Enantioselective Construction of α-Quaternary Cyclobutanones by Catalytic Asymmetric Allylic Alkylation**

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**Materials and Methods.** Unless otherwise stated, reactions were performed in flame-dried glassware under an inert atmosphere of argon or nitrogen using dry, deoxygenated solvents. Reaction progress was monitored by thin-layer chromatography (TLC). THF, Et$_2$O, CH$_2$Cl$_2$, toluene, benzene, CH$_3$CN, and dioxane were dried by passage through an activated alumina column under argon. Triethylamine was distilled over CaH$_2$ prior to use. Brine solutions are saturated aqueous solutions of sodium chloride. 1,3-Cyclopentanedione was purchased from AK Scientific, Inc., reagent grade acetone was purchased from Aldrich and distilled from anhydrous Ca$_2$SO$_4$ and stored over molecular sieves (3 Å) under an atmosphere of argon. para-Acetamidobenzensulfonyl azide (p-ABSA) was prepared following a procedure by Davies et al.\textsuperscript{[1]} 2-Phenylprop-2-en-1-ol, 2-(4-methoxyphenyl)prop-2-en-1-ol and 2-(3-fluorophenyl)prop-2-en-1-ol were prepared according to the method by Gouverneur and Brown.\textsuperscript{[2]} 2-Diazocyclopentane-1,3-dione was prepared through diazotization of 1,3-cyclopentanedione with p-ABSA following a procedure by Coquerel and Rodriguez.\textsuperscript{[3]} Phosphinooxazoline (PHOX) ligands were prepared by methods described in our previous work.\textsuperscript{[4]} Tris(4,4'-(methoxydibenzyldieneacetone)dipalladium(0) (Pd$_2$(pmdba)$_3$) was prepared according to the method of Ibers\textsuperscript{[5]} or Fairlamb.\textsuperscript{[6]} All other reagents were purchased from Sigma-Aldrich, Acros Organics, Strem, or Alfa Aesar and used as received unless otherwise stated. Reaction temperatures were controlled with an IKAmag temperature modulator unless otherwise indicated. Stirring was accomplished with Teflon® coated magnetic stir bars. Microwave-assisted reactions were performed in a Biotage Initiator 2.5 microwave reactor. Glove box manipulations were performed under a N$_2$ atmosphere. TLC was performed using E. Merck silica gel 60 F254 precoated glass plates (0.25 mm) and visualized by UV fluorescence quenching, p-anisaldehyde, or KMnO$_4$ staining. Silicycle SiliaFlash P60 Academic Silica gel (particle size 0.040-0.063 mm) was used for flash column chromatography. $^1$H NMR spectra were recorded on a Varian Inova 500 MHz spectrometer and are reported relative to residual CHCl$_3$ (δ 7.26 ppm), C$_6$H$_6$ (δ 7.16 ppm), or CH$_2$Cl$_2$ (δ 5.32 ppm). $^{13}$C NMR spectra were recorded on a Varian Inova 500 MHz (126 MHz) or Varian Mercury 300 MHz (75 MHz) spectrometer and are reported relative to CHCl$_3$ (δ 77.16 ppm) or C$_6$H$_6$ (δ 128.06 ppm). Data for $^1$H NMR are reported as follows: chemical shift (δ ppm) (multiplicity, coupling constant (Hz), integration). Multiplicities are reported as follows: s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, h = heptet, m = multiplet, br s = broad singlet, br d = broad doublet, app = apparent. Data for $^{13}$C are reported in terms of chemical shifts (δ ppm). IR spectra were obtained using a Perkin Elmer Spectrum BXII spectrometer using thin films deposited on NaCl plates and reported in frequency of absorption (cm$^{-1}$). Optical rotations were measured with a Jasco P-2000 polarimeter operating on the sodium D-line (589 nm) using a 100 mm path-length cell and are reported as: [α]$_D$$^m$ (concentration in g/100 mL, solvent, ee). Analytical UHPLC-LCMS was performed with an Agilent 1290 Infinity Series UHPLC/Agilent 6140 Quadrupole LCMS utilizing an Agilent Eclipse Plus C18 RRHD 1.8 µm column (2.1 x 50 mm), part number 959757-902. High-resolution mass spectra (HRMS) were obtained from the Caltech Mass Spectral Facility (EI+ or FAB+) or on an Agilent 6200 Series TOF with an Agilent G1978A Multimode source in electrospray ionization (ESI), atmospheric pressure chemical ionization (APCI), or mixed (MM: ESI-APCI) ionization mode.
Representative Procedure for the Preparation of 2-Oxocyclobutanecarboxylates

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\text{2-Phenylallyl 2-oxocyclobutanecarboxylate. To a 20 mL microwave vial charged with a magnetic stir bar were added 2-diazocyclopentane-1,3-dione (2, 500 mg, 4.03 mmol), toluene (13.5 mL) and 2-phenylprop-2-en-1-ol (SI1, 540 mg, 4.03 mmol). The vial was sealed with a microwave crimp cap and heated to 180 °C for one hour using a Biotage Initiator microwave reactor (sensitivity set to low; reaction mixture heated gradually over first 2 minutes by increasing the temperature in 20 °C increments). After 30 minutes of stirring, the mixture was cooled to ambient temperature and the pressure was released by puncture of the crimp cap with a needle. The reaction vessel was then subsequently irradiated at 180 °C for an additional 30 minutes. The vessel was then cooled to ambient temperature, the vial uncapped and mixture directly loaded onto a silica gel column followed by elution with hexanes to 20% EtOAc in hexanes to afford of SI2 (635 mg, 68% yield) as a colorless oil. \( R_f = 0.2 \) (20% EtOAc in hexanes); \( ^1H \) NMR (300 MHz, CDCl\(_3\)) \( \delta \) 7.44–7.30 (m, 5H), 5.57–5.55 (m, 1H), 5.40–5.39 (m, 1H), 5.06–5.05 (m, 2H), 4.26–4.20 (m, 1H), 3.20–3.15 (m, 2H), 2.48–2.34 (m, 1H), 2.29–2.16 (m, 1H); \( ^{13}C \) NMR (75 MHz, CDCl\(_3\)) \( \delta \) 199.5, 166.5, 142.0, 137.8, 128.5, 128.1, 126.0, 115.4, 66.5, 64.5, 47.1, 13.6; IR (Neat Film, NaCl) 3448, 3084, 3057, 3024, 2970, 1956, 1790, 1732, 1633, 1600, 1574, 1497, 1445, 1387, 1310, 1046, 915, 780 cm\(^{-1}\); HRMS (MM: ESI-APCI) \( m/z \) calc’d for C\(_{14}\)H\(_{15}\)O\(_3\) [M+H]\(^+\): 231.1016; found 231.1018.

With the exception of compound SI2, all 2-carboxyallylcyclobutanone derivatives were directly used in the following steps without rigorous characterization due to their instability.

2-Phenylallyl 1-ethyl-2-oxocyclobutanecarboxylate (4a). To a solution of SI2 (233 mg, 1.01 mmol) in acetone (14 mL) were added K\(_2\)CO\(_3\) (224 mg, 1.62 mmol) and freshly distilled EtI (787 mg, 5.05 mmol). The mixture was heated to reflux until full consumption of the starting material was indicated by TLC analysis (alkylation reaction times typically ranged from 12 to 24 hours). Upon completion, the mixture was cooled to 25 °C, the solids were removed by filtration through filter paper and the mixture was concentrated in vacuo. The crude material was purified by flash column chromatography (SiO\(_2\), hexanes to 10% EtOAc in hexanes to 20% EtOAc in hexanes) to provide 4a (105 mg, 40% yield) as a colorless oil. \( R_f = 0.3 \) (20% EtOAc in hexanes); \( ^1H \) NMR (300 MHz, CDCl\(_3\)) \( \delta \) 7.42–7.28 (m, 5H), 5.55 (s, 1H), 5.38 (s, 1H), 5.06 (dd, \( J = 9.0, 1.0 \) Hz, 2H), 2.56–2.17 (m, 3H), 1.88-1.63 (m, 3H), 0.69 (t, \( J = 7.5 \) Hz, 3H); \( ^{13}C \) NMR (75 MHz, CDCl\(_3\))
δ 209.4, 171.5, 142.2, 137.8, 128.5, 128.1, 126.1, 116.5, 66.5, 63.7, 35.5, 30.4, 27.1, 8.6; IR (Neat Film, NaCl) 3084, 2972, 2880, 1738, 1709, 1460. 1444, 1231, 1207, 1138 cm⁻¹; HRMS (El+) m/z calc'd for C₁₆H₁₉O₃ [M+H]⁺: 259.1334; found 259.1326.

2-Phenylallyl 1-methyl-2-oxocyclobutanecarboxylate (4b)

Compound 4b was isolated by flash column chromatography (SiO₂, hexanes to 10% EtOAc in hexanes) as a colorless oil. 32% yield. Rf = 0.5 (20% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.40–7.29 (m, 5H), 5.54–553 (m, 1H), 5.35–5.34 (m, 1H), 5.06 (dq, J = 11.2, 1.0 Hz, 1H), 3.20 (ddd, J = 18.3, 11.3, 7.6 Hz, 1H), 3.10 (ddd, J = 18.3, 9.9, 6.3 Hz, 1H), 2.53 (td, J = 11.3, 6.3 Hz, 1H), 1.84 (ddd, J = 11.5, 9.9, 7.6 Hz, 1H), 1.45 (s, 3H); ¹³C NMR (126 MHz, CDCl₃) δ 204.3, 170.0, 142.3, 137.9, 128.5, 128.1, 126.0, 115.2, 69.4, 66.5, 45.3, 23.1, 18.4; IR (Neat Film, NaCl) 2970, 2930, 1788, 1729, 1452, 1274, 1145, 1049 cm⁻¹; HRMS (El+) m/z calc'd for C₁₅H₁₆O₃ [M]⁺: 244.1100; found 244.1103.

2-Phenylallyl 1-benzyl-2-oxocyclobutanecarboxylate (4c)

Compound 4c was isolated by flash column chromatography (SiO₂, hexanes to 10% EtOAc in hexanes) as a colorless oil. 37% yield. Rf = 0.4 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.33–7.14 (m, 8H), 7.04–7.02 (m, 2H), 5.47 (s, 1H), 5.28–5.27 (m, 1H), 5.01–4.95 (m, 2H), 3.12, 3.10 (AB system, J_AB = 14.2 Hz, 2H), 2.95 (ddd, J = 18.3, 10.3, 6.3 Hz, 1H), 2.39 (ddd, J = 11.9, 11.1, 6.3 Hz, 1H), 1.93 (ddd, J = 11.9, 10.3, 7.3 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 203.7, 168.7, 142.1, 137.8, 135.9, 129.7, 128.51, 128.49, 128.1, 126.9, 126.0, 115.5, 75.0, 66.7, 45.2, 37.9, 19.2; IR (Neat Film, NaCl) 3029, 2924, 1788, 1725, 1496, 1270, 1191, 1046 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₄₂H₄₀NaO₆ [2M+Na]⁺: 663.2717; found 663.2692.

2-Phenylallyl 1-(4-fluorobenzyl)-2-oxocyclobutanecarboxylate (4d)

Compound 4d was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes) as a colorless oil. 22% yield. Rf = 0.4 (20% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.40–7.29 (m, 5H), 7.08–7.02 (m, 2H), 6.95–6.91 (m, 2H), 5.54 (s, 1H), 5.34 (d, J = 0.9 Hz, 1H), 5.05 (s, 2H), 3.18, 3.16 (AB system, J_AB = 14.3 Hz, 2H), 3.05 (ddd, J = 18.4, 11.2, 7.4 Hz, 1H), 2.73 (ddd, J = 18.4, 10.2, 6.2 Hz, 1H), 2.46 (ddd, J = 11.8, 11.2, 6.2 Hz, 1H), 1.97 (ddd, J = 11.8, 10.2, 7.4 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 203.4, 168.6, 161.9 (d, J_CF = 245.6 Hz), 142.1, 137.8, 131.6 (d, J_CF = 3.7 Hz), 131.2 (d, J_CF = 8.0 Hz), 128.5, 128.1,
126.0, 115.7, 115.3 (d, $^2J_{CF} = 21.2$ Hz), 75.0, 66.8, 45.2, 37.0, 19.3; IR (Neat Film, NaCl) 3052, 2968, 2928, 1784, 1717, 1506, 1219, 1186, 1042, 912 cm$^{-1}$; HRMS (MM: ESI-APCI) $m/z$ calc’d for C$_{21}$H$_{20}$F$_{19}$O$_3$ [M+H]$^+$: 339.1391; found 339.1387.

2-Phenylallyl 1-(4-methoxybenzyl)-2-oxocyclobutanecarboxylate (4e)

To a solution of NaI (1.88 g, 12.54 mmol) in acetone (20 mL) was added 4-methoxybenzyl chloride (1.55 mL, 11.38 mmol). The mixture was stirred at 25 °C for 2 hours before K$_2$CO$_3$ (504 mg, 3.65 mmol) and SI$_2$ (524 mg, 2.28 mmol) were added. The resulting mixture was heated to reflux for 16 hours until full conversion of the starting material was indicated by TLC analysis. The mixture was cooled to room temperature, the solids removed by filtration and concentrated in vacuo. The crude material was purified by flash column chromatography (SiO$_2$, hexanes to 10% EtOAc in hexanes to 20% EtOAc in hexanes) to provide 4e (506 mg, 63% yield) as a colorless oil. $R_f = 0.5$ (20% EtOAc in hexanes); $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 7.41–7.39 (m, 2H), 7.36–7.29 (m, 3H), 7.04–7.01 (m, 2H), 6.80–6.77 (m, 2H), 5.54 (s, 1H), 5.66–5.35 (m, 1H), 5.08–5.02 (m, 2H), 3.77 (s, 3H), 3.13 (s, 2H), 3.00 (ddd, $J = 18.3, 11.1, 7.2$ Hz, 1H), 2.00 (ddd, $J = 11.8, 10.3, 7.2$ Hz, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 203.9, 168.8, 158.5, 142.1, 137.8, 130.7, 128.5, 128.1, 127.8, 126.0, 115.5, 113.9, 75.2, 66.7, 55.2, 45.0, 37.1, 19.1; IR (Neat Film, NaCl) 2957, 2933, 2836, 1788, 1725, 1513, 1248, 1179, 1037 cm$^{-1}$; HRMS (FAB+) $m/z$ calc’d for C$_{22}$H$_{23}$O$_4$ [M+H]$^+$: 351.1596; found 351.1601.

2-Phenylallyl 1-allyl-2-oxocyclobutanecarboxylate (4f)

Compound 4f was isolated by flash column chromatography (SiO$_2$, 3% EtOAc in hexanes to 4% EtOAc in hexanes) as a colorless oil. 68% yield. $R_f = 0.2$ (10% EtOAc in hexanes); $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 7.49–7.27 (m, 5H), 5.64 (ddt, $J = 17.5, 9.7, 7.1$ Hz, 1H), 5.56 (q, $J = 0.8$ Hz, 1H), 5.38 (q, $J = 1.2$ Hz, 1H), 5.12–5.08 (m, 2H), 5.07 (dd, $J = 1.4, 0.7$ Hz, 2H), 3.14 (ddd, $J = 18.4, 11.0, 7.4$ Hz, 1H), 3.02 (ddd, $J = 18.4, 10.1, 6.4$ Hz, 1H), 2.70 (ddt, $J = 14.3, 7.1, 1.2$ Hz, 1H), 2.59–2.44 (m, 2H), 1.99 (ddd, $J = 11.9, 10.1, 7.4$ Hz, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 203.4, 168.6, 142.3, 137.9, 131.9, 128.5, 128.1, 126.1, 119.2, 115.5, 73.6, 66.6, 45.0, 36.7, 19.5; IR (Neat Film, NaCl) 3072, 2933, 2836, 1788, 1725, 1513, 1248, 1179, 1037 cm$^{-1}$; HRMS (MM: ESI-APCI) $m/z$ calc’d for C$_{17}$H$_{19}$O$_3$ [M+H]$^+$: 271.1329; found 271.1330.

2-Phenylallyl 2-oxo-1-(3-(trimethylsilyl)prop-2-yn-1-yl)cyclobutanecarboxylate (4g)
Compound 4g was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes to 7% EtOAc in hexanes) as a colorless oil. 63% yield. R₇ = 0.3 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.42–7.27 (m, 5H), 5.54 (q, J = 0.7 Hz, 1H), 5.35 (td, J = 1.3, 0.7 Hz, 1H), 5.10–4.98 (m, 2H), 2.82 (d, J = 17.3 Hz, 1H), 2.69 (d, J = 17.3 Hz, 1H), 2.48 (dd, J = 11.8, 11.0, 6.5 Hz, 1H), 2.27 (ddd, J = 11.8, 10.4, 7.4 Hz, 1H), 0.13 (s, 9H); ¹³C NMR (126 MHz, CDCl₃) δ 201.9, 168.1, 142.1, 137.8, 128.5, 128.1, 126.0, 115.4, 100.9, 87.9, 72.1, 66.8, 46.3, 22.8, 19.7, -0.1; IR (Neat Film, NaCl) 3058, 2959, 2177, 1949, 1794, 1732, 1634, 1575, 1496, 1444, 1422, 1315, 1250, 1194, 1161, 1116, 1028, 906, 843, 778, 760, 708 cm⁻¹; HRMS (APCI) m/z calc'd for C₂₀H₂₅O₃Si [M+H]+: 341.1567; found 341.1582.

2-Phenylallyl 1-(benzofuran-2-ylmethyl)-2-oxocyclobutanecarboxylate (4h)

Compound 4h was isolated by flash column chromatography (SiO₂, 5% EtOAc in hexanes to 10% EtOAc in hexanes) as a colorless oil. 27% yield. R₇ = 0.6 (20% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.48–7.46 (m, 1H), 7.40–7.38 (m, 3H), 7.33–7.29 (m, 3H), 7.25–7.18 (m, 2H), 6.37 (d, J = 0.8 Hz, 1H), 5.55 (m, 1H), 5.37 (m, 1H), 5.09 (s, 2H), 3.43 (d, J = 15.6 Hz, 1H), 3.28 (dd, J = 15.6, 0.8 Hz, 1H), 3.18 (ddd, J = 18.4, 11.2, 7.6 Hz, 1H), 2.97 (ddd, J = 18.4, 10.2, 6.1 Hz, 1H), 2.58 (ddd, J = 11.9, 11.2, 6.1 Hz, 1H), 2.11 (ddd, J = 11.9, 10.2, 7.6 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 202.2, 168.1, 154.8, 153.6, 142.1, 137.7, 128.5, 128.4, 128.1, 126.0, 123.8, 122.7, 120.6, 115.7, 110.9, 104.9, 73.1, 67.0, 45.8, 30.9, 19.9; IR (Neat Film, NaCl) 3582, 3056, 3033, 2963, 2928, 1790, 1726, 1601, 1586, 1455, 1253, 1193, 1045 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₂₃H₂₁O₄ [M+H]+: 361.1434; found 361.1427.

2-Methylenebut-3-en-1-yl 1-benzyl-2-oxocyclobutanecarboxylate (4i)

Compound 4i was isolated by flash column chromatography (SiO₂, 1% EtOAc in hexanes to 8% EtOAc in hexanes) as a colorless oil. 51% yield. R₇ = 0.4 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.33–7.20 (m, 3H), 7.19–7.05 (m, 2H), 6.36 (ddd, J = 17.9, 11.1, 0.8 Hz, 1H), 5.28–5.09 (m, 4H), 4.89–4.78 (m, 2H), 3.24 (dd, J = 18.6, 14.2 Hz, 2H), 3.14 (dd, J = 18.3, 11.0, 7.2 Hz, 1H), 2.75 (ddd, J = 18.3, 10.3, 6.4 Hz, 1H), 2.58 (ddd, J = 11.8, 11.0, 6.4 Hz, 1H), 2.06 (ddd, J = 11.8, 10.3, 7.2 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 203.7, 168.7, 140.0, 136.0, 135.9, 129.7, 128.5, 127.0, 118.4, 114.8, 75.1, 64.6, 45.2, 38.0, 19.2; IR (Neat Film,
NaCl) 3987, 3027, 2929, 1789, 1725, 1598, 1495, 1454, 1393, 1266, 1192, 1044, 909, 743 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₁₇H₁₉O₃ [M+H]⁺: 271.1329; found 271.1330.

2-Methylallyl 1-benzyl-2-oxocyclobutanecarboxylate (4j)

Compound 4j was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes) as a colorless oil. 44% yield. Rᵣ = 0.4 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.32–7.24 (m, 3H), 7.19–7.17 (m, 2H), 4.97 (d, J = 15.1 Hz, 2H), 4.60, 4.56 (AB system, JAB = 13.1 Hz, 2H), 3.28, 3.26 (AB system, JAB = 14.2 Hz, 2H), 3.16 (ddd, J = 18.3, 11.0, 7.2 Hz, 1H), 2.77 (ddd, J = 18.3, 10.4, 6.5 Hz, 1H), 2.61 (ddd, J = 11.8, 11.0, 6.5 Hz, 1H), 2.09 (ddd, J = 11.8, 10.4, 7.2 Hz, 1H). HRMS (MM: ESI-APCI) m/z calc'd for C₁₇H₂₀O₃ [M+H]⁺: 271.1329; found 271.1330.

2-Chloroallyl 1-benzyl-2-oxocyclobutanecarboxylate (4k)

Compound 4k was isolated by flash column chromatography (SiO₂, 2% EtOAc in hexanes to 5% EtOAc in hexanes) as a colorless oil. 63% yield. Rᵣ = 0.3 (10% EtOAc in hexanes); ¹H NMR (300 MHz, CDCl₃) δ 7.33–7.24 (m, 3H), 7.18–7.16 (m, 2H), 4.71 (m, 2H), 3.26 (s, 2H), 3.17 (ddd, J = 18.3, 11.0, 7.2 Hz, 1H), 2.77 (ddd, J = 18.3, 10.3, 6.5 Hz, 1H), 2.61 (ddd, J = 11.8, 11.0, 6.5 Hz, 1H), 2.01 (ddd, J = 11.8, 10.3, 7.2 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 203.4, 168.2, 135.7, 135.2, 129.7, 128.6, 127.1, 115.3, 74.9, 66.7, 45.3, 38.0, 19.2; IR (Neat Film, NaCl) 3578, 2918, 1792, 1734, 1637, 1439, 1268, 1191, 1045 cm⁻¹; HRMS (ESI) m/z calc'd for C₁₅H₁₅ClO₃ [M]: 278.0710; found 278.0714.

Allyl 1-benzyl-2-oxocyclobutanecarboxylate (4l)

Compound 4l was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes to 6% EtOAc in hexanes) as a colorless oil. 87% yield. Rᵣ = 0.3 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.30–7.27 (m, 2H), 7.25–7.22 (m, 1H), 7.17–7.14 (m, 2H), 5.88 (ddt, J = 17.2, 10.5, 5.7 Hz, 1H), 5.31 (dq, J = 17.2, 1.4 Hz, 1H), 5.24 (dq, J = 10.5, 1.4 Hz, 1H), 4.64 (dq, J = 5.7, 1.4 Hz, 2H), 3.26, 3.22 (AB system, JAB = 14.2 Hz, 2H), 3.14 (ddd, J = 18.3, 11.0, 7.2 Hz, 1H), 2.75 (ddd, J = 18.3, 10.3, 6.5 Hz, 1H), 2.59 (ddd, J = 11.8, 11.0, 6.5 Hz, 1H), 2.07 (ddd, J = 11.8, 10.3, 7.2 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 203.9, 168.6, 136.0, 131.5, 129.7, 128.5, 127.0, 118.7, 75.1, 66.1, 45.1, 38.1, 19.3; IR (Neat Film, NaCl) 2916, 2848, 1781, 1715, 1438, 1181, 1040 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₁₅H₁₃O₃ [M+H]⁺: 245.1172; found 245.1178.
4-(Benzylxy)-2-methylenebutyl 1-benzyl-2-oxocyclobutanecarboxylate (4m)

Compound 4m was isolated by flash column chromatography (SiO₂, 1% EtOAc in hexanes) as a colorless oil. 51% yield. Rₕ = 0.5 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.47–7.12 (m, 10H), 5.11 (q, J = 1.0 Hz, 1H), 5.04 (h, J = 1.1 Hz, 1H), 4.67, 4.61 (AB system, J_AB = 13.3 Hz, 2H), 4.53 (s, 2H), 3.60 (t, J = 6.6 Hz, 2H), 3.26 (s, 2H), 3.14 (d, J = 18.2 Hz, 1H), 2.42–2.33 (m, 2H), 2.08 (d, J = 11.8 Hz, 7.2 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 203.9, 168.7, 140.7, 138.2, 136.0, 129.7, 128.6, 128.4, 127.7, 127.6, 127.0, 114.4, 75.1, 73.0, 68.5, 68.0, 45.2, 38.1, 33.5, 19.3; IR (Neat Film, NaCl) 3029, 2920, 2849, 1784, 1717, 1495, 1451, 1360, 1268, 1187, 1095, 904, 732 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc’d for C₂₄H₂₇O₄ [M+H]⁺: 379.1904; found 379.1926.

2-(3-Methoxyphenyl)allyl 1-benzyl-2-oxocyclobutanecarboxylate (4n)

Compound 4n was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes) as a colorless oil. 79% yield. Rₕ = 0.35 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.41–7.16 (m, 4H), 7.16–7.09 (m, 2H), 7.05–6.90 (m, 2H), 6.91–6.82 (m, 1H), 5.60–5.53 (m, 1H), 5.37 (q, J = 1.2 Hz, 1H), 5.12–5.01 (m, 2H), 3.84 (s, 3H), 3.24, 3.21 (AB system, J_AB = 14.13 Hz, 2H), 3.06 (d, J = 18.3 Hz, 1H), 2.51 (d, J = 11.9 Hz, 6.3 Hz, 1H), 2.04 (d, J = 11.8 Hz, 10.2 Hz, 7.3 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 203.9, 168.7, 140.7, 138.2, 136.0, 129.7, 128.6, 128.4, 127.7, 127.6, 127.0, 114.4, 75.1, 73.0, 68.5, 68.0, 45.2, 38.1, 33.5, 19.3; IR (Neat Film, NaCl) 2957, 2833, 1786, 1720, 1575, 1494, 1453, 1387, 1221, 1180, 1039, 783 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc’d for C₂₂H₂₃O₄ [M+H]⁺: 351.1591; found 351.1582.

2-(4-Fluorophenyl)allyl 1-benzyl-2-oxocyclobutanecarboxylate (4o)

Compound 4o was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes) as a colorless oil. 93% yield. Rₕ = 0.3 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.40–7.36 (m, 2H), 7.30–7.23 (m, 3H), 7.14–7.11 (m, 2H), 7.07–7.02 (m, 2H), 5.51 (s, 1H), 5.36 (s, 1H), 5.07–5.01 (m, 2H), 3.23, 3.20 (AB system, J_AB = 14.2 Hz, 2H),
3.06 (ddd, $J = 18.3$, 11.0, 7.3 Hz, 1H), 2.74 (ddd, $J = 18.3$, 10.3, 6.4 Hz, 1H), 2.51 (ddd, $J = 11.9$, 11.0, 6.4 Hz, 1H), 2.05 (ddd, $J = 11.9$, 10.3, 7.3 Hz, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$) δ 203.5, 168.6, 162.7 (d, $^1J_{CF} = 247.5$ Hz), 141.1, 135.9, 133.9 (d, $^4J_{CF} = 3.9$ Hz), 129.6, 128.5, 127.7 (d, $^3J_{CF} = 8.6$ Hz), 126.9, 115.7, 115.4 (d, $^2J_{CF} = 21.4$ Hz), 75.0, 66.7, 45.1, 37.8, 19.2; IR (Neat Film, NaCl) 3060, 3029, 2967, 2928, 1790, 1728, 1634, 1602, 1511, 1454, 1386, 1233, 1193, 1162, 1047, 917, 840, 744 cm$^{-1}$; HRMS (MM: ESI-APCI) m/z calc'd for C$_{21}$H$_{20}$O$_3$ [M+H]$^+$: 339.1391; found 339.1397.
Representative Procedure for the Asymmetric Decarboxylative Allylic Alkylation of 2-Carboxallylcyclobutanones

(S)-2-Ethyl-2-(2-phenylallyl)cyclobutanone (5a)

To a 20 mL scintillation vial with a stir bar were added Pd_2(pmdba)_3 (16.4 mg, 0.015 mmol), L2 (21.9 mg, 0.037 mmol) and toluene (9 mL) in a nitrogen–filled glove box. The dark purple mixture was stirred at ambient glove box temperature (ca. 30 °C) for 35 minutes at which point the mixture had become red-orange. 2-Carboxallylcyclobutanone 4a (80.0 mg, 0.31 mmol) was then added. The resulting yellow-greenish reaction mixture was stirred at 20 °C until full conversion of the starting material was indicated by TLC analysis (reaction times typically ranged 18 to 36 hours). The vial was removed from the glove box, uncapped and directly purified by flash column chromatography (SiO_2, pentane to 15% Et_2O in pentane) afforded 5a (41 mg, 62% yield) as colorless oil. R_f = 0.3 (15% Et_2O in pentane); ^1H NMR (300 MHz, CDCl_3) δ 7.46–7.25 (m, 5H), 5.55 (d, J = 0.9 Hz, 1H), 5.38 (d, J = 1.1 Hz, 1H), 5.16–4.92 (m, 2H), 2.51 (ddd, J = 14.7, 10.5, 2.0 Hz, 1H), 2.42–2.30 (m, 1H), 2.29–2.14 (m, 1H), 1.93–1.77 (m, 2H), 1.73–1.59 (m, 1H), 0.69 (t, J = 7.4 Hz, 3H); ^13C NMR (75 MHz, CDCl_3) δ 215.1, 145.2, 141.9, 128.3, 127.6, 126.5, 116.5, 63.8, 42.8, 40.6, 23.5, 21.6, 8.4; IR (Neat Film, NaCl) 3078, 2966, 1699, 1443, 905 cm⁻¹; HRMS (FAB+) m/z calc'd for C_{15}H_{17}O [(M+H)−H_2]⁺: 213.1279; found 213.1274; [α]_D^{26.0} +8.50 (c 1.00, CHCl_3, 99% ee).

(S)-2-Methyl-2-(2-phenylallyl)cyclobutanone (5b)

Cyclobutanone 5b was isolated by flash column chromatography (SiO_2, 10% Et_2O in pentane) as a colorless oil. R_f = 0.3 (10% Et_2O in pentane); ^1H NMR (300 MHz, CDCl_3) δ 7.31–7.19 (m, 5H), 5.25 (d, J = 1.5 Hz, 1H), 5.04–5.03 (m, 1H), 2.93–2.66 (m, 3 H), 2.56 (d, J = 14.1 Hz, 1H), 1.82 (ddd, J = 11.4, 10.5, 6.9 Hz, 1H), 1.47 (ddd, J = 11.4, 10.2, 6.6 Hz, 1H), 1.09 (s, 3H); ^13C NMR (75 MHz, CDCl_3) δ 215.1, 145.2, 141.9, 128.3, 127.6, 126.5, 116.5, 63.8, 42.8, 40.6, 23.5, 21.6; IR (Neat Film, NaCl) 2080, 2865, 1774, 1443, 1059 cm⁻¹; HRMS (FAB+) m/z calc'd for C_{14}H_{17}O [M+H]^+: 201.1279; found 201.1286; [α]_D^{26.0} –83.9 (c 1.00, CHCl_3, 90% ee).

(R)-2-Benzyl-2-(2-phenylallyl)cyclobutanone (5c)
Cyclobutanone 5c was isolated by flash column chromatography (SiO₂, 5% Et₂O in petroleum ether) as a colorless oil. 81% yield. Rf = 0.6 (10% EtOAc in hexanes); 1H NMR (500 MHz, CDCl₃) δ 7.36–7.26 (m, 8H), 7.13–7.11 (m, 2H), 5.37 (d, J = 1.4 Hz, 1H), 5.15–5.14 (m, 1H), 2.94 (t, J = 14.9 Hz, 2H), 2.72 (t, J = 14.2 Hz, 2H), 2.61 (ddd, J = 18.1, 9.6, 7.2 Hz, 1H), 2.32 (ddd, J = 18.1, 10.0, 7.5 Hz, 1H), 1.86–1.77 (m, 2H); 13C NMR (126 MHz, CDCl₃) δ 214.7, 161.7 (d, JCF = 244.8 Hz), 144.9, 141.8, 132.9 (d, JCF = 3.8 Hz), 131.5 (d, JCF = 8.3 Hz), 128.8, 127.2, 126.4, 117.0, 115.1 (d, JCF = 21.1 Hz), 68.7, 43.7, 40.2, 39.9, 19.9; IR (Neat Film, NaCl) 3028, 2918, 1770, 1494, 1453, 1074, 905 cm⁻¹; HRMS (EI+) m/z calc'd for C₂₀H₂₇O [M+H⁺]: 277.1587; found 277.1587; \([\alpha]D^{26.0} = −2.91\) (c 1.14, CHCl₃, 95% ee).

(R)-2-(4-Fluorobenzyl)-2-(2-phenylally)cyclobutanone (5d)

Cyclobutanone 5d was isolated by flash column chromatography (SiO₂, hexanes to 3% Et₂O in hexanes) as a colorless oil. 71% yield. Rf = 0.3 (25% EtOAc in hexanes); 1H NMR (500 MHz, CDCl₃) δ 7.36–7.26 (m, 5H), 7.09–7.05 (m, 2H), 6.97–6.93 (m, 2H), 5.37 (d, J = 1.4 Hz, 1H), 5.14 (d, J = 0.9 Hz, 1H), 2.93–2.89 (m, 2H), 2.74–2.67 (m, 2H), 2.33 (ddd, J = 18.1, 10.7, 6.9 Hz, 1H), 2.62 (ddd, J = 18.1, 10.4, 6.5 Hz, 1H), 1.83 (ddd, J = 11.7, 10.4, 6.9 Hz, 1H), 1.75 (ddd, J = 11.7, 10.7, 6.5 Hz, 1H); 13C NMR (126 MHz, CDCl₃) δ 214.7, 161.7 (d, JCF = 244.8 Hz), 144.9, 141.8, 132.9 (d, JCF = 3.8 Hz), 131.5 (d, JCF = 8.3 Hz), 128.8, 127.2, 126.4, 117.0, 115.1 (d, JCF = 21.1 Hz), 68.7, 43.7, 40.2, 39.9, 19.9; IR (Neat Film, NaCl) 3047, 2918, 2848, 1772, 1599, 1508, 1221, 1158, 1060 836 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₂₀H₂₀FO [M+H⁺]: 294.1420; found 294.1408; \([\alpha]D^{26.0} = −9.9\) (c 0.59, CHCl₃, 94% ee).

(R)-2-(4-Methoxybenzyl)-2-(2-phenylally)cyclobutanone (5e)

Cyclobutanone 5e was isolated by flash column chromatography (SiO₂, 10% EtOAc in hexanes) as a colorless oil. 83% yield. Rf = 0.3 (10% EtOAc in hexanes); 1H NMR (300 MHz, CDCl₃) δ 7.37–7.26 (m, 5H), 7.06–7.01 (m, 2H), 6.83–6.78 (m, 2H), 5.37 (d, J = 1.2 Hz, 1H), 5.14 (s, 1H), 3.78 (s, 3H), 2.91 (dd, J = 14.5, 3.1 Hz, 2H), 2.69 (dd, J = 14.5, 1.9 Hz, 2H), 2.64–2.53 (m, 1H), 2.37–2.26 (m, 1H) 1.78 (ddd, J = 10.1. 7.2, 2.6 Hz, 2H); 13C NMR (126 MHz, CDCl₃) δ 215.1, 158.2, 145.0, 141.8, 131.0, 129.2, 128.3, 127.6, 126.4, 116.8, 113.6, 68.9, 55.1, 43.6, 40.3, 39.8; IR (Neat Film, NaCl) 3080, 2913, 2835, 1770, 1611, 1513, 1248, 1179, 1035, 907 cm⁻¹; HRMS (El+) m/z calc'd for C₂₁H₂₂O₂ [M⁺]: 306.1620; found 306.1614; \([\alpha]D^{26.0} = −0.60\) (c 1.00, CHCl₃, 95% ee).

(R)-2-Allyl-2-(2-phenylally)cyclobutanone (5f)
Cyclobutanone 5f was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes to 4% EtOAc in hexanes) as a colorless oil. 86% yield. R₂ = 0.2 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.42–7.25 (m, 5H), 5.84–5.71 (m, 1H), 5.37 (d, J = 1.5 Hz, 1H), 5.14 (d, J = 1.0 Hz, 1H), 5.15–5.05 (m, 2H), 2.91, 2.70 (AB system, JAB = 14.4 Hz, 2H), 2.87–2.65 (m, 2H), 2.36 (ddt, J = 13.9, 7.1, 1.2 Hz, 1H), 2.27 (ddt, J = 13.9, 7.6, 1.1 Hz, 1H), 1.85 (ddd, J = 11.7, 10.4, 6.8 Hz, 1H), 1.77–1.64 (m, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 214.5, 145.1, 141.8, 133.3, 128.3, 128.3, 126.5, 118.7, 116.9, 67.5, 43.3, 39.7, 39.1, 20.3; IR (Neat Film, NaCl) 3078, 2921, 1774, 1625, 1493, 1443, 1387, 1059, 1000, 908, 779 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₁₅H₁₉O [M+H]⁺: 227.1430; found 227.1418; [α]D²⁵ −13.98 (c 0.51, CHCl₃, 92% ee).

(S)-2-(2-Phenylallyl)-2-[3-(trimethylsilyl)prop-2-yn-1-yl]cyclobutanone (5g)

Cyclobutanone 5g was isolated by flash column chromatography (SiO₂, 1% EtOAc in hexanes to 3% EtOAc in hexanes) as a colorless oil. 90% yield. R₂ = 0.2 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.51–7.08 (m, 5H), 5.37 (d, J = 1.4 Hz, 1H), 5.13 (d, J = 1.1 Hz, 1H), 2.93–2.86 (m, 2H), 2.82–2.75 (m, 2H), 2.42, 2.37 (AB system, JAB = 17.0 Hz, 2H), 1.96–1.85 (m, 2H) 0.15 (s, 9H); ¹³C NMR (126 MHz, CDCl₃) δ 212.6, 144.5, 141.4, 128.4, 127.7, 126.4, 116.9, 102.7, 87.2, 66.6, 43.9, 38.9, 25.8, 20.9, 0.0; IR (Neat Film, NaCl) 2957, 2169, 1776, 1713, 1444, 1249, 1177, 1061, 1031, 834, 760 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₁₅H₂₃OSi [M+H]⁺: 297.1681; found 297.1683; [α]D²⁵ +10.76 (c 0.29, CHCl₃, 93% ee).

(S)-2-(Benzo[1,2-c:4,5-c']furan-2-ylmethyl)-2-(2-phenylallyl)cyclobutanone (5h)

Cyclobutanone 5h was isolated by flash column chromatography (SiO₂, hexanes to 10% EtOAc in hexanes) as a colorless oil. 82% yield. R₂ = 0.5 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.50–7.48 (m, 1H), 7.42–7.40 (m, 1H), 7.38–7.36 (m, 2H), 7.33–7.28 (m, 3H), 7.25–7.18 (m, 2H), 6.44 (s, 1H), 5.40 (d, J = 1.34 Hz, 1H), 5.17 (d, J = 1.0 Hz, 1H), 2.98 (dd, J = 14.3, 0.9 Hz, 1H), 2.96 (d, J = 15.0 Hz, 1H), 2.82 (d, J = 14.3 Hz, 1H), 2.79–2.64 (m, 2H), 1.96–1.86 (m, 2H); ¹³C NMR (126 MHz, CDCl₃) δ 213.2, 155.0, 154.7, 144.7, 141.6, 128.5, 128.4, 127.8, 126.4, 123.6, 120.5, 117.2, 110.9, 105.0, 67.2, 43.8, 39.6, 33.7, 20.9; IR (Neat Film, NaCl) 3054, 2917, 2849, 1770, 1598, 1585, 1453, 1251, 1104, 1061, 905 cm⁻¹; HRMS (MM ESI-APCI) m/z calc'd for C₂₂H₂₁O₂ [M+H]⁺: 317.1536; found 317.1530; [α]D²⁶ +56.4 (c 1.00, CHCl₃, 92% ee).

(S)-2-Benzyl-2-(2-methylenebut-3-en-1-yl)cyclobutanone (5i)
Cyclobutanone 5i was isolated by flash column chromatography (SiO₂, hexanes to 5% Et₂O in hexanes) as a colorless oil. 92% yield. Rₛ = 0.3 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.33–7.27 (m, 3H), 7.25–7.20 (m, 2H), 7.19–7.12 (m, 1H), 6.59–6.19 (m, 1H), 5.24–5.06 (m, 2H), 5.05 (s, 2H), 3.01 (d, J = 13.6 Hz, 1H), 2.80 (d, J = 13.6 Hz, 1H), 2.68 (ddd, J = 18.1, 10.3, 6.8 Hz, 1H), 2.57 (dd, J = 14.4, 1.0 Hz, 1H), 2.45 (ddd, J = 18.1, 10.3, 6.9 Hz, 1H), 2.40 (d, J = 14.4 Hz, 1H), 1.95 (qdd, J = 11.6, 10.2, 6.8 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 215.2, 142.4, 139.4, 137.3, 130.1, 128.3, 126.6, 119.2, 114.5, 68.6, 43.9, 41.4, 35.5, 20.2; IR (Neat Film, NaCl) 3022, 2921, 2843, 1768, 1590, 1493, 1452, 1384, 1065, 989, 898, 755 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₈H₁₂O [M+H]+: 227.1430; found 227.1433; [α]D²⁵ +0.44 (c 1.60, CHCl₃, 91% ee).

(S)-2-Benzyl-2-(2-methylallyl)cyclobutanone (5j)

Cyclobutanone 5j was isolated by flash column chromatography (SiO₂, 2% Et₂O in hexanes to 5% Et₂O in hexanes) as a colorless oil. 82% yield. Rₛ = 0.3 (10% EtOAc in hexanes); ¹H NMR (300 MHz, CDCl₃) δ 7.41–7.12 (m, 5H), 4.91 (t, J = 1.7 Hz, 1H), 4.78 (dd, J = 2.0 Hz, 1.0, 1H), 2.88, 2.65 (AB system, Jₐₕ = 13.7 Hz, 2H), 2.77 (ddd, d = 18.1, 9.6, 6.9 Hz, 1H), 2.43–2.33 (m, 1H), 2.33, 2.22 (AB system, Jₐₕ = 14.2 Hz, 2H), 1.97 (ddd, J = 9.4, 7.2, 3.1, 2H), 1.80–1.72 (m, 3H); ¹³C NMR (126 MHz, CDCl₃) δ 215.3, 141.8, 137.4, 130.1, 128.3, 126.5, 114.8, 68.2, 43.6, 43.2, 40.6, 24.0, 20.7; IR (Neat Film, NaCl) 3072, 3027, 2964, 2919, 1772, 1322, 1131, 1062, 894 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₁₅H₂₀O [M+H]+: 214.1358, found 214.1346; [α]D²⁶ −2.4° (c 0.48, CHCl₃, 90% ee).

(R)-2-Benzyl-2-(2-chloroallyl)cyclobutanone (5k)

Cyclobutanone 5k was isolated by flash column chromatography (SiO₂, hexanes to 3% EtOAc in hexanes) as a colorless oil. 67% yield. Rₛ = 0.3 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.33–7.21 (m, 3H), 7.18–7.15 (m, 2H), 5.33 (d, J = 1.3 Hz, 1H), 5.22–5.21 (m, 1H), 2.97 (d, J = 13.7 Hz, 1H), 2.90–2.76 (m, 1H), 2.82 (d, J = 13.7 Hz, 1H), 2.74 (dd, J = 14.7, 1.0 Hz, 1H), 2.59 (d, J = 14.7 Hz, 1H), 2.43 (ddd, J = 18.1, 10.8, 7.3 Hz, 1H), 2.19 (ddd, J = 11.8, 10.2, 7.2 Hz, 1H), 2.04 (dd, J = 11.8, 10.8, 6.1 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 213.7, 138.4, 136.7, 130.1, 128.4, 126.8, 116.4, 67.5, 44.1, 43.8, 40.5, 20.7; IR (Neat Film, NaCl) 3028, 2919, 2848, 1772, 1631, 1494, 1453, 1063, 888 cm⁻¹; HRMS (MM ESI-APCI) m/z calc'd for C₁₅H₁₅ClO [M+H]+: 235.0884; found 235.0883; [α]D²⁶ +1.51 (c 0.56, CHCl₃, 94% ee).

(S)-2-Allyl-2-benzylecyclobutanone (5l)

Cyclobutanone 5l was isolated by flash column chromatography (SiO₂, 2% Et₂O in hexanes to 5% Et₂O in hexanes) as a colorless oil. 82% yield. Rₛ = 0.4 (10% EtOAc in hexanes); ¹H NMR
(500 MHz, CDCl₃) δ 7.30–7.27 (m, 2H), 7.24–7.21 (m, 1H), 7.16–7.15 (m, 2H), 5.81 (ddt, J = 17.2, 10.0, 7.4 Hz, 1H), 5.16–5.10 (m, 2H), 2.97 (d, J = 13.7 Hz, 1H), 2.78 (ddd, J = 18.2, 10.3, 6.5 Hz, 1H), 2.72 (d, J = 13.7 Hz, 1H), 2.49 (ddd, J = 18.2, 10.6, 6.8 Hz, 1H), 2.39 (ddd, J = 13.9, 7.4, 1.1 Hz, 1H), 2.67 (d, J = 13.9, 7.4, 1.1 Hz, 1H), 1.94 (ddd, J = 11.5, 10.6, 6.5 Hz, 1H), 1.86 (ddd, J = 11.5, 10.3, 6.8 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 214.9, 137.3, 133.2, 130.0, 128.3, 126.5, 118.7, 68.4, 42.9, 40.3, 39.5, 19.8; IR (Neat Film, NaCl) 3029, 2918, 1771, 1495, 1437, 1454, 1076, 920 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₁₄H₁₆O [M⁺]: 200.1201; found 200.1199; [α]D₂⁶ +4.69 (c 0.55, CHCl₃, 88% ee).

(S)-2-Benzyl-2-[4-(benzyloxy)-2-methylenebutyl]cyclobutanone (5m)

Cyclobutanone 5m was isolated by flash column chromatography (SiO₂, 1% EtOAc in hexanes to 3% EtOAc in hexanes) as a colorless oil (95% yield). Rf = 0.2 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.41–7.12 (m, 10H), 5.01 (q, J = 1.4 Hz, 1H), 4.93–4.92 (m, 1H), 4.54 (s, 2H), 3.59 (td, J = 6.8, 0.7, 2H), 2.95, 2.73 (AB system, JAB = 13.7, 2H), 2.83–2.71 (m, 1H), 2.51–2.27 (m, 5H), 2.04–1.92 (m, 2H); ¹³C NMR (126 MHz, CDCl₃) δ 215.2, 142.6, 138.4, 137.4, 130.1, 128.4, 128.3, 127.7, 127.4, 115.1, 72.9, 68.7, 68.3, 43.6, 41.5, 40.6, 37.0, 20.7; IR (Neat Film, NaCl) 3022, 2923, 2853, 1768, 1641, 1494, 1452, 1360, 1099, 899, 735 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₂₃H₂₇O₂ [M+H⁺]: 335.2006; found 335.2020; Enantiomeric excess determined for the corresponding Baeyer-Villiger product, which was obtained by general procedure below. Lactone SI₃ was isolated by flash column chromatography (SiO₂, 4% EtOAc in hexanes) as a colorless oil (93% yield). Rf = 0.2 (20% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.40–7.18 (m, 10H), 5.09 (q, J = 1.5 Hz, 1H), 4.98 (dd, J = 1.7, 0.9 Hz, 1H), 4.51 (s, 2H), 3.61 (t, J = 6.5 Hz, 2H), 3.09 (d, J = 14.1 Hz, 1H), 2.75 (d, J = 14.1 Hz, 1H), 2.61–2.38 (m, 4H), 2.23 (ddd, J = 17.6, 9.4, 5.9 Hz, 1H), 2.17–2.03 (m, 2H), 1.68 (ddd, J = 17.6, 10.0, 8.6 Hz, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 176.9, 141.8, 138.4, 135.5, 130.5, 128.5, 128.3, 127.7, 127.5, 127.1, 117.1, 87.8, 72.8, 68.5, 46.7, 45.6, 37.0, 29.3, 29.2; IR (Neat Film, NaCl) 3524, 3062, 3029, 2919, 2855, 1958, 1770, 1642, 1603, 1495, 1454, 1416, 1361, 1271, 1232, 1177, 1101, 1080, 1029, 932, 741 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₂₃H₂₇O₃ [M+H⁺]: 351.1955; found 351.1951; [α]D₂⁵ +21.17 (c 0.44, CHCl₃, 89% ee).

(R)-2-Benzyl-2-(2-[3-methoxyphenyl]allyl)cyclobutanone (5n)
Cyclobutanone 5n was isolated by flash column chromatography (SiO₂, 1% EtOAc in hexanes to 3% EtOAc in hexanes) as a colorless oil. 91% yield. Rₛ = 0.2 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.37–7.19 (m, 4H), 7.19–7.10 (m, 2H), 6.98 (ddd, J = 7.7, 1.7, 0.9 Hz, 1H), 6.91 (dd, J = 2.5, 1.6 Hz, 1H), 6.85 (ddd, J = 8.2, 2.6, 0.9 Hz, 1H), 5.41 (d, J = 1.4 Hz, 1H), 5.17 (q, J = 1.1 Hz, 1H), 3.83 (s, 3H), 3.03–2.86 (m, 2H), 2.86–2.68 (m, 2H), 2.63 (ddd, J = 18.1, 9.7, 7.1 Hz, 1H), 2.35 (ddd, J = 18.1, 10.1, 7.4 Hz, 1H), 1.96–1.72 (m, 2H); ¹³C NMR (126 MHz, CDCl₃) δ 215.0, 159.6, 144.9, 143.5, 137.3, 130.1, 129.4, 128.4, 126.6, 119.0, 117.1, 112.9, 112.4, 68.9, 55.3, 43.8, 41.2, 40.0, 20.0; IR (Neat Film, NaCl) 2913, 2829, 1766, 1595, 1572, 1488, 1451, 1286, 1221, 1170, 1039, 898, 873, 779 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc’d for C₂₁H₂₃O₂ [M+H]⁺: 307.1693; found 307.1693; [α]D²⁵ +4.78 (c 0.45, CHCl₃, 92% ee).

(R)-2-Benzyl-2-(2-(4-fluorophenyl)allyl)cyclobutanone (5o)

Cyclobutanone 5o was isolated by flash column chromatography (SiO₂, 3% EtOAc in hexanes to 7% EtOAc in hexanes) as a colorless oil. 94% yield. Rₛ = 0.3 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.25–7.12 (m, 5H), 7.05–7.03 (m, 2H), 6.95–6.90 (m, 2H), 5.25 (d, J = 1.3 Hz, 1H), 5.05 (s, 1H), 2.88 (d, J = 13.7 Hz, 1H), 2.82 (dd, J = 14.4, 1.0 Hz, 1H), 2.66 (d, J = 13.7 Hz, 1H), 2.59 (d, J = 14.4 Hz, 1H), 2.54–2.47 (m, 1H), 2.29–2.22 (m, 1H), 1.73 (t, J = 8.6 Hz, 2H); ¹³C NMR (126 MHz, CDCl₃) δ 214.6, 162.3 (d, ¹JCF = 246.8 Hz), 144.0, 137.8 (d, ²JCF = 3.3 Hz), 137.1, 130.0, 128.3, 128.0 (d, ³JCF = 7.9 Hz), 126.6, 116.9, 115.2 (d, ⁴JCF = 21.3 Hz), 68.6, 43.7, 41.2, 40.5, 20.0; IR (Neat Film, NaCl) 2913, 1766, 1597, 1505, 1219, 1055, 837 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc’d for C₂₀H₂₀FΟ [M+H]⁺: 295.1493; found 295.1502; [α]D²⁵ +3.53 (c 0.16, CHCl₃, 94% ee).
**Procedures for Derivatization of α-Quaternary Cyclobutanones and Absolute Configuration Determination**

**(R)-5-Benzyl-5-(2-phenylallyl)dihydrofuran-2(3H)-one (6).** To a stirred solution of cyclobutanone 5c (43 mg, 0.23 mmol) in MeOH (4.6 mL) was added NaOH (1 M in H₂O, 0.23 μL, 0.23 mmol) followed by H₂O₂ (50 wt% in H₂O, 17 mg, 0.46 mmol). The resulting mixture was stirred at room temperature for 1 h. The reaction mixture was then acidified to pH 7 with 1 N aqueous HCl and extracted with dichloromethane (2 mL x 5). The combined organic layers were dried over MgSO₄ and concentrated *in vacuo*. The crude oil was purified by flash column chromatography (SiO₂, 15% EtOAc in hexanes) to afford lactone 6 (37 mg, 0.17 mmol, 80% yield) as a colorless oil. R² = 0.2 (20% EtOAc in hexanes); ¹H NMR (300 MHz, CDCl₃) δ 7.41–7.18 (m, 10H), 5.46 (d, J = 1.4 Hz, 1H), 5.27 (s, 1H), 3.08–2.92 (m, 3H), 2.79 (d, J = 14.1 Hz, 1H), 2.17 (ddd, J = 17.4, 9.8, 6.4 Hz, 1H), 2.04–1.86 (m, 2H), 1.76–1.62 (m, 1H); ¹³C NMR (126 MHz, CDCl₃) δ 176.7, 143.4, 141.7, 135.4, 130.6, 128.6, 128.5, 127.8, 127.0, 126.3, 119.2, 87.7, 46.1, 45.3, 29.3, 28.8; IR (Neat Film, NaCl) 3029, 2918, 1771, 1495, 1437, 1454, 1076, 920 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc’d for C₂₀H₂₁O₂ [M+H]⁺: 293.1536; found 293.1536; [α]D²⁶ = −0.60 (c 1.00, CHCl₃, 89% ee).

**(S)-2-(2-Phenylallyl)-2-(3-(trimethylsilyl)prop-2-yn-1-yl)cyclopentanone (7).** To a solution of 5g (0.1023 g, 0.345 mmol) in Et₂O (3.5 mL), cooled to 0 °C with a water/ice bath, under an atmosphere of N₂, was added BF₃ etherate (0.112 mL, 0.379 mmol) dropwise followed by trimethylsilyldiazomethane (0.345 mL, 2 M solution in hexane) dropwise. The mixture was allowed to warm to 25 °C and stirred for 18 hours, at which point the reaction was determined to be complete by TLC analysis. To the mixture was added 3 mL of saturated aqueous NaHCO₃. After stirring for 30 minutes, this mixture was extracted with Et₂O (5 mL x 3), dried over MgSO₄ and concentrated *in vacuo*. The crude product was purified by flash column chromatography (SiO₂, 1% EtOAc in hexanes to 5% EtOAc in hexanes) to afford trimethylsilylcyclopentanone SI4 as a colorless oil. The identity of the α-trimethylsilylcyclopentanone SI4 was confirmed by NMR analysis; the product was taken on without further characterization. R² = 0.3 (10% EtOAc in hexanes); To a solution of trimethylsilylcyclopentanone SI4 (61 mg, 0.159 mmol) in 2 mL dichloromethane was added 2 mL of 1 N aqueous HCl in H₂O at 25 °C. The mixture was stirred for 24 hours at which point the reaction was determined to be complete by TLC analysis. The mixture was diluted with dichloromethane (2 ml) and then extracted with dichloromethane (5 mL x 3). The collected organic layers were then washed with brine (5 mL), dried over MgSO₄, filtered and concentrated *in vacuo*. The crude oil was purified by flash column chromatography (SiO₂, hexanes to 1% EtOAc in hexanes) to afford cyclopentanone 7 (47 mg, 0.153 mmol, 69% yield over two steps) as a colorless oil. R² = 0.3 (10% EtOAc in hexanes); ¹H NMR (500 MHz, CDCl₃) δ 7.58–7.12 (m, 5H), 5.32 (d, J = 1.6 Hz, 1H), 5.14–4.97 (m, 1H), 2.83–2.73 (m, 2H), 2.22 (dd, J = 16.9, 38.9 Hz, 2H), 2.16–2.08 (m, 1H), 2.03–1.91 (m, 2H), 1.89–1.71 (m, 3H), 0.14
(R)-5-Allyl-5-(2-phenylallyl)pyrrolidin-2-one (8). To a solution of cyclobutanone 5o (65 mg, 0.221 mmol) in 7 mL absolute ethanol was added hydroxylamine hydrochloride (76 mg, 1.104 mmol), followed by pyridine (0.27 ml, 3.31 mmol) and the mixture was stirred at 25 °C for 24 hours. The crude mixture was washed with H$_2$O (5 mL), triethylamine (0.06 mL, 0.43 mmol) and catalytic 4-dimethylaminopyridine in 2.5 mL of dichloromethane under an atmosphere of N$_2$ was added dropwise a solution of oxime 8 (54 mg, 0.175 mmol) in 1 mL of dichloromethane. The mixture was stirred at 25 °C for 4 hours. The crude mixture was washed with H$_2$O (5 mL), washed with brine (5 mL), dried over Na$_2$SO$_4$ and concentrated in vacuo. The crude oil was purified by flash column chromatography (SiO$_2$, 3% EtOAc in hexanes to EtOAc) to afford lactam 8 (16 mg, 0.05 mmol, 22% yield over two steps) as a pale yellow oil. R$_f$ = 0.4 (EtOAc); $^1$H NMR (500 MHz, CDCl$_3$) δ 7.34–7.07 (m, 7H), 7.07–6.96 (m, 2H), 5.35 (d, $J$ = 1.3 Hz, 1H), 5.26 (s, 1H), 5.15 (q, $J$ = 1.0 Hz, 1H), 2.87–2.63 (m, 4H), 2.06–1.85 (m, 3H), 1.69–1.55 (m, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$) δ = 136.1, 130.3, 128.5, 127.8 (d, $J_{CF}$ = 12.4 Hz), 136.1, 130.3, 128.5, 127.8 (d, $J_{CF}$ = 13.6 Hz), 127.0, 118.6, 115.7 (d, $J_{CF}$ = 11.4 Hz), 62.0, 47.0, 46.5, 30.9, 30.1; IR (Neat Film, NaCl) 3085, 2958, 2926, 1693, 1601, 1507, 1452, 1260, 1224, 1159, 1087, 906, 842, 750 cm$^{-1}$; HRMS (EI+) m/z calc'd for C$_{20}$H$_{20}$ONF [M]$^+$: 309.1529; found 309.1517; [$\alpha$]$_D^{25}$ +53.19 (c 0.08, CHCl$_3$, 94% ee).

(R)-6-phenylspiro[3.4]oct-6-en-1-one (9). To a flask charged with Grubbs-Hoveyda an atmosphere of argon was added a solution of cyclobutanone 5f (50 mg, 0.221 mmol) in 5 mL benzene. The reaction mixture was heated to 50 °C and stirred for one hour, at which point the reaction was determined to be complete by TLC analysis. The reaction vessel was cooled to 25 °C and 1 mL of ethyl vinyl ether was added. After 30 minutes of stirring, the crude mixture was purified directly by flash column chromatography (SiO$_2$, hexanes to 3% EtOAc in hexanes) to afford spirocycle 9 (43 mg, 0.215 mmol, 97% yield) as a colorless oil. R$_f$ = 0.3 (10% EtOAc in hexanes); $^1$H NMR (500 MHz, CDCl$_3$) δ 7.37–7.20 (m, 2H), 7.32–7.21 (m, 2H), 7.24–7.15 (m, 1H), 5.97 (p, $J$ = 2.4 Hz, 1H), 3.19 (dq, $J$ = 16.0, 2.2 Hz, 1H), 3.04 (t, $J$ = 8.6 Hz, 2H), 3.04–
(S)-5-allyl-5-methylidihydrofuran-2(3H)-one (14). Dihydrofuranone 14 was generated from 2-Carboxyallylcyclobutanone 12, via cyclobutanone 13, following the general procedures described above (see SI 3, SI 10 and SI 16). When compared with known compound (5S)-(+) -5-allyl-5-methylidihydrofuran-2(3H)-one, the optical rotation value for 14 was found to be of the same sign and of nearly identical magnitude ([α]_D^{25} +2.96 (c 1.5, CH3OH), literature value: [α]_D^{17} +3.33 (c 1.27, CH3OH)). The absolute configurations of all other compounds described herein were established by analogy to 13. Cyclobutanone 12 was isolated by flash column chromatography (SiO₂, 3% Et₂O in pentane to 7% Et₂O in pentane) as a colorless oil. 84% yield. R_f = 0.4 (15% EtOAc in hexanes); ¹H NMR (300 MHz, CDCl₃) δ 5.90 (ddt, J = 17.2, 10.5, 5.6 Hz, 1H), 5.38–5.14 (m, 2H), 4.63 (dt, J = 5.6, 1.4 Hz, 2H), 3.42–3.06 (m, 2H), 2.65 (td, J = 11.3, 6.3 Hz, 1H), 1.88 (ddd, J = 11.6, 9.9, 7.5 Hz, 1H), 1.49 (s, 3H); ¹³C NMR (126 MHz, CDCl₃) δ 204.6, 169.8, 131.6, 118.4, 65.9, 45.2, 23.1, 18.6; IR (Neat Film, NaCl) 2933, 2924, 1765, 1595, 1491, 1385, 1298, 1214, 1156, 747 cm⁻¹; HRMS (MM: ESI-APCI) m/z calc'd for C₁₅H₁₅O [M+H]+: 199.1117; found 199.1120; [α]_D^{25} -41.23 (c 0.30, CHCl₃, 92% ee).

[Diagram of the transformation from 12 to 14]
## Determination of Enantiomeric Excess

<table>
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<tr>
<th>entry</th>
<th>compound</th>
<th>assay method and conditions</th>
<th>retention time of major isomer (min)</th>
<th>retention time of minor isomer (min)</th>
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<td>SFC, 10% MeOH in CO₂, 2.5 mL/min, AS-H col.</td>
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References


$^1$H NMR (500 MHz, CDCl$_3$) of compound 4a.

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SI 22
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4a.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4b.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4b.
$\text{H NMR (500 MHz, CDCl$_3$) of compound 4c.}$
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4c.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4d.
\[ ^{13}C \text{ NMR (126 MHz, CDCl}_3 \text{) of compound 4d.} \]
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4e.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4e.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4f.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4f.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4g.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4g.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4h.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound $4h$. 

[Diagram of compound $4h$]
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4i.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4i.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4j.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4j.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4k.
$\text{${}^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4k.}$
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4l.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4l.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 4m.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4m.
$^{1}H$ NMR (500 MHz, CDCl$_3$) of compound 4n.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4n.
$^{1}H$ NMR (500 MHz, CDCl$_3$) of compound 4o.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 4o.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5a.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5a.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5b.
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$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5b.
Figure SI-18A. $^1$H NMR (500 MHz, CDCl$_3$) of compound 5c.
Figure SI-18B. $^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5c.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5d.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5d.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5e.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound $5e$. 

![NMR spectrum of compound 5e.](image.png)
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5f.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5f.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5g.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5g.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5h.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5h.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5i.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5i.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5j.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5j.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5k.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5k.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5l.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5l.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5m.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5m.
$^1$H NMR (500 MHz, CDCl$_3$) of compound SI-3.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound SI-3.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 5n.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5n.
$^{1}$H NMR (500 MHz, CDCl$_3$) of compound 5o.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 5o.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 6.

Structure of compound 6.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 6.
$^{1}H$ NMR (500 MHz, CDCl$_3$) of compound 7.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 7.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 8.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 8.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 9.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 9.

![Chemical Structure](image)
$^1$H NMR (300 MHz, CDCl$_3$) of compound 12.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 12.
$^1$H NMR (500 MHz, CDCl$_3$) of compound 13.
$^{13}$C NMR (126 MHz, CDCl$_3$) of compound 13.