Cp^{*}RuCl-Catalyzed Formal Intermolecular Cyclotrimerization of Three Unsymmetrical Alkynes through a Boron Temporary Tether. Regioselective Four-Component Coupling Synthesis of Phthalides

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Experimental Section

General Considerations. Column chromatography was performed with silica gel (Cica silica gel 60N) or alumina (Merck aluminium oxide 90 standardized) eluted with mixed solvents [hexane / ethyl acetate]. ¹H and ¹³C NMR spectra were obtained for samples in CDCl₃ solution at 25 °C. ¹H NMR chemical shifts are reported in terms of chemical shift (δ, ppm) relative to the singlet at 7.26 ppm for chloroform. Splitting patterns are designated as follows: s, singlet; d, doublet; t, triplet; q, quartet; quint, quintet; sext, sextet; sept, septet; m, multiplet. Coupling constants are reported in Hz. ¹³C NMR spectra were fully decoupled and are reported in terms of chemical shift (δ, ppm) relative to the triplet at δ = 77.0 ppm for CDCl₃. Elemental analyses were performed by the Instrumental Analysis Facility of Nagoya University. Melting points were obtained in capillary tubes and are uncorrected. 1,2-Dichloroethane and toluene were distilled from CaH₂, and degassed before use. MeOH was distilled from Mg. Cp^{*}RuCl(cod) and alkynylboronates were obtained according to the

literature procedures.^{1,2}

Synthesis of Boraphthalide 5aab from 1-Hexynylborate 2a, Propargyl Alcohol 3a, and Methyl Propargyl Ether 4b. To a solution of Cp*RuCl(cod) (**1**) (9.6 mg, 0.025 mmol), 1-hexynylboronate **2a** (105.1 mg, 0.50 mmol), and methyl propargyl ether **4b** (140.9 mg, 2.0 mmol) in dry degassed 1,2-dichloroethane (1 mL) was added a solution of propargyl alcohol **3a** (31.0 mg, 0.55 mmol) in dry degassed 1,2-dichloroethane (3 mL) over 15 min at room temperature under Ar atmosphere. The solution was stirred at room temperature under Ar atmosphere for 5 h, and then, the solvent was removed under reduced pressure. The residue was diluted with ether (10 mL), and washed with 1 N aq. HCl (3 mL). The aqueous layer was extracted with ether (3 mL × 2), and the combined organic layer was washed with brine (3 mL), dried with MgSO₄, and concentrated in vacuo. The residue was purified by silica gel flash column chromatography (hexane-AcOEt 15:1) to give **6aab** (177.9 mg, 76%) as colorless solids (mp. 85.1-85.7 °C; R_f 0.4, hexane-AcOEt = 2:1): IR (neat) 3351 cm⁻¹; ¹H NMR (300 MHz, CDCl₃): δ 0.93 (t, *J* = 7.5 Hz, 3 H), 1.38 (sext, *J* = 7.5 Hz, 2 H), 1.59-1.69 (m, 2 H), 2.83 (t, *J* = 7.8 Hz, 2 H), 3.42 (s, 3 H), 4.49 (s, 2 H), 4.75 (br s, 1 H), 5.05 (s, 2 H), 7.11 (s, 1 H), 7.13 (s, 1 H); ¹³C NMR (75 MHz, CDCl₃): δ 14.12, 22.61, 34.20, 34.47, 58.33, 70.79, 74.69, 117.29, 126.49, 141.57, 147.99, 154.16; MS (EI): *m/z* (%): 234 (59) [M⁺], 202 (21) [M⁺-HOMe], 190 (49) [M⁺-H-(CH₂)₂CH₃], 177 (53) [M⁺-(CH₂)₃CH₃], 160 (100) [M⁺-OMe-(CH₂)₃CH₃]; EA calcd (%) for C₁₃H₁₉BO₃ (234.10): C 66.70, H 8.18; found: C 66.67, H 8.25.

Crystallographic Structural Determination of 6aab.

A single crystal was mounted on a quartz fiber, and diffraction data were collected at 173 K on a Bruker SMART APEX CCD diffractometer with graphite-monochromated Mo Kα radiation (λ = 0.71073 Å). An absorption correction was made using SADABS. The structure was solved by direct

methods and refined by full-matrix least squares on F^2 by using SHELXTL.³ All non-hydrogen atoms were refined with anisotropic displacement parameters. All hydrogen atoms were placed in calculated positions.

The supplementary crystallographic data for this paper [CCDC 257348] can also be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033; or deposit@ccdc.cam.ac.uk).

Synthesis of Ketone 8 from 1-Hexynylborate 2a, Propargyl Alcohol 3a, 1-Hexyne 4a, and Methyl Vinyl Ketone. To a solution of Cp^{*}RuCl(cod) (**1**) (9.5 mg, 0.025 mmol), 1-hexynylboronate **2a** (105.0 mg, 0.50 mmol), and 1-hexyne **4a** (165.4 mg, 2.0 mmol) in dry degassed 1,2-dichloroethane (1 mL) was added a solution of propargyl alcohol **3a** (30.6 mg, 0.55 mmol) in dry degassed 1,2-dichloroethane (3 mL) over 15 min at room temperature under Ar atmosphere. The solution was stirred at room temperature under Ar atmosphere for 5 h, and then, the solvent was removed under reduced pressure. The reaction mixture was passed through short column (silica gel, 15 × 1 cm, hexane-AcOEt 10:1), and the solvents were evaporated to give crude boraphthalide **6aaa**, which was directly used for the next operation.

To the degassed solution of **6aaa** in a mixed solvent THF/H₂O (10:1 v/v, 3 mL) were added [Rh(OH)(cod)]₂ (3.5 mg, 0.0075 mmol) and MVK (70.7 mg, 1.0 mmol), and the reaction mixture was degassed at -78 °C under reduced pressure. After heating at 50 °C under Ar atmosphere for 2 h, the resultant solution was filtered through a celite pad, extracted with AcOEt (3 mL × 3) and the organic layer was dried with MgSO₄. The solvent was evaporated and the crude product was then treated with acetic anhydride (255.8 mg, 2.5 mmol) and DMAP (12.7 mg, 0.1 mmol) in a mixed solvent CH₂Cl₂/Et₃N (6:1 v/v, 3 mL) at ambient temperature for 2 h. The reaction mixture was washed with H₂O, 1 N aq. HCl, sat. aq. NaHCO₃, and brine (each 3 mL × 2), and the aqueous layer was extracted with CHCl₃ (3 mL). The organic layer was combined, dried with MgSO₄, and

concentrated in vacuo. The residue was purified by silica gel flash column chromatography (hexane-AcOEt 1:0~16:1) to give **8** (106.9 mg, 64%) as pale yellow oil (R_f 0.25, hexane-AcOEt = 3:1): IR (neat) 1737, 1718 cm⁻¹; ¹H NMR (300 MHz, CDCl₃): δ 0.93 (t, *J* = 7.5 Hz, 3 H), 0.95 (t, *J* = 7.2 Hz, 3 H), 1.28-1.46 (m, 4 H), 1.51-1.63 (m, 4 H), 2.08 (s, 3 H), 2.17 (s, 3 H), 1.60-1.70 (m, 2 H), 2.55 (t, *J* = 7.2 Hz, 2 H), 2.55 (t, *J* = 7.8 Hz, 2 H), 2.62-2.68 (m, 2 H), 2.88-2.93 (m, 2 H), 5.08 (s, 2 H), 7.00 (s, 2 H); ¹³C NMR (75 MHz, CDCl₃): δ 14.04, 14.10, 21.18, 22.29, 22.55, 22.96, 29.88, 32.56, 33.62, 33.91, 35.19, 44.84, 65.18, 128.16, 130.08, 133.38, 134.92, 140.77, 141.24, 170.57, 207.43; MS (EI): *m/z* (%): 332 (4) [M⁺], 272 (100) [M⁺-HOAc], 229 (37) [M⁺-HOAc-(CH₂)₂CH₃], 215 (88) [M⁺-HOAc-(CH₂)₃CH₃]; EA calcd (%) for C₂₁H₃₂O₃ (332.48): C 75.86, H 9.70; found: C 76.13, H 9.93.

Synthesis of Phenol Acetate **9** from 1-Hexynylborate **2a**, Propargyl Alcohol **3a**, and 1-Hexyne **4a**.

To a solution of Cp^{*}RuCl(cod) (**1**) (9.8 mg, 0.026 mmol), 1-hexynylboronate **2a** (105.9 mg, 0.50 mmol), and 1-hexyne **4a** (165.2 mg, 2.0 mmol) in dry degassed 1,2-dichloroethane (1 mL) was added a solution of propargyl alcohol **3a** (31.1 mg, 0.55 mmol) in dry degassed 1,2-dichloroethane (3 mL) over 15 min at room temperature under Ar atmosphere. The solution was stirred at room temperature under Ar atmosphere for 5 h, and then, the solvent was removed under reduced pressure. The reaction mixture was passed through short column (silica gel, 7 × 1 cm, hexane-AcOEt 30:1), and the solvents were evaporated to give crude boraphthalide **6aaa**, which was directly used for the next operation.

To a solution of **6aaa** in THF (5 mL) was added a mixture of 1 N aq. NaOH and 30% hydrogen peroxide (2:1 v/v, 1 mL) at ambient temperature, and the reaction mixture was stirred for over 15 min. The resultant solution was extracted with AcOEt (3 mL × 3). The organic layer was washed with brine (3 mL), dried with MgSO₄, and concentrated in vacuo. The crude product was then treated with acetic anhydride (256.1 mg, 2.5 mmol) and DMAP (12.5 mg, 0.1 mmol) in a mixed solvent CH₂Cl₂/Et₃N (6:1 v/v, 3 mL) at ambient temperature for 2 h. The reaction mixture was

washed with H₂O, 1 N aq. HCl, sat. aq. NaHCO₃, and brine (each 3 mL × 2), and the aqueous layer was extracted with CHCl₃ (3 mL). The organic layer was combined, dried with MgSO₄, and concentrated in vacuo. The residue was purified by silica gel flash column chromatography (hexane-AcOEt 30:1) to give **9** (105.1 mg, 65%) as pale yellow oil (R_f 0.35, hexane-AcOEt = 3:1): IR (neat) 1764, 1742 cm⁻¹; ¹H NMR (300 MHz, CDCl₃): δ 0.93 (t, *J* = 7.5 Hz, 3 H), 0.93 (t, *J* = 7.5 Hz, 3 H), 1.35 (sext, *J* = 7.5 Hz, 2 H), 1.37 (sext, *J* = 7.5 Hz, 2 H), 1.50-1.64 (m, 4 H), 2.07 (s, 3 H), 2.32 (s, 3 H), 2.44 (t, *J* = 7.5 Hz, 2 H), 2.57 (t, *J* = 7.8 Hz, 2 H), 5.01 (s, 2 H), 7.04 (d, *J* = 2.0 Hz, 1 H), 7.07 (d, *J* = 2.0 Hz, 1 H); ¹³C NMR (75 MHz, CDCl₃): δ 13.98, 14.04, 20.66, 21.00, 22.53, 22.69, 29.91, 32.03, 33.58, 35.15, 61.98, 127.57, 127.88, 130.30, 134.80, 140.64, 145.28, 169.25, 170.53; MS (EI): *m/z* (%): 320 (21) [M⁺], 278 (46) [M⁺-CH₂=CHCH₃], 218 (100) [M⁺-(CH₂)₂CH₃-OAc], 176 (51) [M⁺-CH₂=CHCH₃-(CH₂)₂CH₃-OAc]; EA calcd (%) for C₁₉H₂₈O₄ (320.42): C 71.22, H 8.81; found: C 71.37, H 8.98.

Representative Procedure for Sequential Cyclotrimerization/Carbonylation: Synthesis of Phthalide 10aaa from 1-Hexynylboronate 2a, Propargyl Alcohol 3a, and 1-Hexyne 4a. To a solution of Cp*RuCl(cod) **1** (9.5 mg, 0.025 mmol), 1-hexynylboronate **2a** (106.2 mg, 0.50 mmol), and 1-hexyne **4a** (165.8 mg, 2.0 mmol) in dry degassed 1,2-dichloroethane (1 mL) was added a solution of propargyl alcohol **3a** (31.1 mg, 0.55 mmol) in dry degassed 1,2-dichloroethane (3 mL) over 15 min at room temperature under Ar atmosphere. The solution was stirred at room temperature under Ar atmosphere for 5 h, and then, the solvent was removed under reduced pressure. The reaction mixture was passed through short column (silica gel, 15 × 1 cm, hexane-AcOEt 10:1), and the solvents were evaporated to give a crude boronate, which was directly used for the next operation.

To the degassed solution of the obtained boronate in dry MeOH (5 mL) were added Pd(OAc)₂ (5.6 mg, 0.025 mmol), PPh₃ (16.0 mg, 0.061 mmol) and *p*-benzoquinone (54.1 mg, 0.50 mmol), and the reaction mixture was stirred at room temperature under CO atmosphere. After stirring for 1 h, the

resultant solution was treated with conc HCl (1 drop) at room temperature for 15 min. To this solution were added K₂CO₃ (1 g), and the solvent was evaporated. The residue was diluted with hexane and filtered through celite. The filtrate was concentrated in vacuo, and the crude material was purified by silica gel flash column chromatography (hexane-AcOEt 10:1) to give phthalide **10aaa** (91.4 mg, 73%) as colorless yellow oil (Rf 0.5, hexane-AcOEt 3:1): IR (neat) 1758, 1613 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25 °C): δ 0.93 (t, *J* = 7.2 Hz, 3 H), 0.94 (t, *J* = 7.2 Hz, 3 H), 1.38 (sept, *J* = 7.2 Hz, 4 H), 1.55-1.68 (m, 4 H), 2.69 (t, *J* = 7.8 Hz, 2 H), 3.05 (t, *J* = 7.8 Hz, 2 H), 5.20 (s, 2 H), 7.07 (s, 1 H), 7.09 (s, 1 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 13.95, 14.01, 22.40, 22.57, 30.69, 33.21, 33.46, 35.99, 68.59, 118.94, 120.32, 130.06, 144.38, 147.63, 149.69, 170.75; MS (EI): *m/z* (%): 246 (81) [M⁺], 231 (27) [M⁺-Me], 217 (100) [M⁺-Et], 204 (53) [M⁺-CH₂=CHMe]; EA calcd (%) for C₁₆H₂₂O₂ (246.34): C 78.01, H 9.00; found: C 78.26, H 9.22.

10aab: oil (Rf 0.45, hexane-AcOEt 2:1); IR (neat) 1748, 1615 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25 °C): δ 0.92 (t, *J* = 7.2 Hz, 3 H), 1.38 (sext, *J* = 7.2 Hz, 2 H), 1.57-1.67 (m, 2 H), 3.07 (t, *J* = 7.2 Hz, 2 H), 3.43 (s, 3 H), 4.52 (s, 2 H), 5.21 (s, 2 H), 7.22 (s, 1 H), 7.25 (s, 1 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 13.99, 22.56, 30.63, 33.14, 58.60, 68.65, 73.93, 117.71, 121.90, 128.39, 144.74, 144.81, 147.56, 170.51; MS (EI): *m/z* (%): 234 (83) [M⁺], 219 (11) [M⁺-Me], 205 (100) [M⁺-Et], 192 (24) [M⁺-CH₂=CHMe]; EA calcd (%) for C₁₄H₁₈O₃ (234.29): C 71.77, H 7.74; found: C 71.60, H 7.91.

10aac: oil (Rf 0.55, hexane-AcOEt 2:1); IR (neat) 1758, 1611 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25 °C): δ 0.94 (t, *J* = 7.2 Hz, 3 H), 1.40 (sext, *J* = 7.2 Hz, 2 H), 1.57-1.68 (m, 2 H), 2.07-2.16 (m, 2 H), 2.88 (t, *J* = 7.5 Hz, 2 H), 3.06 (t, *J* = 7.5 Hz, 2 H), 3.54 (t, *J* = 6.6 Hz, 2 H), 5.21 (s, 2 H), 7.10 (s, 1 H), 7.11 (s, 1 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 13.97, 22.52, 30.60, 32.98, 33.13, 33.68, 43.91, 68.55, 119.18, 120.80, 130.07, 144.67, 147.39, 147.76, 170.52; MS (EI): *m/z* (%): 266 (71) [M⁺], 251 (8) [M⁺-Me], 237 (100) [M⁺-Et], 224 (38) [M⁺-CH₂=CHMe]; EA calcd (%) for C₁₅H₁₉ClO₂ (266.76): C 67.54, H 7.18; found: C 67.45, H 7.28.

10aad: oil (Rf 0.55, hexane-AcOEt 2.5:1); IR (neat) 1747, 1612 cm⁻¹; ¹H NMR (300 MHz,

CDCl₃, 25 °C): δ 0.90 (t, J = 7.2 Hz, 3 H), 1.36 (sext, J = 7.2 Hz, 2 H), 1.95 (quint, J = 7.2 Hz, 2 H), 2.33 (t, J = 7.5 Hz, 2 H), 2.71 (t, J = 7.5 Hz, 2 H), 3.02 (t, J = 6.6 Hz, 2 H), 3.65 (s, 3 H), 5.18 (s, 2 H), 7.07 (s, 2 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 13.95, 22.51, 26.25, 30.60, 33.13, 33.19, 35.29, 51.56, 68.54, 119.03, 120.63, 130.02, 144.53, 147.68, 148.09, 170.56, 173.30; MS (EI): m/z (%): 290 (100) [M⁺], 275 (5) [M⁺-Me], 261 (77) [M⁺-Et], 248 (25) [M⁺-CH₂=CHMe]; EA calcd (%) for C₁₇H₂₂O₄ (290.35): C 70.32, H 7.64; found: C 70.17, H 7.79.

10aac: mp. 60.8-61.2 °C (Rf 0.45, hexane-AcOEt 3:1); IR (neat) 1742, 1605 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25 °C): δ 0.95 (t, J = 7.5 Hz, 3 H), 1.43 (sext, J = 7.5 Hz, 2 H), 1.64-1.74 (m, 2 H), 3.15 (t, J = 7.5 Hz, 2 H), 5.30 (s, 2 H), 7.40-7.52 (m, 5 H), 7.59-7.63 (2 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 14.07, 22.61, 30.88, 33.25, 68.77, 117.80, 121.49, 127.39, 128.35, 128.89, 139.74, 144.99, 146.89, 147.92, 170.63; MS (EI): m/z (%): 266 (76) [M⁺], 251 (9) [M⁺-Me], 237 (100) [M⁺-Et], 224 (65) [M⁺-CH₂=CHMe]; EA calcd (%) for C₁₈H₁₈O₂ (266.33): C 81.17, H 6.81; found: C 81.27, H 6.91.

10aaf: mp. 71.4-71.7 °C (Rf 0.45, hexane-AcOEt 3:1); IR (neat) 1750, 1608 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25 °C): δ 0.96 (t, J = 7.5 Hz, 3 H), 1.43 (sext, J = 7.5 Hz, 2 H), 1.63-1.73 (m, 2 H), 3.09 (t, J = 7.5 Hz, 2 H), 4.06 (s, 5 H), 4.42 (t, J = 2.0 Hz, 2 H), 4.42 (t, J = 2.0 Hz, 2 H), 5.25 (s, 2 H), 7.31 (s, 1 H), 7.36 (s, 2 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 14.10, 22.57, 30.82, 33.21, 67.14, 68.61, 69.86, 67.00, 83.05, 116.03, 120.14, 127.45, 144.26, 146.50, 147.75, 170.72; MS (EI): m/z (%): 374 (100) [M⁺], 331 (8) [M⁺-Pr]; EA calcd (%) for C₂₂H₂₂FeO₂ (374.25): C 70.60, H 5.93; found: C 70.64, H 6.14.

10aag: mp. 49.0-49.6 °C (Rf 0.35, hexane-AcOEt 3:1); IR (neat) 1747, 1600 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25 °C): δ 0.93 (t, J = 7.5 Hz, 3 H), 1.40 (sext, J = 7.5 Hz, 2 H), 1.59-1.69 (m, 2 H), 3.10 (t, J = 7.5 Hz, 2 H), 5.25 (s, 2 H), 7.28 (d, J = 7.5 Hz, 1 H), 7.29 (d, J = 7.5 Hz, 1 H), 7.55 (t, J = 7.5 Hz, 1 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 14.04, 22.57, 30.64, 33.19, 68.77, 119.22, 122.65, 129.56, 133.61, 144.84, 147.08, 170.75; MS (EI): m/z (%): 374 (100) [M⁺], 331 (8) [M⁺-Pr]; EA calcd (%) for C₁₂H₁₄O₂ (190.24): C 75.76, H 7.42; found: C 75.76, H 7.40.

10baa: mp. 34.8-35.1 °C (Rf 0.6, hexane-AcOEt 2:1); IR (neat) 1756, 1612 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3 , 25 °C): δ 0.93 (t, J = 7.5 Hz, 3 H), 1.37 (sext, J = 7.2 Hz, 2 H), 1.58-1.69 (m, 2 H), 2.73 (t, J = 7.8 Hz, 2 H), 3.52 (s, 3 H), 4.96 (s, 2 H), 5.25 (s, 2 H), 7.16 (s, 1 H), 7.45 (s, 1 H); ^{13}C NMR (75 MHz, CDCl_3 , 25 °C): δ 13.98, 22.44, 33.47, 36.18, 58.91, 69.24, 69.30, 119.64, 120.22, 127.41, 139.41, 147.35, 150.35, 170.58; MS (EI): m/z (%): 234 (54) [M^+], 219 (100) [$\text{M}^+ - \text{Me}$], 202 (13) [$\text{M}^+ - \text{HOMe}$], 174 (34) [$\text{M}^+ - \text{HOMe} - \text{CH}_2 = \text{CH}_2$]; EA calcd (%) for $\text{C}_{14}\text{H}_{18}\text{O}_3$ (234.29): C 71.77, H 7.74; found: C 71.78, H 7.83.

10caa: oil (Rf 0.55, hexane-AcOEt 2:1); IR (neat) 1745, 1611 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3 , 25 °C): δ 0.94 (t, J = 7.2 Hz, 3 H), 1.37 (sext, J = 7.2 Hz, 2 H), 1.58-1.68 (m, 2 H), 2.10-2.20 (m, 2 H), 2.70 (t, J = 7.5 Hz, 2 H), 3.19 (t, J = 7.5 Hz, 2 H), 3.56 (t, J = 6.6 Hz, 2 H), 5.22 (s, 2 H), 7.12 (s, 1 H), 7.13 (s, 1 H); ^{13}C NMR (75 MHz, CDCl_3 , 25 °C): δ 13.94, 22.37, 28.35, 32.98, 33.43, 33.40, 35.94, 44.41, 68.77, 119.62, 120.48, 130.47, 141.94, 147.89, 150.04, 170.64; MS (EI): m/z (%): 266 (75) [M^+], 231 (83) [$\text{M}^+ - \text{Cl}$], 217 (100) [$\text{M}^+ - \text{CH}_2\text{Cl}$], 203 (39) [$\text{M}^+ - \text{CH}_2\text{CH}_2\text{Cl}$]; EA calcd (%) for $\text{C}_{15}\text{H}_{19}\text{ClO}_2$ (266.76): C 67.54, H 7.18; found: C 67.67, H 7.23.

10abg: oil (Rf 0.4, hexane-AcOEt 3:1); IR (neat) 1758, 1594 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3 , 25 °C): δ 0.92 (t, J = 7.5 Hz, 3 H), 1.38 (sext, J = 7.5 Hz, 2 H), 1.56-1.66 (m, 2 H), 2.29 (s, 3 H), 3.05 (t, J = 7.8 Hz, 2 H), 5.17 (s, 2 H), 7.19 (d, J = 7.5 Hz, 1 H), 7.32 (d, J = 7.5 Hz, 1 H); ^{13}C NMR (75 MHz, CDCl_3 , 25 °C): δ 14.04, 17.05, 22.53, 30.25, 33.27, 68.22, 122.25, 129.12, 129.74, 134.33, 141.93, 145.84, 171.16; MS (EI): m/z (%): 204 (71) [M^+], 175 (100) [$\text{M}^+ - \text{Et}$], 161 (50) [$\text{M}^+ - \text{Pr}$], 133 (35) [$\text{M}^+ - \text{Pr} - \text{CO}$]; EA calcd (%) for $\text{C}_{13}\text{H}_{16}\text{O}_2$ (204.26): C 76.44, H 7.90; found: C 76.34, H 8.00.

(S)-10aca: oil (Rf 0.5, hexane-AcOEt 8:1); $[\alpha]_D^{23} = -48.3^\circ$ (c = 1.02, CHCl_3); IR (neat) 1754, 1609 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3 , 25 °C): δ 0.88 (t, J = 7.5 Hz, 3 H), 0.93 (t, J = 7.2 Hz, 3 H), 0.94 (t, J = 7.2 Hz, 3 H), 1.26-1.76 (m, 15 H), 1.93-2.04 (m, 1 H), 2.68 (t, J = 7.5 Hz, 2 H), 3.04 (t, J = 7.5 Hz, 1 H), 3.06 (dt, J = 7.5, 4.2 Hz, 1 H), 5.32 (dd, J = 8.1, 3.9 Hz, 1 H), 7.00 (s, 1 H), 7.25 (s, 1 H); ^{13}C NMR (75 MHz, CDCl_3 , 25 °C): δ 14.00, 14.07, 22.47, 22.51, 22.62, 24.64,

30.73, 31.60, 33.21, 33.52, 35.03, 36.08, 80.09, 118.62, 120.70, 129.99, 144.32, 149.51, 151.26, 170.37; MS (EI): m/z (%): 316 (100) [M^+], 287 (47) [M^+ -Et], 274 (23) [M^+ -CH₂=CHMe], 259 (56) [M^+ -Bu], 245 (82) [M^+ -(CH₂)₄Me]; EA calcd (%) for C₂₁H₃₂O₂ (316.48): C 79.70, H 10.19; found: C 79.47, H 10.31.

The optical purity of (*S*)-**10aca** was confirmed by HPLC with DAICEL CHIRALPAC ADH (Hexane:PrOH = 99:1, 0.5 mL/min).

Figure S1. HPLC charts for *rac*-**10aca** (upper) and (*S*)-**10aca** (lower).

19: mp. 104.9-105.4 °C (Rf 0.3, hexane-AcOEt 3:1); IR (neat) 1763 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25 °C): δ 1.81 (quint, J = 3.3 Hz, 4 H), 2.25 (s, 3 H), 2.79 (br s, 2 H), 3.17 (br s, 2 H), 5.13 (s, 2 H), 7.13 (s, 1 H); ¹³C NMR (75 MHz, CDCl₃, 25 °C): δ 16.98, 22.35, 22.70, 24.62, 29.35, 68.10, 122.32, 128.29, 135.55, 135.59, 138.27, 143.74, 171.54; MS (EI): m/z (%): 202 (100) [M^+], 187 (16) [M^+ -Me], 174 (11) [M^+ -CO], 157 (15) [M^+ -H-CO₂]; EA calcd (%) for C₁₃H₁₄O₂ (202.25): C 77.20, H 6.98; found: C 77.22, H 7.18.

22: oil (Rf 0.6, hexane-AcOEt 2:1); IR (neat) 1751, 1590 cm⁻¹; ¹H NMR (300 MHz, CDCl₃, 25

°C): δ 0.92 (t, J = 7.2 Hz, 3 H), 1.38 (sext, J = 7.2 Hz, 2 H), 1.55-1.65 (m, 2 H), 1.82-1.87 (m, 4 H), 2.56-2.62 (m, 2 H), 2.81-2.85 (m, 2 H), 2.99 (t, J = 7.8 Hz, 2 H), 5.09 (s, 2 H), 6.98 (s, 1 H); ^{13}C NMR (75 MHz, CDCl_3 , 25 °C): δ 14.04, 22.38, 22.58, 22.69, 24.86, 29.74, 30.31, 33.33, 67.96, 119.82, 128.43, 130.60, 140.99, 143.43, 146.42, 171.22; MS (EI): m/z (%): 244 (83) [M^+], 215 (100) [$\text{M}^+ - \text{Et}$], 202 (53) [$\text{M}^+ - \text{CH}_2 = \text{CHMe}$], 173 (24) [$\text{M}^+ - \text{Pr} - \text{CO}$]; EA calcd (%) for $\text{C}_{16}\text{H}_{20}\text{O}_2$ (244.33): C 78.65, H 8.25; found: C 78.41, H 8.49.

Synthesis of Cyclic Imidate **23 from 1-Hexynylboronate **2a**, Propargyl Alcohol **3a**, 1-Hexyne **4a**, and $t\text{-BuNC}$.** To a solution of $\text{Cp}^*\text{RuCl}(\text{cod})$ **1** (9.6 mg, 0.025 mmol), 1-hexynylboronate **2a** (105.3 mg, 0.50 mmol), and 1-hexyne **4a** (165.4 mg, 2.0 mmol) in dry degassed 1,2-dichloroethane (1 mL) was added a solution of propargyl alcohol **3a** (31.9 mg, 0.55 mmol) in dry degassed 1,2-dichloroethane (3 mL) over 15 min at room temperature under Ar atmosphere. The solution was stirred at room temperature under Ar atmosphere for 5 h, and then, the solvent was removed under reduced pressure. The reaction mixture was passed through short column (silica gel, 15 $\times$ 1 cm, hexane-AcOEt 10:1), and the solvents were evaporated to give a crude boronate, which was directly used for the next operation.

To the degassed solution of the boronate in dry degassed toluene (5 mL) were added $\text{Pd}(\text{OAc})_2$ (113.1 mg, 0.50 mmol) and $t\text{-BuNC}$ (83.4 mg, 1.0 mmol), and the reaction mixture was stirred at room temperature under Ar atmosphere. After stirring for 24 h, the solvent was evaporated. The residue was diluted with ether and filtered through celite. The filtrate was concentrated in vacuo, and the crude material was purified by alumina column chromatography (hexane-AcOEt 50:1) to give imidate **23** (53.7 mg, 36%) as colorless oil (R_f 0.6, hexane-AcOEt 10:1): IR (neat) 1694 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3 , 25 °C): δ 0.94 (t, J = 7.2 Hz, 3 H), 0.96 (t, J = 7.2 Hz, 3 H), 1.37 (s, 9 H), 1.39 (sext, J = 7.2 Hz, 4 H), 1.55-1.65 (m, 4 H), 2.63 (t, J = 7.5 Hz, 2 H), 3.09 (t, J = 7.8 Hz, 2 H), 5.19 (s, 2 H), 6.94 (s, 1 H), 6.97 (s, 1 H); ^{13}C NMR (75 MHz, CDCl_3 , 25 °C): δ 14.05, 14.19, 22.43, 22.93, 30.38, 31.27, 33.27, 33.75, 35.75, 53.50, 70.91, 118.06, 126.38, 129.77, 142.21, 143.40, 145.38, 155.12; MS (EI): m/z (%): 301 (55) [M^+], 286 (59) [$\text{M}^+ - \text{Me}$], 272 (89) [$\text{M}^+ - \text{Et}$], 244 (11) [$\text{M}^+ - \text{Bu}$], 216 (100) [$\text{M}^+ - \text{Et} - \text{CH}_2 = \text{CMe}_2$]; EA calcd (%) for $\text{C}_{20}\text{H}_{31}\text{NO}$ (301.47):

C 79.68, H 10.36, N 4.65; found: C 79.57, H 10.47, N 4.58.

Computational Methods.

The Q-chem 2.0 program⁴ in Spartan '02 software package⁵ was used for geometry optimizations, and atomic charges for the optimized geometries were obtained with the Gaussian 98 program package.⁶ The geometries of ruthenacycles **I-III** were fully optimized by means of the Becke's three-parameter hybrid density functional method (B3LYP)⁷ with the LACVP* basis set, which uses a double- ζ basis set with the relativistic effective core potential of Hay and Wadt (LanL2 ECP)⁸ for Ru and the 6-31G(d)⁹ basis sets for other elements. Natural charges were computed at the B3LYP/LACVP* level using the natural population analysis method as implemented in Gaussian 98.¹⁰

Typical bond lengths (Å)

	Ru-Cl	Ru-C1	Ru-C4	C1-C2	C2-C3	C3-C4	C2-C5	C5-O	O-C6	C6-C3	O-B	B-C3
I	2.364	1.950	1.954	1.396	1.408	1.397	1.509	1.439	-	-	1.386	1.559
II	2.350	1.963	1.964	1.389	1.398	1.387	1.504	1.444	1.385	1.482	-	-
III	2.366	1.959	-	1.391	1.400	-	1.504	1.437	-	-	-	-

Figure S2. DFT-optimized geometries of model ruthenacycles **I-III** at the B3LYP/LACVP* level (bold numbers indicate natural charges).

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