5.1, 5.1, 8.1 Hz, 1H), 0.32 (ddd, J = 5.1, 5.1, 8.1 Hz, 1H), 0.44–0.54 (m, 1H), 0.66–0.76 (m, 1H), 0.87 (t, J = 6.9 Hz, 3H), 1.16–1.43 (m, 8H), 2.27 (dd, J = 7.2, 22.2 Hz, 1H), 2.35 (dd, J = 7.2, 15.9 Hz, 1H), 3.21 (d, J = 6.9 Hz, 2H), 5.09–5.20 (m, 2H), 5.29 ppm (ddt, J = 10.2, 17.1, 6.9 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 11.90, 13.76, 14.19, 18.92, 22.74, 29.16, 31.77, 33.96, 47.26, 47.35, 118.58, 130.58, 198.51 ppm; IR (neat): $\tilde{\nu}$ = 3065, 2957, 2924, 2855, 1717, 1638, 1458, 1398, 1325, 1028, 993, 918 cm^{-1}; elemental analysis calcd (%) for $C_{13}H_{22}O$: C 80.35, H 11.41; found: C 80.43, H 11.63. The *trans* stereochemistry of the cyclopropanes **14** was deduced by coupling constants according to the literature.[33]

3,3-Dimethyl-1-(2-pentylcyclopropyl)-4-penten-2-one (14b): ^{1}H NMR ($CDCl_3$): δ = 0.16 (ddd, J = 4.2, 4.2, 8.4 Hz, 1H), 0.26 (ddd, J = 4.8, 4.8, 8.4 Hz, 1H), 0.34–0.45 (m, 1H), 0.66–0.78 (m, 1H), 0.87 (t, J = 7.2 Hz, 3H), 1.20 (s, 6H), 1.16–1.40 (m, 8H), 2.35 (d, J = 6.9 Hz, 2H), 5.08–5.14 (m, 2H), 5.87 ppm (dd, J = 9.9, 16.8 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 11.72, 13.76, 14.20, 18.81, 22.74, 23.45, 23.45, 29.14, 31.77, 34.00, 42.22, 50.59, 114.07, 142.36, 212.52 ppm; IR (neat): $\tilde{\nu}$ = 2961, 2926, 2855, 1713, 1636, 1468, 1379, 1364, 1018, 997, 918 cm^{-1}; elemental analysis calcd (%) for $C_{15}H_{26}O$: C 81.02, H 11.79; found: C 81.18, H 11.54.

3-Methyl-1-(2-pentylcyclopropyl)-4-penten-2-one (**14c**, diastereomer ratio is 1:1): ^{1}H NMR ($CDCl_3$): δ = 0.18–0.24 (m, 1H), 0.26–0.33 (m, 1H), 0.38–0.52 (m, 1H), 0.66–0.76 (m, 1H), 0.87 (t, J = 6.6 Hz, 3H), 1.17 (d, J = 4.5 Hz, 3H), 1.16–1.42 (m, 8H), 2.36 (d, J = 6.9 Hz, 2H), 3.25 (dq, J = 6.9, 6.9 Hz, 1H), 5.11–5.17 (m, 2H), 5.79 ppm (ddd, J = 5.1, 9.9, 17.1 Hz, 1H); ^{13}C NMR ($CDCl_3$) for mixture of diastereomers: δ = (11.76, 11.91, assigned to each diastereomer), 13.62, 14.19, 15.83, (18.77, 18.94, assigned to each diastereomer), 22.74, 29.15, 31.77, 33.99, 45.66, 50.85, 116.63, 137.42, 211.01 ppm; IR (neat): $\tilde{\nu}$ = 3063, 2959, 2926, 2855, 1715, 1636, 1458, 1371, 995, 918 cm^{-1}; elemental analysis calcd (%) for $C_{14}H_{24}O$: C 80.71, H 11.61; found: C 80.56, H 11.84.

4-(4-Methoxyphenyl)-4,5,5-trimethyl-1-hexanol (17): ^{1}H NMR ($CDCl_3$): δ = 0.83 (s, 9H), 1.10–1.50 (m, 3H), 1.29 (s, 3H), 1.59 (dt, J = 5.1, 12.6 Hz, 1H), 2.17 (dt, J = 3.0, 12.6 Hz, 1H), 3.61 (t, J = 6.6 Hz, 2H), 3.80 (s, 3H), 6.81 (d, J = 9.0 Hz, 2H), 7.18 ppm (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 21.00, 26.12, 28.37, 30.51, 36.67, 45.29, 55.06, 63.89, 112.35, 129.93, 136.66, 157.32 ppm; IR (neat): $\tilde{\nu}$ = 829, 1040, 1188, 1252, 1292, 1375, 1466, 1514, 1611, 2876, 2955, 3342 cm^{-1}; HRMS found 250.1934 $[M]^+$; $C_{16}H_{26}O_2$ calcd 250.1939.

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