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Reactions and Mechanistic Studies of Rhenium-Catalyzed Insertion of α,β-Unsaturated Carbonyl Compounds into a C–H Bond

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A rhenium complex, $[ReBr(CO)_3(thf)]_2$, catalyzes the insertion of α,β-unsaturated carbonyl compounds into a C–H bond of aromatic compounds having nitrogen-containing directing groups. In this reaction, $Re_2(CO)_{10}$ can also be used as a catalyst. When imines are employed as the aromatic substrates, sequential cyclization proceeds and indene derivatives are obtained in good to excellent yields. This reactivity is in contrast to those of ruthenium and rhodium complexes, which are usually used as catalysts in the insertion reactions of unsaturated molecules into a C–H bond. Investigations on the reaction mechanism indicate that the rhenium catalyst promotes C–H bond activation of aromatic compounds, the insertion of α,β-unsaturated carbonyl compounds into a Re–C bond, and intramolecular nucleophilic cyclization followed by reductive elimination and the elimination of an amine.

Transformations via the insertion of unsaturated molecules into an inactivated C–H bond are efficient and useful methods to synthesize more complex molecules.[1] Previously, ruthenium and rhodium complexes have usually been employed as catalysts in such transformations.[1] These reactions proceed via C–H bond activation, insertion of unsaturated molecules into the metal–hydrogen bond, and reductive elimination.[2–4] We have recently reported on rhenium-catalyzed C–H bond activation followed by the insertion of unsaturated molecules, such as acetylenes,[5,6] isocyanates,[6] aldehydes,[7] and acrylates.[8] However, the reaction style is quite different from that with ruthenium and rhodium catalysts. Although only the insertion of unsaturated molecules into a C–H bond proceeds in the case of the ruthenium- and rhodium-catalyzed transformations, the rhenium catalyst can promote both the insertion of unsaturated molecules and intramolecular nucleophilic cyclization.[9] Thus, we have been interested in the reaction mechanism of the rhenium-catalyzed transformations. Here, we focus on the reactions of aromatic compounds having a directing group with acrylates. When aromatic ketimines were used as the aromatic compounds, indene derivatives were synthesized in one operation.[8]

Results and Discussion

In the first half of the paper, we discuss the rhenium-catalyzed insertion of α,β-unsaturated carbonyl compounds into an aromatic C–H bond of 2-phenylpyridine. Several mechanistic studies using H/D scrambling between an aromatic compound and an acrylate are also described. In the second half of the paper, we employ aromatic ketimines as the substrate, and the reaction and its mechanistic studies are discussed. We show that when an imine moiety is used as the directing group, intramolecular cyclization occurs after insertion of α,β-unsaturated carbonyl compounds.

Insertion of Ethyl Acrylate into an Aromatic C–H Bond at the Ortho Position of a Directing Group. Survey of Catalysts: Using the reaction between 2-phenylpyridine (**1a**) with ethyl acrylate (**2a**) as a probe, the catalytic activity of several transition-metal complexes was surveyed. Treatment of **1a** with acrylate **2a** in the presence of a catalytic amount of a rhenium complex, $Re_2(CO)_{10}$, at 150 °C for 24 h, gave mono-adduct **3a** and di-adduct **4a** in 61% and 39% yields, respectively (Table 1, Entry 1). Rhenium complexes, $[Re(CO)_4(PPh_3)]_2$ (**3a**, 88%; **4a**, 8%, Entry 2), $ReBr(CO)_5$ (**3a**, 86%; **4a**, 12%, Entry 3), and $[ReBr(CO)_3(thf)]_2$ (**3a**, 81%; **4a**, 19%, Entry 4), also showed high catalytic activities. In contrast, $ReCp^*(CO)_3$ and $ReMeO_3$ were ineffective (Entries 5 and 6). Although manganese complexes, $Mn_2(CO)_{10}$ and $MnBr(CO)_5$, have catalytic activities, the yields of **3a** and **4a** were low (Entries 7 and 8). No reaction was observed with ruthenium complexes, $Ru_3(CO)_{12}$ and $RuH_2(CO)(PPh_3)_3$, which are usually employed as catalysts to promote the insertion of unsaturated molecules into a C–H bond under the same reaction conditions (Entries 9 and 10). In contrast, by using a rhodium complex, $RhCl(PPh_3)_3$, insertion of **2a** into a C–H bond of **1a** proceeded and mono-alkylated product **3a** was formed in 18% yield (Entry 11).[10]

Survey of Directing Groups: A nitrogen atom of sp^2 hybridization proved to be effective as the direction group for the

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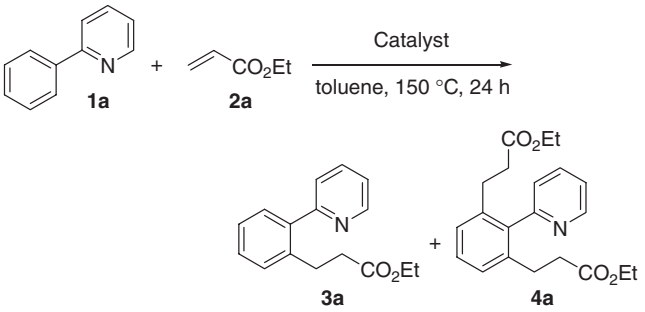
Table 1. Investigation of Catalysts[a)]



Entry	Catalyst (mol %)	Yield/%[b)]		
		3a + **4a**	**3a**	**4a**
1	$Re_2(CO)_{10}$ (3.0)	100	61	39
2	$[Re(CO)_4(PPh_3)]_2$ (3.0)	96	88	8
3	$ReBr(CO)_5$ (6.0)	98	86	12
4	$[ReBr(CO)_3(thf)]_2$ (3.0)	100[c)]	81	19
5	$ReCp^*(CO)_3$ (6.0)	0	0	0
6	$ReMeO_3$ (6.0)	0	0	0
7	$Mn_2(CO)_{10}$ (3.0)	23	23	<1
8	$MnBr(CO)_5$ (6.0)	6	6	0
9	$Ru_3(CO)_{12}$ (2.0)	0	0	0
10	$RuH_2(CO)(PPh_3)_3$ (6.0)	0	0	0
11	$RhCl(PPh_3)_3$ (6.0)	18	18	0

a) **1** (1.0 equiv); **2a** (1.5 equiv). b) The yield was determined by ^{1}H NMR. c) Isolated yield.

rhenium-catalyzed C–H activation. However, neither *N*,*N*-dimethylbenzylamine nor 2,5-diphenylfuran gave the desired adduct upon treatment with acrylate **2a** in the presence of a catalytic amount of $ReBr(CO)_5$. In contrast, a pyridyl group was a good directing group for the transformation; for example, 2-phenylpyridine gave a mixture of mono- and di-adducts **3a** and **4a** in quantitative yield (Table 2, Entry 1). 2-*o*-Tolylpyridine (**1b**) afforded the corresponding adduct **3b** in 34% yield (Entry 2); however, a rhenium complex, $Re_2(CO)_{10}$, showed higher reactivity, and gave **3b** quantitatively (Entry 3). By using 3-methyl-2-phenylpyridine (**1c**), only mono-adduct **3c** was formed in 77% yield selectively (Entry 4).[11] In the case of 2-naphthalen-2-ylpyridine (**1d**), mono- and di-adducts **3d** and **4d** were obtained in 53% and 14% yields, respectively, and the 3-position was functionalized regioselectively (1-adduct:3-adduct = 9:91) (Entry 5). The regioselectivity deserves further comment; if the reaction proceeded via the Friedel–Crafts type electrophilic addition, the main product should be 1-adduct, so the result also supports a C–H activation pathway (vide infra). The effectiveness of oxazolinyl groups depends on the substituent. For example, di-adduct **4f** was formed quantitatively with **1f** having a 4,4-dimethyloxazolinyl group (Entry 7); however, a reaction of **1e** having a simple oxazoline with **2a** gave a complex mixture (Entry 6). When an effective oxazolinyl group was placed at the 1-position of naphthalene, the reaction proceeded only at the ortho position of the directing group (Entry 8).

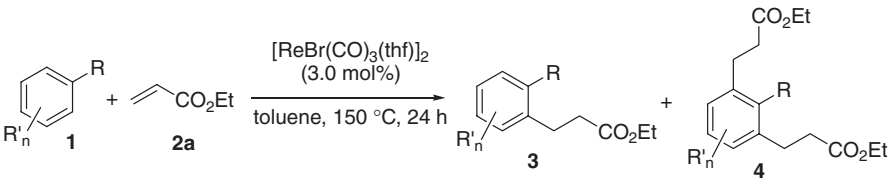
Mechanistic Studies of Rhenium-Catalyzed Insertion of Acrylates into a C–H Bond of 2-Phenylpyridine. Possible routes for metal-catalyzed coupling reactions of 2-phenylpyridine **i** with acrylates at the ortho position of **i** are shown in Scheme 1. In the case of a rhenium catalyst (Mtl = Re), two main routes can be considered for the reaction: 1) C–H bond activation is accelerated by the coordination of a nitrogen atom of **i** to the rhenium center (step **[1]**), and insertion of an acrylate occurs, and 2) Friedel–Crafts-type electrophilic addition (steps **[15]** and **[16]**).

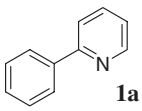
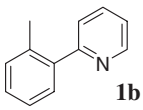
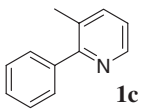
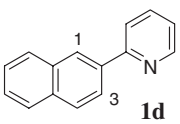
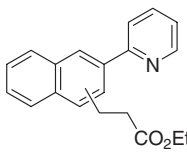
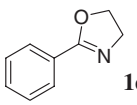
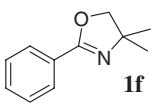
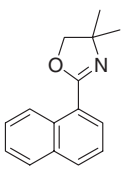
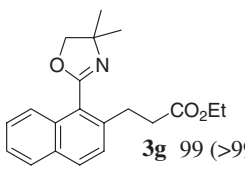
Although the rhenium complex shows Lewis acidity in some cases,[12] the insertion of acrylates into a C–H bond of 2-phenylpyridine should not proceed via the latter electrophilic addition pathway (steps **[15]** and **[16]**) from the following observations. (1) The insertion of acrylates took place similarly even in the presence of stoichiometric amounts of tributylamine, which is a Lewis base. (2) If the reaction proceeds via electrophilic addition, the reaction should also proceed at meta and para positions. However, we observed only the reaction products at the ortho positions. (3) The corresponding coupling product was not formed from anisol, an electron-rich aromatic compound, and ethyl acrylate under the same reaction conditions. (4) In the case of 2-naphthylpyridine (**1d**), a less reactive C–H bond for electrophilic addition (3-position of the naphthalene ring) was selectively functionalized in the reaction (Table 2, Entry 5).

Once rhenium inserts into a C–H bond at the ortho position, an α,β-unsaturated carbonyl compound can insert into the Re–H bond (step **[3]** or **[7]**) or the Re–C bond (step **[5]** or **[9]**) of an aryl–rhenium intermediate **ii**. Reductive elimination from intermediate **iii** or **iv** gives adduct **vii** via steps **[11]** or **[12]**, respectively. Similarly, intermediates **v** or **vi** could give inserted product **viii**, a regioisomer of **vii**; however, the formation of **viii** was not observed.

We then examined the following H/D scrambling reaction to clarify the difference in the reactivity between the rhenium complex, $[ReBr(CO)_3(thf)]_2$, and a rhodium complex, $RhCl(PPh_3)_3$ (Table 3). The rhenium catalyst promoted the coupling reaction between **1a** and **2b** leading to **3a′** faster than the rhodium catalyst. However, the complete scrambling was only observed in the case of the rhodium catalyst. Therefore, steps **[3]**, **[4]**, **[7]**, and **[8]** proceed faster than the reductive elimination step **[11]** in the case of the rhodium catalyst (Mtl = Rh). Although the formation of **v** was suggested by H/D scrambling of acrylate at the internal olefin moiety, **viii** was not obtained. This indicates that the rate of the reductive elimination step **[13]** is much slower than that of step **[11]**. It has been suggested that the rhodium complex promotes the insertion of unsaturated molecules into a Mtl–H bond of arylmetal intermediate **ii** (Mtl = Rh).[10] Rhodium-catalyzed H/D scrambling supports this suggestion. On the other hand, the rhenium catalyst, $[ReBr(CO)_3(thf)]_2$, did not promote H/D scrambling.[13] This suggests that the rhenium catalyst promotes other pathways; (1) insertion of unsaturated molecules into a Re–C bond of **ii** (step **[5]**) followed by reductive elimination (step **[12]**), and/or (2) insertion of unsaturated molecules into a Re–H bond of **ii** (step **[3]**) and reductive elimination (step **[11]**), which occurs faster than β-elimination (step **[4]**). No H/D scrambling also suggests that the equilibrium between **ii** and **v** (steps **[7]** and **[8]**) should be slow compared to the sequential steps leading to **vii** (**[5]** → **[12]** and/or **[3]** → **[11]**).

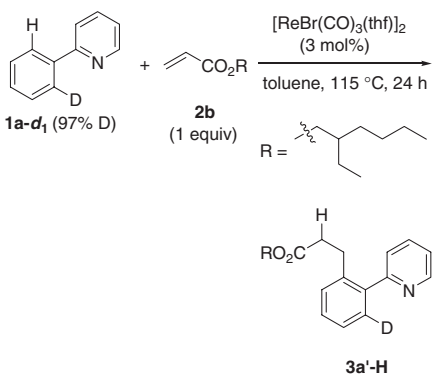
Table 2. Reactions of Aromatic Compounds Having a Directing Group R with Ethyl Acrylate[a)]



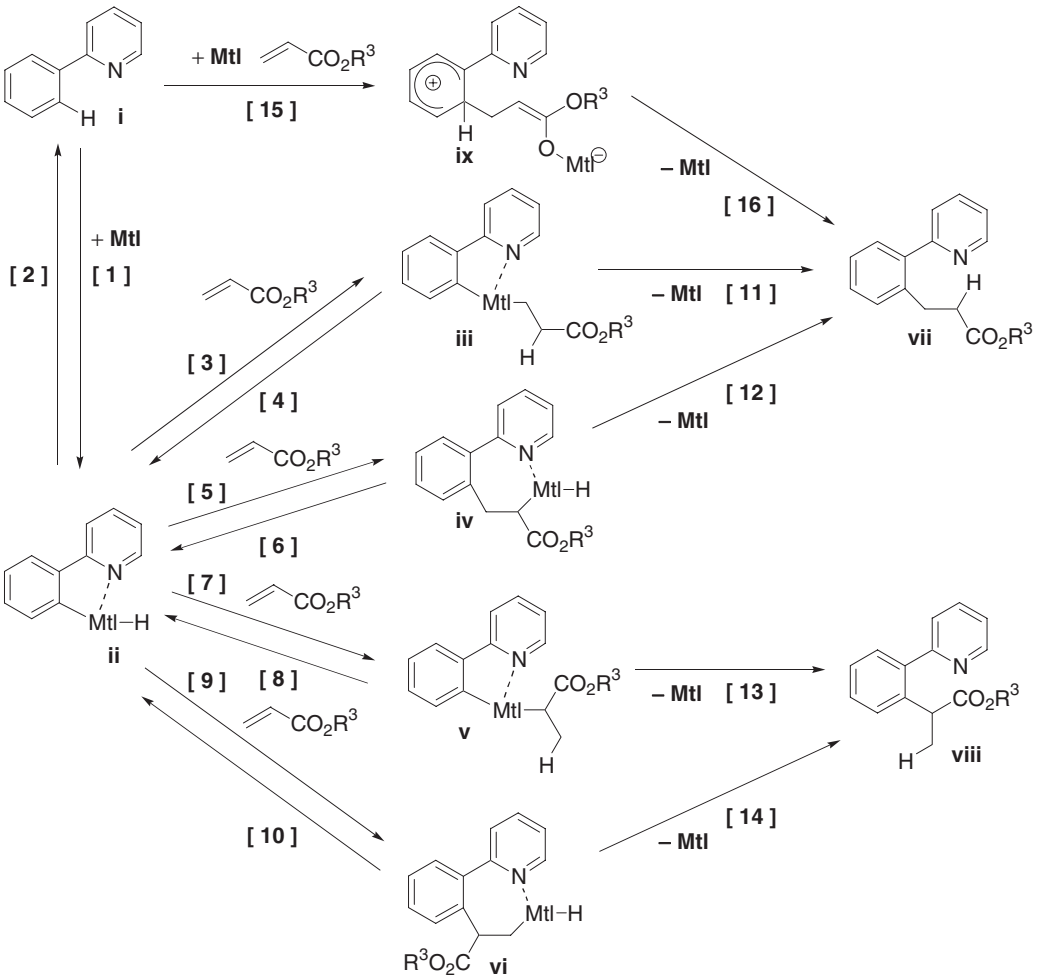
Entry	1	Yield/%[b)]		
		3 + **4**	**3**	**4**
1	 **1a**	100	**3a** 81	**4a** 19
2	 **1b**	34 (35)	**3b** 34 (35)	—
3[c)]		99 (>99)	**3b** 99 (>99)	—
4	 **1c**	77 (83)	**3c** 77 (83)	—
5[d)]	 **1d**	67 (77)	 **3d** 53 (59) [1-adduct:3-adduct = 9:91]	**4d** 14 (18)
6	 **1e**	a complex mixture		
7[e)]	 **1f**	99 (>99)	0 (0)	**4f** 99 (>99)
8	 **1g**	 **3g** 99 (>99)		

a) **1** (1.0 equiv); **2a** (1.5 equiv). b) Isolated yield. The yield determined by ^{1}H NMR is reported in parentheses. c) $Re_2(CO)_{10}$ (3.0 mol %) was used as a catalyst. 180 °C. d) **2a** (1.0 equiv). e) **2a** (3.0 equiv).

Because the H/D scrambling between 2-phenylpyridine **1a**-d_5 and acrylate **2b** was not observed in the case of a rhenium complex, we next examined the difference between C–H and C–D bond insertion reactions. If the C–H activation is a rate-determining step, a kinetic isotope effect (KIE)[14] using a mono-deuterated 2-phenylpyridine **1a**-d_1 should be observed. Treatment of **1a**-d_1 with acrylate **2b** in the presence of a rhenium complex, $[ReBr(CO)_3(thf)]_2$, in toluene at 115 °C for 24 h gave inserted products **3a′**-H and **3a′**-D in 61% yield (**3a′**-H:**3a′**-D = 73:27, KIE = 2.6) (eq 1).[15] This result suggests that C–H bond activation is a rate-determining step of the reaction between 2-phenylpyridine and acrylate.

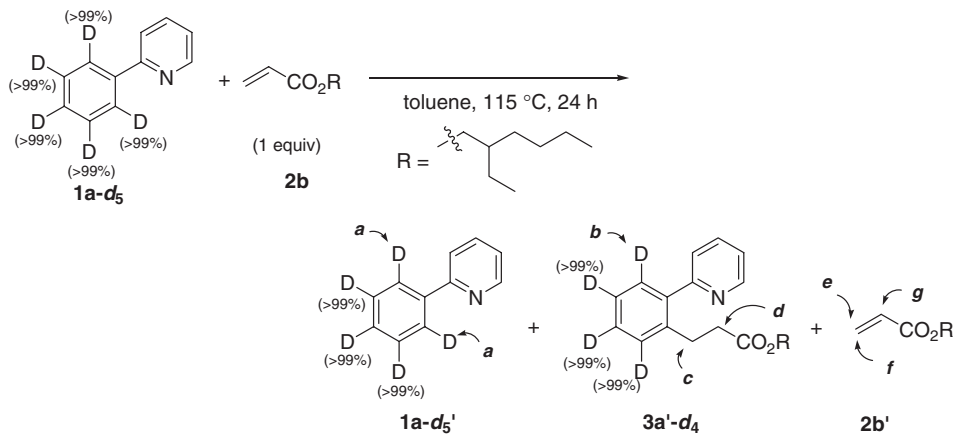


(1)



Scheme 1. Possible routes for the insertion of an acrylate into a C–H bond.

Table 3. H/D Scrambling Experiment Using Rhenium and Rhodium Catalysts

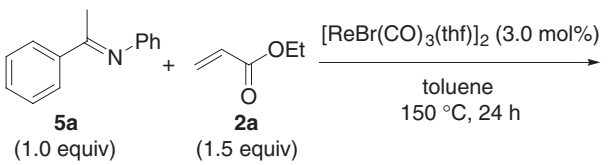


Catalyst	Yield/%		^{1}H NMR integration value						
	1a-d_5	**3a′**-d_4	***a***	***b***	***c***	***d***	***e***	***f***	***g***
$[ReBr(CO)_3(thf)]_2$ (3.0 mol %)	38	62	0.07	0.04	1.99	1.01	0.99	0.99	0.97
$RhCl(PPh_3)_3$ (6.0 mol %)	90	6	0.58	0.54	1.08	1.11	0.57	0.56	0.57

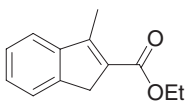
In order to obtain information for the initial arylrhenium intermediate **ii**, we conducted a stoichiometric reaction of 2-phenylpyridine with $[ReBr(CO)_3(thf)]_2$ in toluene-d_8 at 150 °C for 1.5 h, and measured the resulting mixture by ^{1}H NMR. No proton signal connected to the rhenium atom was observed, but the shifted signals of 2-phenylpyridine were seen.[16] This observation suggests that the C–H activation step with the rhenium complex is an uphill process, which is consistent with the KIE experiment. It also suggests that the C–H activation step is the rate-determining step.

Based on the investigations using a reaction between 2-phenylpyridine and acrylate with the rhenium complex (Mtl = Re), we conclude that the coordination of a nitrogen atom of 2-phenylpyridine **i** to the rhenium center, and arylrhenium intermediate **ii** is generated via C–H activation (step **[1]**), and the step is the rate-determining step. However, at this point, we cannot determine if either or both pathways (1) and (2) occur after the C–H activation: (1) the insertion of an α,β-unsaturated compound into the Re–C bond of the arylrhenium intermediate **ii** (step **[5]**) and reductive elimination (step **[12]**); (2) the insertion of an α,β-unsaturated compound into the Re–H bond of the intermediate **iv** (step **[3]**) and reductive elimination (step **[11]**).

Synthesis of Indene Derivatives by the Treatment of Aromatic Imines with α,β-Unsaturated Carbonyl Compounds. By the reaction between aromatic ketimine **5a** and acrylate **2a** in the presence of a rhenium complex, $[ReBr(CO)_3(thf)]_2$, indene derivative **6a** was obtained in 87% yield (eq 2).[17,18] The formation of **6a** with the rhenium catalyst is in sharp contrast to the result with a rhodium complex, $RhCl(PPh_3)_3$, which catalyzes only C–H bond activation and insertion of an acrylate.[10]



5a (1.0 equiv) **2a** (1.5 equiv) (2)



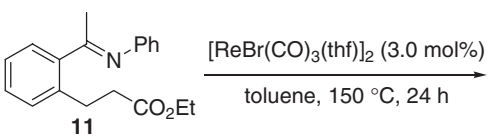
6a 87%

Next, we investigated the substituent on a nitrogen atom of the imine moiety. An aromatic ketimine bearing a benzyl group **5b** gave indene derivative **6a** and aminoindane **7a** in 11% and 62% yields, respectively (Table 4, Entry 1). On the other hand, ketimines having a methoxy group on a nitrogen atom and hydrazones did not afford the indene or aminoindane derivatives.

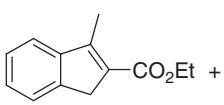
Aromatic ketimines bearing a methoxy or trifluoromethyl group at the para position gave indene derivatives **6b** or **6c** in 75% and 33% yields, respectively (Table 4, Entries 2 and 3). Treatment of naphthylketimine **5e** with ethyl acrylate (**2a**), produced a mixture of **6d** and **6e** in 90% yield (**6d**:**6e** = 80:20, Table 4, Entry 4). By using acrylates **2c** and **2d**, the reaction proceeded and indene derivatives **6f** and **6g** were obtained in 63% and 72% yields, respectively (Table 4, Entries 5 and 6). However, an acrylate having a bulky substituent, *t*-butyl acrylate, did not afford an indene derivative. Vinyl ketone **2e** also produced the corresponding indene derivative **6h** in 44% yield (Table 4, Entry 7). Replacing the ketimine with aromatic aldimine **5f** promoted the reaction in low yield (Table 4, Entry 8). By using a rhenium complex, $Re_2(CO)_{10}$, as a catalyst, aminoindane **7b** was obtained in good yield (Table 4, Entry 9).[19]

Mechanistic Studies of Rhenium-Catalyzed Synthesis of Indene Derivatives. Scheme 2 shows possible routes for the rhenium-catalyzed synthesis of indene derivatives from aromatic ketimines and α,β-unsaturated esters. Two reaction pathways can be considered; carbon–carbon bond formation initiated by C–H bond activation (via step **[1]**) and electrophilic addition (via step **[3]**). Similar to the reaction between 2-phenylpyridine and acrylates, we conclude that the reaction proceeds via the C–H bond activation pathway from the following results: (1) stoichiometric amount of base did not inhibit the reaction, (2) only the ortho position of the aromatic ring was functionalized, and (3) the 3-position of the naphthalene skeleton, a less reactive position for electrophilic addition, was functionalized regioselectively (Table 4, Entry 4).

When ketimines are used instead of 2-phenylpyridine, further intramolecular cyclization leading to indene derivatives occurs, because the imine moiety is a good acceptor for nucleophilic addition, and the Re–C bond is relatively polarized. The cyclization to **ix** should proceed from **vi** (step **[15]**), and so, if insertion of an acrylate into the Re–H bond of **iii** occurs (step **[6]**), indene derivative **xi** should be produced from **vi** via **viii** (step **[14]**) because reductive elimination of **v** generates **viii** (step **[12]**). Thus, we prepared the key intermediate **viii**, which would be formed via the C–H activation followed by the insertion of an acrylate into the Re–H bond (steps **[6]** and **[12]**),[20] and examined the reaction (eq 3). Treatment of **11** with a catalytic amount of $[ReBr(CO)_3(thf)]_2$ under the same reaction conditions gave indene **6a** in only 9% yield and most of **11** remained unchanged. In addition, we did not observe **11** in the reaction mixture between **5a** and ethyl acrylate (**2a**) (eq 2). These results suggest that the main pathway does not go through **viii** (via steps **[6]** and **[12]**), and the pre-cyclization intermediate **vi** should be generated directly by the insertion of an acrylate into the Re–C bond (step **[8]**).



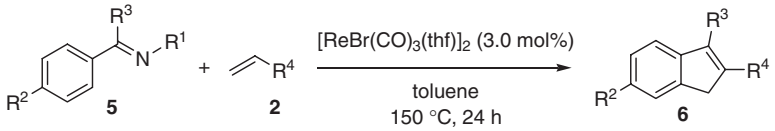
11 (3)

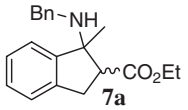
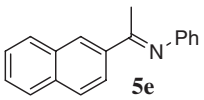
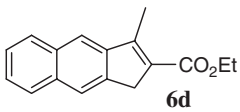
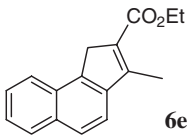
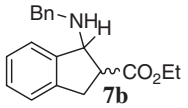


6a 9% 91% recovery

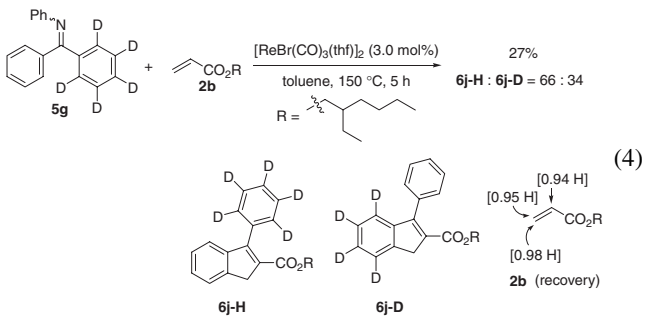
Treatment of deuterated ketimine **5g** with acrylate **2b** in the presence of a rhenium complex, $[ReBr(CO)_3(thf)]_2$, in toluene at 150 °C for 5 h gave a mixture of indene derivatives **6j**-H and **6j**-D in 27% yield (**6j**-H:**6j**-D = 66:34, KIE = 2.0) (eq 4).[15] This is in accordance with the result obtained by the KIE experiment shown in eq 1. The C–H activation step is also the rate-determining step in the formation of indene derivatives.

Table 4. Rhenium-Catalyzed Synthesis of Indene Derivatives from Aromatic Ketimines and α,β-Unsaturated Carbonyl Compounds[a)]



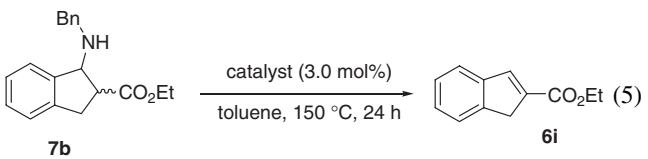
Entry	Ketimine	Olefin	Product	Yield/%[b)]
1	**5b** (R^1 = Bn; R^2 = H; R^3 = Me)	**2a** (R^4 = CO_2Et)	**6a**	11 (15)
			 **7a**	62 (75)
2	**5c** (R^1 = Ph; R^2 = OMe; R^3 = Me)	**2a**	**6b** (R^2 = OMe; R^3 = Me; R^4 = CO_2Et)	75 (77)
3	**5d** (R^1 = Ph; R^2 = CF_3; R^3 = Me)	**2a**	**6c** (R^2 = CF_3; R^3 = Me; R^4 = CO_2Et)	33 (47)
4	 **5e**	**2a**	 **6d**  **6e**	90 (91) [**6d**:**6e** = 80:20]
5	**5a** (R^1 = Ph; R^2 = H; R^3 = Me)	**2c** (R^4 = CO_2Me)	**6f** (R^2 = H; R^3 = Me; R^4 = CO_2Me)	63 (72)
6	**5a**	**2d** (R^4 = CO_2Ph)	**6g** (R^2 = H; R^3 = Me; R^4 = CO_2Ph)	72 (76)
7	**5a**	**2e** (R^4 = COEt)	**6h** (R^2 = H; R^3 = Me; R^4 = COEt)	44 (53)
8	**5f** (R^1 = Bn; R^2 = H; R^3 = H)	**2a**	**6i** (R^2 = H; R^3 = H; R^4 = CO_2Et)	8 (21)
9[c)]	**5f**	**2a**	 **7b**	75 (80)[d)]

a) Olefin (1.5 equiv). b) Isolated yield. The yield determined by ^{1}H NMR is reported in parentheses. c) $Re_2(CO)_{10}$ (3.0 mol %) was used as a catalyst. d) Yield of **7b**.



(4)

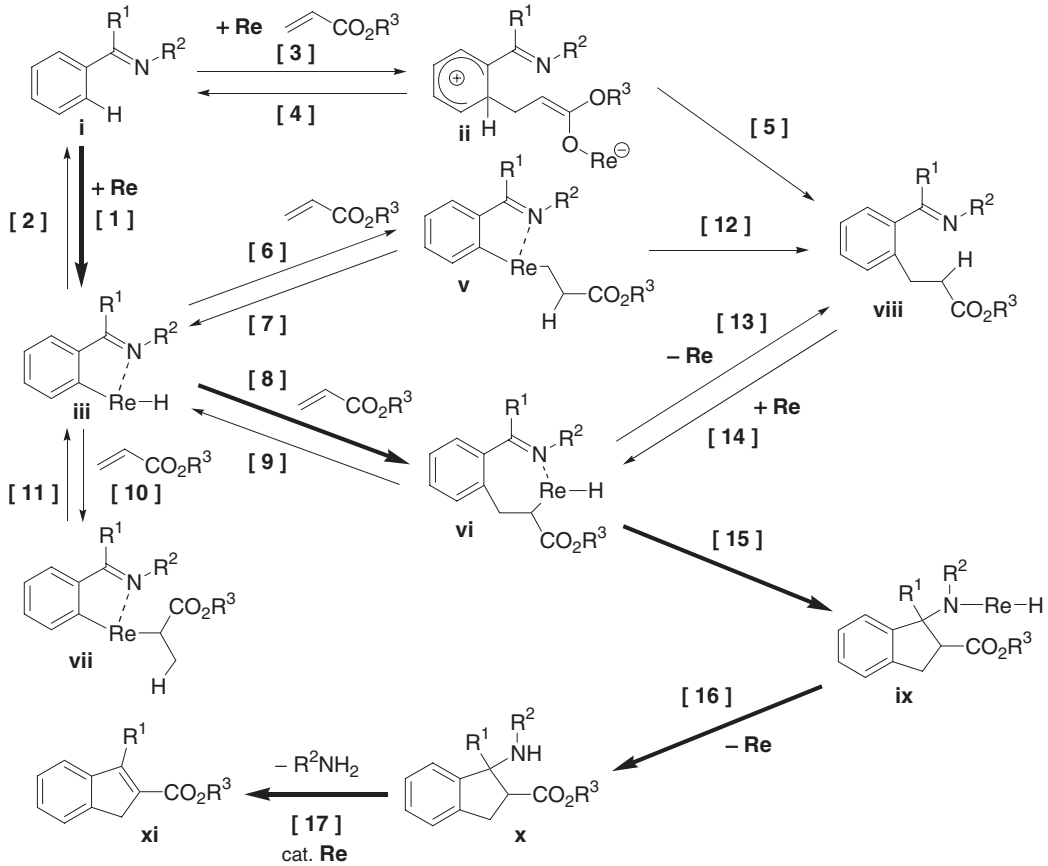
The rhenium catalyst was found to act as a Lewis acid to promote the elimination of amines from **x** (step **[16]**). Treatment of aminoindane derivative **7b** without any catalyst at 150 °C for 24 h resulted in recovery of **7b** (eq 5). In contrast, addition of a catalytic amount of $[ReBr(CO)_3(thf)]_2$ to the reaction mixture gave indene derivative **6i** in 85% yield. Similarly, the elimination of benzylamine also proceeded with a catalytic amount of $FeCl_3$. From these experiments, the rhenium catalyst acts as a Lewis acid to promote the elimination of amine.



(5)

none, 0%; $[ReBr(CO)_3(thf)]_2$, 85%; $FeCl_3$, 84%

Based on our investigations, the mechanism for the formation of indene derivatives is proposed as bold arrows in Scheme 2.[21] C–H bond activation is accelerated by the coordination of a nitrogen atom of the ketimine derivative **i** to the rhenium center, and the arylrhenium intermediate **iii** is generated (step **[1]**). After C–H bond activation, an α,β-unsaturated compound inserts into the Re–C bond of the arylrhenium intermediate **iii** to generate **vi** (step **[8]**). The intramolecular nucleophilic cyclization of a Re–C bond to the imine moiety of **vi** (step **[15]**) followed by reductive elimination (step **[16]**) and the elimination of aniline (step **[17]**) affords the indene derivative **xi**. The elimination of aniline is accelerated by the rhenium catalyst.



Scheme 2. Possible routes for the formation of indene derivatives.

Conclusion

The insertion of α,β-unsaturated carbonyl compounds into a C–H bond of aromatic rings using a rhenium catalyst, $[ReBr(CO)_3(thf)]_2$ or $Re_2(CO)_{10}$, proceeded. The reactions between aromatic imines and α,β-unsaturated carbonyl compounds provided indene derivatives in good to excellent yields. Such cyclization reactions have not occurred with ruthenium or rhodium complexes, which are usually employed as catalysts to promote the insertion of unsaturated molecules into a C–H bond. The difference in the reaction with the rhenium complex derives from the insertion of the unsaturated bond into the Re–C bond[22] instead of the Re–H bond. In addition, the nucleophilic reactivity of the carbon connected to rhenium promotes further cyclization from the insertion intermediate.

Experimental

General. All reactions were carried out in dry toluene under an argon atmosphere. Toluene was purchased from Wako Pure Chemical Industries and was dried and degassed before use. $[ReBr(CO)_3(thf)]_2$ was prepared by heating a THF solution of $ReBr(CO)_5$ at reflux temperature for 16 h.[23] The resulting solution was concentrated in vacuo and recrystallized from THF/hexane to give $[ReBr(CO)_3(thf)]_2$ as a white solid in 75% yield.[24] Ketimines were prepared by condensation of the corresponding ketones with aniline in the presence of molecular sieves (4A) in toluene under reflux conditions for 10 h, and were used after distillation. Ketones, α,β-unsaturated carbonyl compounds, anilines, and bromobenzene-d_5 were purchased from Wako Pure Chemical Industries, Tokyo Kasei Kogyo Co., Nacalai Tesque, and Aldrich Co., and used after distillation.

^{1}H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded using a JEOL JNM-LA400 spectrometer. Proton chemical shifts are reported relative to Me_4Si ($CDCl_3$) at δ 0.00 or residual solvent peak ($CDCl_3$ at δ 7.26). Carbon chemical shifts are reported relative to $CDCl_3$ at δ 77.00. IR spectra were recorded on a Nicolet Protégé 460 spectrometer. HR-MS spectra were measured using a Waters LCT (ESI-TOF MS).

Indene derivatives **6a–6i** are already known. The structures of the reaction products were determined by a comparison of the spectrum data reported previously.[8]

Ethyl 3-[2-(2-Pyridyl)phenyl]propionate (3a). A mixture of **1a** (77.6 mg, 0.500 mmol), **2a** (75.1 mg, 0.750 mmol), and $[ReBr(CO)_3(thf)]_2$ (6.2 mg, 0.0063 mmol) was dissolved in toluene (1.0 mL), and stirred at 150 °C for 24 h in a screw-capped test tube. The crude product was purified by column chromatography on silica gel to give **3a** in 81% yield (103 mg).

^{1}H NMR ($CDCl_3$): δ 1.19 (t, $J = 7.1$ Hz, 3H), 2.53 (t, $J = 7.9$ Hz, 2H), 3.05 (t, $J = 7.9$ Hz, 2H), 4.06 (q, $J = 7.1$ Hz, 2H), 7.23–7.38 (m, 5H), 7.41 (d, $J = 7.8$ Hz, 1H), 7.76 (t, $J = 7.8$ Hz, 1H), 8.66–8.71 (m, 1H); ^{13}C NMR ($CDCl_3$): δ 14.0, 28.4, 35.6, 60.1, 121.7, 123.8, 126.3, 128.4, 129.6, 129.8, 136.3, 138.6, 140.3, 149.0, 159.8, 172.9; IR (nujol, ν/cm^{-1}): 1734, 1585, 1563, 1460, 1424, 1374, 1289, 1182, 1027, 789, 752; Anal. Calcd for $C_{16}H_{17}NO_2$: C, 75.27; H, 6.71; N, 5.49%. Found: C, 75.38; H, 6.80; N, 5.46%.

Ethyl 3-[2-(2-Pyridyl)-3-methylphenyl)propionate (3b). ^{1}H NMR ($CDCl_3$): δ 1.18 (t, $J = 7.2$ Hz, 3H), 2.03 (s, 3H), 2.43 (br, 2H), 2.67 (br, 2H), 4.04 (q, $J = 7.2$ Hz, 2H), 7.13–7.18 (m,

2H), 7.22–7.30 (m, 3H), 7.72–7.73 (m, 1H), 7.78 (td, $J = 7.5$, 1.5 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 14.0, 20.1, 28.6, 35.3, 60.1, 121.8, 124.4, 126.3, 128.0, 135.9, 136.2, 138.2, 140.2, 149.5, 159.1, 172.8; IR (nujol, ν/cm^{-1}): 1734, 1585, 1563, 1460, 1424, 1374, 1289, 1182, 1027, 789, 752; HRMS Calcd for $C_{17}H_{19}NO_2$ [M$^+$]: 269.1415. Found: 269.1409.

Ethyl 3-[2-(3-Methyl-2-pyridyl)phenyl]propionate (3c). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.17 (t, $J = 7.2$ Hz, 3H), 2.12 (s, 3H), 2.43 (t, $J = 8.1$ Hz, 2H), 2.68–2.83 (m, 2H), 4.04 (q, $J = 7.2$ Hz, 2H), 7.16 (d, $J = 7.2$ Hz, 1H), 7.21 (dd, $J = 4.8$, 7.5 Hz, 1H), 7.24–7.34 (m, 3H), 7.60 (d, $J = 7.8$ Hz, 1H), 8.50 (d, $J = 3.9$ Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.1 (1C), 19.2 (1C), 28.3 (1C), 35.1 (1C), 60.2 (1C), 122.3 (1C), 126.3 (1C), 128.2 (1C), 128.9 (1C), 129.2 (1C), 131.5 (1C), 137.9 (1C), 138.2 (1C), 139.9 (1C), 146.6 (1C), 159.1 (1C), 172.9 (1C); IR (nujol, ν/cm^{-1}): 1738 (s), 1566 (m), 1348 (w), 1157 (m), 1119 (m), 1024 (m), 908 (w), 793 (m), 756 (m), 627 (m); HRMS Calcd for $C_{17}H_{19}NO_2$ [M$^+$] 269.1415. Found: 269.1422.

Ethyl 3-[3-(2-Pyridyl)-2-naphthyl)propionate (3d). ^{1}H NMR ($CDCl_3$): δ 1.17 (t, $J = 7.2$ Hz, 3H), 2.55 (t, $J =$ 7.8 Hz, 2H), 3.24 (t, $J = 7.8$ Hz, 2H), 4.07 (q, $J = 7.2$ Hz, 2H), 7.22–7.32 (m, 1H), 7.39–7.57 (m, 3H), 7.70–7.89 (m, 5H), 8.70 (d, $J = 4.8$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 14.1, 28.7, 35.4, 60.2, 121.8, 124.1, 125.7, 126.3, 127.1, 127.7, 128.2, 129.2, 131.9, 133.2, 136.4, 136.5, 149.0, 159.8, 173.0; IR (neat, ν/cm^{-1}): 3057, 2980, 2907, 1728, 1701, 1585, 1558, 1477, 1458, 1436, 1371, 1182, 1039, 889, 785, 750; HRMS Calcd for $C_{20}H_{19}NO_2$ [M$^+$]: 305.3704. Found: 305.3702.

Ethyl 3-[1-(4,4-Dimethyloxazolinyl)-2-naphthyl]propionate (3g). ^{1}H NMR ($CDCl_3$): δ 1.24 (t, $J = 7.2$ Hz, 3H), 1.52 (s, 6H), 2.71 (t, $J = 8.1$ Hz, 2H), 3.16 (t, $J = 8.1$ Hz, 2H), 4.14 (q, $J = 7.2$ Hz, 2H), 4.24 (s, 2H), 7.37 (d, $J = 8.4$ Hz, 1H), 7.41–7.52 (m, 2H), 7.77–7.84 (m, 2H), 7.90 (d, $J = 8.1$ Hz, 1H); HRMS Calcd for $C_{20}H_{23}NO_3$ [M$^+$]: 325.1678. Found: 325.1680.

Ethyl 3-[(3-Ethoxycarbonylethyl)-2-(2-pyridyl)phenyl]propionate (4a). ^{1}H NMR ($CDCl_3$): δ 1.16 (t, $J = 7.1$ Hz, 6H), 2.36–2.44 (m, 4H), 2.60–2.69 (m, 4H), 4.04 (q, $J = 7.1$ Hz, 4H), 7.17 (d, $J = 7.5$ Hz, 2H), 7.27–7.32 (m, 3H), 7.78 (t, $J = 7.5$ Hz, 1H), 8.71 (d, $J = 3.9$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 14.0, 28.6, 35.3, 60.2, 122.1, 124.6, 127.0, 128.4, 136.3, 138.63, 149.62, 158.53, 172.84; HRMS Calcd for $C_{21}H_{25}NO_4$ [M$^+$]: 355.1784. Found: 355.1777.

Ethyl 3-[(3-Ethoxycarbonylethyl)-2-(2-pyridyl)-1-naphthyl]propionate (4d). ^{1}H NMR ($CDCl_3$): δ 1.17 (t, $J = 7.2$ Hz, 6H), 2.44–2.55 (m, 3H), 2.58–2.69 (m, 1H), 2.69–2.84 (m, 2H), 2.95–3.07 (m, 1H), 3.07–3.21 (m, 1H), 4.06 (q, $J = 7.2$ Hz, 4H), 7.30–7.38 (m, 2H), 7.45–7.58 (m, 2H), 7.66 (s, 1H), 7.77–7.87 (m, 2H), 8.03 (d, $J = 7.8$ Hz, 1H), 8.75 (d, $J = 4.5$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 14.1, 25.2, 29.1, 35.0, 35.1, 60.2, 60.3, 122.3, 123.8, 124.7, 126.0, 126.1, 126.3, 128.4, 130.3, 133.6, 134.7, 136.2, 136.4, 138.8, 149.7, 159.1, 172.9, 172.9; IR (neat, ν/cm^{-1}): 2979, 2936, 1732, 1585, 1560, 1477, 1425, 1175, 1041, 889, 748; HRMS Calcd for $C_{25}H_{27}NO_4$ [M$^+$]: 405.4862. Found: 405.4853.

Ethyl 3-[2-(4,4-Dimethyloxazolinyl)-3-ethoxycarbonylethylphenyl]propionate (4f). ^{1}H NMR ($CDCl_3$): δ 1.21 (t, $J = 7.2$ Hz, 6H), 1.44 (s, 6H), 2.62 (t, $J = 7.8$ Hz, 4H), 2.95 (t, $J = 7.8$ Hz, 4H), 4.13 (q, $J = 7.2$ Hz, 4H), 4.14 (s, 2H), 7.09 (d, $J =$ 7.8 Hz, 2H), 7.24 (t, $J = 7.8$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 14.1, 28.1, 29.0, 36.0, 60.2, 68.0, 127.1, 128.6, 129.7, 139.6, 161.4, 172.7; IR (nujol, ν/cm^{-1}): 1734, 1664, 1464, 1374, 1348, 1297, 1184, 1096, 1040, 961, 761; HRMS Calcd for $C_{21}H_{29}NO_5$ [M$^+$]: 375.2046. Found: 375.2049.

Aromatic Ketimine-d_5 (5g). To a mixture of magnesium (0.21 g, 8.40 mmol) and ether (5.0 mL), bromobenzene-d_5 (1.24 g, 7.60 mmol) was added dropwise. After gentle reflux, the reaction mixture was stirred for 20 min and cooled to -78 °C. To this mixture, a solution of benzaldehyde (891 mg, 8.40 mmol) in ether (3.0 mL) was added, and stirred for 10 min. The mixture was allowed to warm to room temperature before being quenched with aqueous NH_4Cl. The mixture was extracted with ether, and the organic layer was dried with Na_2SO_4 to give crude diphenylmethanol-d_5. Then CH_2Cl_2 and MnO_2 (4.80 g, 55.0 mmol) were added, and stirred vigorously for 18 h. The mixture was filtered, washed with CH_2Cl_2, concentrated under reduced pressure, and purified by column chromatography on silica gel to give benzophenone-d_5 in 76% yield (1.08 g). A mixture of benzophenone-d_5 (800 mg, 4.27 mmol), aniline (550 mg, 5.91 mmol), molecular sieves 4A (5.00 g), and toluene (6.0 mL) was heated at reflux for 22 h. The mixture was filtered, washed with toluene, and concentrated to about 3.0 mL under reduced pressure. Then hexane (5.0 mL) was added and cooled to 0 °C. The precipitate was filtered and washed rapidly with hexane to give **5g** as a yellow solid in 42% yield (470 mg).

Ethyl 1-Benzylamino-1-methylindane-2-carboxylate (7a). ^{1}H NMR ($CDCl_3$): δ 1.32 (t, $J = 7.2$ Hz, 3H), 1.60 (s, 3H), 1.60 (br, 1H), 3.04–3.13 (m, 2H), 3.23–3.35 (m, 1H), 3.44–3.58 (m, 2H), 4.20–4.35 (m, 2H), 7.12–7.34 (m, 9H); ^{13}C NMR ($CDCl_3$): δ 14.4, 27.1, 33.4, 47.5, 55.5, 60.5, 67.2, 123.4, 124.8, 126.7, 127.9, 128.0, 128.1, 141.1, 145.7, 172.7; Anal. Calcd for $C_{20}H_{23}NO_2$: C, 77.64; H, 7.49%. Found: C, 77.89; H, 7.65%.

Ethyl 1-Benzylaminoindane-2-carboxylate (7b). ^{1}H NMR ($CDCl_3$): δ 1.30 (t, $J = 7.2$ Hz, 3H), 1.78 (br, 1H), 2.96–3.08 (m, 1H), 3.40–3.52 (m, 2H), 3.78–3.89 (m, 2H), 4.23 (q, $J = 7.2$ Hz, 2H), 4.44 (d, $J = 7.2$ Hz, 1H), 7.18–7.40 (m, 9H); ^{13}C NMR ($CDCl_3$): δ 14.3, 33.2, 49.5, 50.9, 60.5, 63.3, 124.5, 124.9, 126.4, 126.8, 127.9, 128.0, 128.3, 140.3, 141.5, 143.4, 173.0; HRMS Calcd for $C_{19}H_{21}NO_2$ [M$^+$]: 295.1572. Found: 295.1566.

Synthesis of Alkylated Aromatic Ketimine 11. Alkylated aromatic ketimine **11** was prepared by a modified procedure.[10] A mixture of ketimine **5a** (97.6 mg, 0.500 mmol), ethyl acrylate (**2a**, 75.0 mg, 0.750 mmol), and $RhCl(PPh_3)_3$ (23.1 mg, 0.025 mmol) was dissolved in toluene (1.0 mL) and stirred at 150 °C for 24 h. The crude product was purified by column chromatography on silica gel and GPC to give **11** in 50% yield (73.8 mg).

Synthesis of Indene Derivative 6a from Alkylated Aromatic Ketimine 11. A mixture of **11** (73.8 mg, 0.250 mmol) and $[ReBr(CO)_3(thf)]_2$ (6.2 mg, 0.0063 mmol) was dissolved in toluene (0.5 mL), and stirred at 150 °C for 24 h. The crude product was purified by column chromatography on silica gel to give **6a** in 9% yield (4.6 mg).

Synthesis of Aminoindane Derivative 7b. A mixture of aromatic aldimine **5f** (97.6 mg, 0.500 mmol) and $Re_2(CO)_{10}$ (9.8 mg, 0.015 mmol) was dissolved in toluene (1 mL), and stirred at 150 °C for 24 h. The crude product was purified by column chromatography on silica gel to give **7b** in 75% yield (111 mg). ^{1}H NMR ($CDCl_3$): δ 1.30 (t, $J = 7.2$ Hz, 3H), 1.78 (br, 1H), 2.96–3.08 (m, 1H), 3.40–3.52 (m, 2H), 3.78–3.89 (m, 2H), 4.23 (q, $J = 7.2$ Hz, 2H), 4.44 (d, $J = 7.2$ Hz, 1H), 7.18–7.40 (m, 9H); ^{13}C NMR ($CDCl_3$): δ 14.3, 33.2, 49.5, 50.9, 60.5, 63.3, 124.5, 124.9, 126.4, 126.8, 127.9, 128.0, 128.3, 140.3, 141.5, 143.4, 173.0; HRMS Calcd for $C_{19}H_{21}NO_2$ [M$^+$]: 295.1572. Found: 295.1566.

Elimination of Benzylamine from Aminoindane Derivative 7b. A mixture of aminoindane derivative **7b** (29.5 mg, 0.100 mmol) and $[ReBr(CO)_3(thf)]_2$ (2.5 mg, 0.30 μmol) was dissolved in toluene (0.20 mL), and stirred at 150 °C for 24 h. The crude product was purified by column chromatography on silica gel to give **6i** in 85% yield (16.0 mg).

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Supporting Information

^{1}H NMR charts of compounds **1a**-d_5 (Table 3), **3a′**-d_4 (Table 3), **2b′** (Table 3), **1a**-d_1 (eq 1), **3a′**-H + **3a′**-D (eq 1), **2b** (eq 1), **6n′**-D + **6n′**-H (eq 4), and **2b** (eq 4). This material is available free of charge on the Web at: http://www.csj.jp/journals/bcsj/.

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13 A little H/D scrambling at the ortho-positions was observed. A 4% scrambling also occurred by treating 2-phenylpyridine (**1a**-d_5) with a catalytic amount of $[ReBr(CO)_3(thf)]_2$ under the same conditions using toluene or toluene-d_8 as a solvent. The result suggests that the hydrogen came from water in the reaction mixture.

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15 We neglected H/D scrambling between the ortho-positions of an aromatic ring and water, because the values were considered to be small enough.

16 After usual workup with aq HCl, 2-phenylpyridine was recovered in 91%.

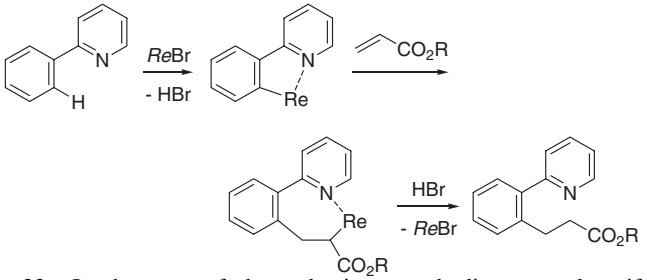
17 We have reported on the rhenium-catalyzed synthesis of indene derivatives via C–H bond activation, in which aromatic imines were prepared in situ. See Ref. 8.

18 A rhenium complex, $Re_2(CO)_{10}$, also produced indene derivative **6a** in 64% yield.

19 Ethyl methacrylate, ethyl *trans*-crotonate, and *t*-butyl acrylate did not afford the indene derivatives. Phenyl vinyl sulfone, *N*,*N*-dimethylacrylamide and acrylonitrile did not give the indene derivatives either, due to the polymerization of these α,β-unsaturated compounds under the reaction conditions.

20 The electrophilic addition path (steps **[3]** and **[5]**) also produces **11**.

21 Although we propose the aryl–Re–H intermediate **ii** in Scheme 1 and **iii** in Scheme 2, there is another possibility that the formation of an aryl–Re species without a hydride ligand. One possibility is as follows: (1) ortho metalation (cyclometalation) via the elimination of HBr; (2) insertion of an acrylate into a rhenium–carbon bond; and (3) protonation by HBr. This mechanism is also consistent with the results obtained by H/D scrambling and KIE experiments, and Ref. 16.



22 In the case of the ruthenium or rhodium complex, if unsaturated compounds insert into a metal–carbon bond, successive β-hydride elimination gives an alkenylated product. See: a) K. Sasaki, T. Sakakura, Y. Tokunaga, K. Wada, M. Tanaka, *Chem. Lett.* **1988**, 685. b) H. Weissman, X. Song, D. Milstein, *J. Am. Chem. Soc.* **2001**, *123*, 337.

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