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Intermolecular Three-Component Synthesis of Fluorene Derivatives by Rhodium-Catalyzed Stitching Reaction/Remote Nucleophilic Substitution Sequence

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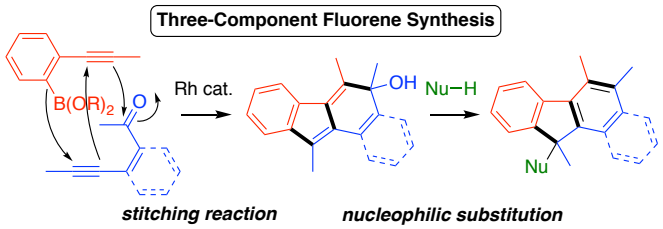


Abstract: A three-component synthesis of multi-substituted fluorene derivatives has been developed by devising a rhodium-catalyzed stitching reaction/remote nucleophilic substitution sequence. A variety of nucleophiles can be installed in the second step including both heteroatom and carbon nucleophiles. An efficient synthesis of 5*H*-benzo[*a*]fluoren-5-ones has also been realized by using *N*-(2-alkynyl)benzoylpyrrole as the reaction partner through a new reaction pathway.

Introduction

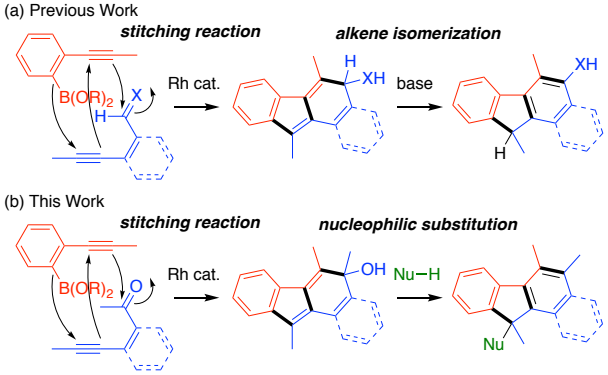
Catalytic intermolecular multi-component reactions represent a convergent and efficient approach for the synthesis of complex organic molecules from relatively simple precursors with minimal synthetic operations.[1] Such a synthetic approach also allows for a rapid preparation of a diverse array of analogs by modifying each reaction component, and is therefore particularly desirable for the synthesis of functional organic compounds where utilities and properties can be altered through the change of positions and types of substituents.

Among the functional π-conjugated organic compounds, fluorenes constitute one of the basic structures that can be utilized as luminescent or electronic materials in the form of small molecules as well as polymers/oligomers.[2] In addition, anionic forms of fluorene derivatives are often employed as effective ligands to transition metals, and some of those metal complexes can be used as catalysts for organic transformations including olefin polymerization.[3] Furthermore, some fluorenes having a heteroatom substituent at their bridging carbon (9-

position) are known to exhibit biological activity.[4] Because of the high utility of this structural motif, various synthetic methods of fluorenes and their derivatives have been developed to date,[5] but most of the existing methods rely on the use of intramolecular processes as exemplified in the classical Friedel–Crafts cyclization,[6] radical cyclization,[7] and more recent transition-metal-catalyzed cyclization involving C–H bond activation.[8] With regard to the more desirable intermolecular processes in view of convergent nature and structural diversity, several approaches have been reported, including palladium-catalyzed tandem cross-coupling/cyclization reactions to give 9*H*-fluorenones[9] or 9-unsubstituted 9*H*-fluorenes,[10] palladium-catalyzed methylenation reactions of 2-halobiaryls to give 9-unsubstituted 9*H*-fluorenes[11] or 9,9-disubstituted 9*H*-fluorenes,[12] and Brønsted acid-catalyzed three-component reactions to give 11-methoxy-11-aryl-11*H*-benzo[*a*]fluorenes.[13] Despite these recent progresses,[14] development of new and efficient intermolecular synthetic methods of fluorene derivatives continues to be of high importance to diversify accessible structures from easily available fragments.

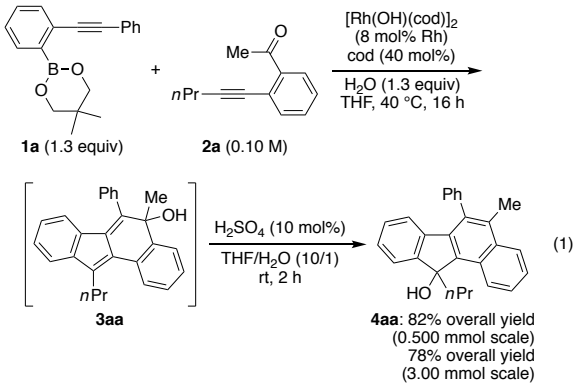
In this context, we recently reported an intermolecular synthesis of fluorene derivatives by employing a sequence of rhodium-catalyzed stitching reaction followed by alkene isomerization (Scheme 1a).[15] This method realized unprecedented bond connections toward the formation of a fluorene skeleton in a convergent manner to give a variety of 11-monosubstituted 11*H*-benzo[*a*]fluorenes and their analogs. Based on this synthetic approach, we imagined that it could be further extended to the synthesis of more substituted (benzo)fluorenes by combining the stitching reaction of 2-alkynylarylboronates and 2-alkynylaryl ketones/aldehydes under rhodium catalysis with a subsequent aromatization-driven remote nucleophilic substitution reaction. In this article, we describe our accomplishment of this new mode of intermolecular three-component synthesis of 11,11-disubstituted 11*H*-benzo[*a*]fluorenes and their analogs.

Scheme 1. (a) Previous Synthesis of (Benzo)fluorenes by Rhodium-Catalyzed Stitching Reaction Followed by Alkene Isomerization (X = O, NR, etc.) (b) Newly Devised Synthesis of (Benzo)fluorenes by Rhodium-Catalyzed Stitching Reaction Followed by Remote Nucleophilic Substitution



Results and Discussion

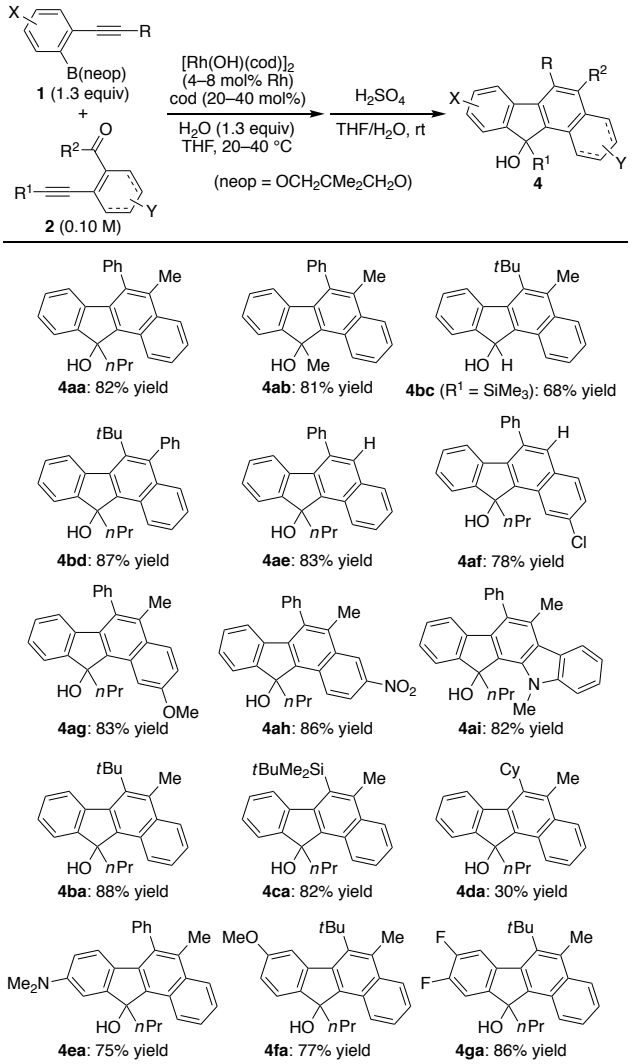
Initially, we chose 2-(phenylethynyl)phenylboronate **1a** and *o*-(1-pentynyl)acetophenone (**2a**; 0.500 mmol scale) as a model substrate combination for the rhodium-catalyzed stitching reaction (eq 1),[16] and found that, similarly to our previous report,[15] the reaction proceeded smoothly at 40 °C by using catalytic $[Rh(OH)(cod)]_2$ with additional 1,5-cyclooctadiene in the presence of H_2O in THF to cleanly provide corresponding stitched product **3aa**. Subsequent addition of H_2O as the nucleophile and a catalytic amount of H_2SO_4 in a one-pot manner without isolation of **3aa** led to the formation of 11*H*-benzo[*a*]fluoren-11-ol **4aa** in 82% overall yield through an aromatization-driven conjugate 1,5-nucleophilic substitution reaction.[17] The reaction can be readily scaled up and compound **4aa** was obtained in 78% overall yield on a 3.00 mmol scale.



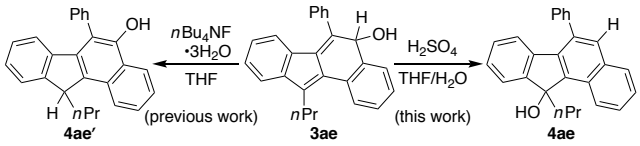
The present reaction sequence using H_2O as the nucleophile under acidic conditions in the second step was found to be readily applicable to the synthesis of various substituted 11*H*-

benzo[*a*]fluoren-11-ol derivatives as summarized in Scheme 2.[18] For example, substituents on the alkyne of ketones **2** can be either an alkyl group (**2a–b**) or a silyl group (**2c**), which is removable by treatment with *n*Bu$_4$NF after the stitching reaction, to give corresponding benzofluorenes **4aa**, **4ab**, and **4bc** in relatively high overall yields (68–82% yield).[19] In addition, phenyl ketone **2d** as well as aldehyde **2e** are similarly applicable to this reaction, giving **4bd** and **4ae**, respectively (83–87% yield). It is worth noting that, under our previous conditions,[15] selective alkene isomerization took place from stitched product **3ae** to give 11*H*-benzo[*a*]fluoren-5-ol **4ae'**, but isomeric 11*H*-benzo[*a*]fluoren-11-ol **4ae** was exclusively obtained under the present nucleophilic substitution conditions, showing the complementary nature of these two systems (Scheme 3). Furthermore, compounds **2** having substituents on the benzene ring (**2f–h**) as well as an heteroaryl group (**2i**) can also be used to give substituted benzofluorenes **4af–ah** and heteroarene-fused fluorene **4ai** in uniformly high yields (78–86% yield). With regard to the variation of arylboronates **1**, substituents on the alkyne can be changed from phenyl to *tert*-butyl group (**1b**) or a silyl group (**1c**) with similarly high efficiency (82–88% yield), but somewhat smaller substituents such as cyclohexyl group (**1d**) significantly decrease the reaction efficiency (30% yield) and even smaller *n*-propyl group cannot be effectively employed in the present reaction (16% ^{1}H NMR yield, not shown in Scheme 2). Electronically different arylboronates (**1e–g**) are well tolerated, giving corresponding products **4ea–ga** in 75–88% yield.

Scheme 2. Scope of Rhodium-Catalyzed Stitching Reaction Followed by Nucleophilic Substitution with H_2O



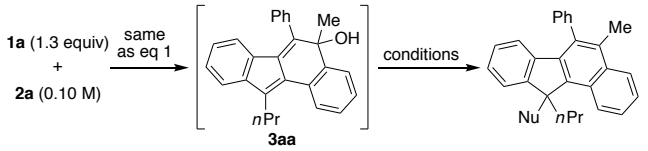
Scheme 3. Complementary Conversion of Stitched Product **3ae** to 11*H*-Benzo[*a*]fluoren-5-ol **4ae'** (left: previous work) and 11*H*-Benzo[*a*]fluoren-11-ol **4ae** (right: this work)



Importantly, the nucleophile that can be used in the second step of the present reaction sequence is not limited to H_2O. As shown in Table 1, several other heteroatom nucleophiles can be effectively employed as well to install OMe (**5**),[20] SCH_2Ph (**6**),[21] N_3 (**7**),[22] and Cl (**8**)[23] at 11-position of 11*H*-benzo[*a*]fluorenes (71–88% yield; entries 1–4). It is worth comparing the reactivity between non-aromatized stitched product **3aa** and aromatized 11*H*-benzo[*a*]fluoren-11-ol **4aa** toward nucleophilic substitution with MeOH (Scheme 4). While **3aa** can be readily converted to compound **5** at room temperature, **4aa** shows much lower

reactivity under the same conditions, indicating that aromatization from **3aa** functions as the driving force in the present conjugate nucleophilic substitution reaction. In addition to the heteroatom nucleophiles described above, allylation and hydride reduction can also take place to give compounds **9** and **10**, respectively, in high yields (77–78% yield; entries 5 and 6). Furthermore, treatment of **3aa** with *p*-toluenesulfonic acid in the absence of a nucleophile led to stereoselective 1,6-elimination to give 11-alkylidene-11*H*-benzo[*a*]fluorene (*E*)-**11** in 74% yield (eq 2).[24]

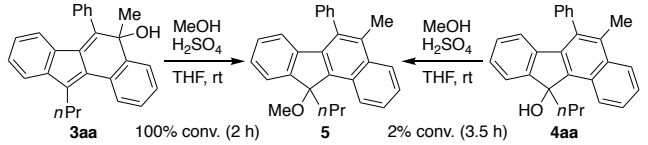
Table 1. Scope of Nucleophiles

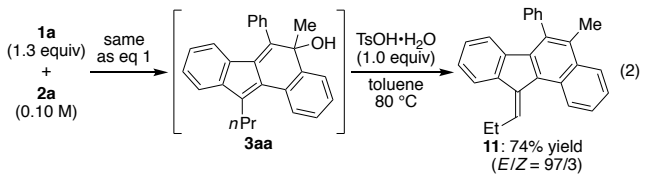


entry	conditions	product (Nu)	yield (%)[a]
1[b]	MeOH (20 equiv), H_2SO_4 (10 mol%), THF, rt	**5** (OMe)	78
2	$PhCH_2SH$ (1.0 equiv), CF_3CO_2H (1.0 equiv), CH_2Cl_2, 0 °C→rt	**6** (SCH_2Ph)	78
3	1. HCl (1.0 equiv), dioxane, rt; 2. NaN_3 (2.0 equiv), $ZnCl_2$ (1.0 equiv), DMF, 40 °C	**7** (N_3)	71
4	HClaq (20 equiv), toluene, rt	**8** (Cl)	88
5	CH_2=$CHCH_2SiMe_3$ (2.0 equiv), CF_3CO_2H (3.0 equiv), CH_2Cl_2, 0 °C→rt	**9** (CH_2CH=CH_2)	77
6	$HSiEt_3$ (2.0 equiv), CF_3CO_2H (3.0 equiv), CH_2Cl_2, 0 °C→rt	**10** (H)	78

[a] Overall isolated yield. [b] The stitching reaction was conducted in the presence of MeOH (20 equiv) instead of H_2O (1.3 equiv) and H_2SO_4 was subsequently added to the reaction mixture.

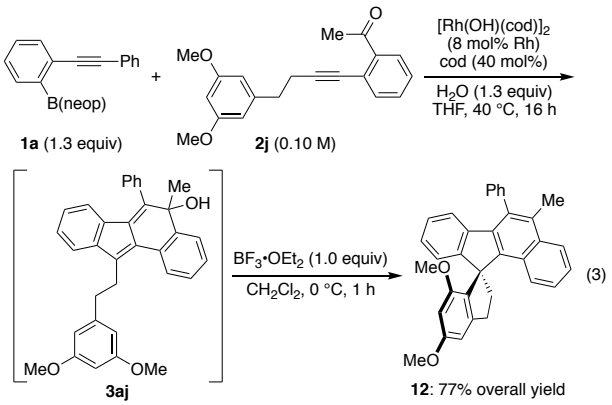
Scheme 4. Comparison of Nucleophilic Substitution of **3aa** and **4aa** with MeOH to Give **5**



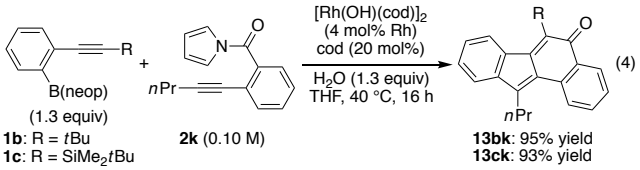


The present stitching reaction/nucleophilic substitution sequence can be extended to the synthesis of a more complex spirocyclic compound by using an *o*-alkynylacetophenone

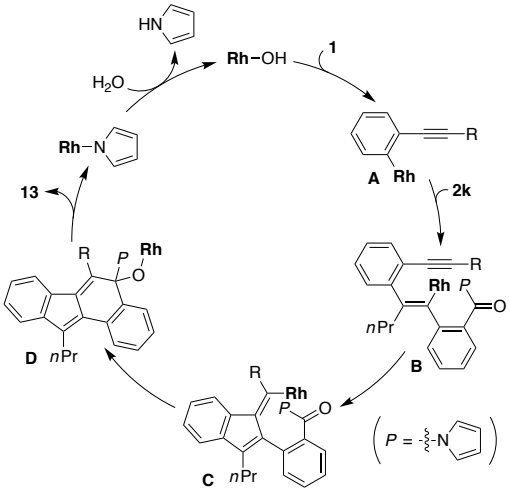
possessing a pronucleophile. For example, a rhodium-catalyzed stitching reaction of arylboronate **1a** with compound **2j** bearing 3,5-dimethoxyphenyl group gave intermediate **3aj**, which smoothly underwent intramolecular Friedel–Crafts-type substitution reaction by treating it with BF_3•OEt_2 to give corresponding spirocycle **12** in 77% yield (eq 3).[25]



During the course of our study, we found that the use of *N*-(2-alkynyl)benzoylpyrrole **2k** for the stitching reaction of arylboronate **1b** led to the formation of 5*H*-benzo[*a*]fluoren-5-one **13bk**[26] in 95% yield via elimination of the pyrrole moiety (eq 4). A similarly high yield of **13ck** was also achieved for the reaction of **1c** with **2k**, and these reactions represent the first example where *N*-acylpyrroles act as an acyl-donor in the rhodium-catalyzed carbon–carbon bond-forming reaction as far as we are aware.[27] Based on the fact that *N*-(hydroxymethyl)pyrroles are usually stable once they are formed[28] and that the reaction of **1b** with **2k** in the absence of H_2O shows much lower reactivity (28% yield of **13bk** under otherwise the same conditions), a proposed catalytic cycle of this transformation is illustrated in Scheme 5.[29] Initially, transmetalation of **1** with a hydroxorhodium catalyst gives arylrhodium species **A**. Insertion of alkyne of **2k** then leads to alkenylrhodium species **B**, which undergoes five-membered ring-forming intramolecular insertion of alkyne derived from **1** to give another alkenylrhodium species **C**. Subsequent intramolecular insertion of the carbonyl moiety in a stitching manner gives alkoxorhodium species **D**, and β-nitrogen elimination from this intermediate generates product **13** along with the formation of a rhodium pyrrolide species. Finally, hydrolysis with H_2O gives pyrrole and a hydroxorhodium species to close the catalytic cycle.[30]



Scheme 5. Proposed Catalytic Cycle for the Reaction of **1** with to Give **13** (**Rh** = Rh(cod))



Conclusion

We have developed a three-component synthesis of fluorene derivatives by devising a rhodium-catalyzed stitching reaction/remote nucleophilic substitution sequence. A variety of nucleophiles can be installed in the second step including both heteroatom and carbon nucleophiles. We have also found that 5*H*-benzo[*a*]fluoren-5-ones, which were previously difficult to synthesize, can be readily prepared by using *N*-(2-alkynyl)benzoylpyrrole as the reaction partner through a new reaction pathway. Future studies will be directed toward further development of new and efficient synthetic methods for other functional organic compounds.

Experimental Section

General Methods. All air- and moisture-sensitive manipulations were carried out with standard Schlenk techniques under nitrogen. The reactions with heating were performed using an oil bath. Et_3N was distilled over KOH under vacuum. MeOH was distilled over Mg turnings under nitrogen. Dehydrated THF, Et_2O, CH_2Cl_2, DMF, 1,4-dioxane, and toluene were degassed by purging nitrogen. **1a**,[31] **1c**,[16b] **2e**,[32] **2f**,[15] $PdCl_2(PPh_3)_2$,[33] $Pd(PPh_3)_4$,[34] and $[Rh(OH)(cod)]_2$[35] were synthesized following the literature procedures. All other commercial chemicals and solvents were used as received.

2-(*tert*-Butylethynyl)phenylboronic acid neopentylglycol ester (1b). *n*BuLi (6.26 mL, 9.70 mmol; 1.55 M solution in hexane) was added slowly over 1 h to a solution of 1-bromo-2-(*tert*-butylethynyl)benzene[36] (2.19 g, 9.24 mmol) and triisopropyl borate (2.34 mL, 10.2 mmol) in THF (40 mL) at –78 °C, and the mixture was stirred for 30 min at –78 °C and for 1.5 h at room temperature. The reaction was quenched with 1 M HClaq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/Et_2O = 7/2. The resulting boronic acid and 2,2-dimethyl-1,3-propanediol (897 mg, 8.61 mmol) were dissolved in CH_2Cl_2 (40 mL) and $MgSO_4$ (3.11 g, 25.8 mmol) was added to it, and the mixture was stirred for 2 h at room temperature. The solids were filtered off with CH_2Cl_2 and the solvents were removed under vacuum. The residue was dissolved in pentane, filtered through a PTFE membrane (pore size: 0.22 μm), and concentrated under vacuum to afford compound **1b** as a white solid (2.32 g, 8.59 mmol; 93% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.64 (dd, *J* = 7.4, 1.4 Hz, 1H), 7.39 (dd, *J* = 6.9, 1.4 Hz, 1H), 7.28 (td, *J* = 7.6, 1.4 Hz, 1H), 7.21 (td, *J* = 7.3, 1.4 Hz, 1H), 3.79 (s, 4H), 1.33 (s, 9H), 1.06 (s, 6H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 134.1, 132.6, 129.6, 128.1, 126.6, 99.7, 80.3, 72.4, 31.9, 31.2, 28.2, 22.1. Mp: 90–92 °C. HRMS (FAB, sector) calcd for $C_{17}H_{23}BO_2$ (M^+) 270.1786, found 270.1791.

2-(Cyclohexylethynyl)phenylboronic acid neopentylglycol ester (1d). This was synthesized following the procedure for compound **1b**. 92% yield (908 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.64 (dd, *J* = 7.3, 0.9 Hz, 1H), 7.40 (dd, *J* = 7.8, 0.9 Hz, 1H), 7.28 (td, *J* = 7.6, 1.4 Hz, 1H), 7.21 (td, *J* = 7.3, 1.4 Hz, 1H), 3.78 (s, 4H), 2.68-2.57 (m, 1H), 1.93-1.73 (m, 4H), 1.63-1.49 (m, 3H), 1.43-1.30 (m, 3H), 1.06 (s, 6H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 134.1, 132.7, 129.6, 128.2, 126.6, 95.7, 81.8, 72.5, 32.9, 31.9, 30.0, 26.2, 24.9, 22.1. HRMS (FAB, sector) calcd for $C_{19}H_{25}BO_2$ (M^+) 296.1942, found 296.1947.

2-(Phenylethynyl)-5-(dimethylamino)phenylboronic acid neopentylglycol ester (1e). This was synthesized following the procedure for compound **1b**. 86% yield (498 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.51-7.45 (m, 2H), 7.43 (d, *J* = 8.7 Hz, 1H), 7.34-7.28 (m, 2H), 7.28-7.22 (m, 1H), 7.07 (d, *J* = 2.7 Hz, 1H), 6.71 (dd, *J* = 8.7, 2.8 Hz, 1H), 3.83 (s, 4H), 3.00 (s, 6H), 1.08 (s, 6H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 149.5, 133.9, 131.3, 128.2, 127.2, 125.2, 117.7, 114.4, 113.7, 92.4, 88.6, 72.6, 40.4, 31.9, 22.1. Mp: 137–139 °C. HRMS (FAB, sector) calcd for $C_{21}H_{24}BNO_2$ (M^+) 333.1895, found 333.1904.

2-(*tert*-Butylethynyl)-4-methoxyphenylboronic acid neopentylglycol ester (1f). This was synthesized following the procedure for compound **1b**. 88% yield (817 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.60 (d, *J* = 8.2 Hz, 1H), 6.92 (d, *J* = 2.7 Hz, 1H), 6.78 (dd, *J* = 8.2, 2.7

Hz, 1H) 3.79 (s, 3H), 3.76 (s, 4H), 1.33 (s, 9H), 1.04 (s, 6H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 160.8, 136.0, 129.8, 117.4, 113.5, 99.6, 80.3, 72.4, 55.2, 31.9, 31.2, 28.2, 22.1. Mp: 90–92 °C. HRMS (FAB, sector) calcd for $C_{18}H_{25}BO_3$ (M^+) 300.1891, found 300.1903.

2-(*tert*-Butylethynyl)-4,5-difluorophenylboronic acid neopentylglycol ester (1g). This was synthesized following the procedure for compound **1b**. 91% yield (457 mg). ^1H NMR ($CDCl_3$, 400 MHz): δ 7.44 (dd, *J* = 11.4, 9.2 Hz, 1H), 7.17 (dd, *J* = 11.4, 7.8 Hz, 1H), 3.77 (s, 4H), 1.31 (s, 9H), 1.04 (s, 6H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 151.0 (dd, *J* = 251, 13.4 Hz), 149.5 (dd, *J* = 250, 12.5 Hz), 125.4 (dd, *J* = 7.7, 3.8 Hz), 123.0 (d, *J* = 15.3 Hz), 121.4 (d, *J* = 17.3 Hz), 100.3 (d, *J* = 1.9 Hz), 78.6 (d, *J* = 3.8 Hz), 72.5, 31.9, 31.0, 28.2, 22.1. Mp: 90–91 °C. HRMS (FAB, sector) calcd for $C_{17}H_{21}BF_2O_2$ (M^+) 306.1597, found 306.1604.

1-(2-(1-Pentynyl)phenyl)ethanone (2a) (CAS no. 1858190-38-1). 1-Pentyne (352 μL, 3.60 mmol) was added to a mixture of 1-(2-iodophenyl)ethanone[37] (738 mg, 3.00 mmol), $PdCl_2(PPh_3)_2$ (42.1 mg, 60.0 μmol), CuI (22.9 mg, 120 μmol), and Et_3N (1.25 mL, 9.00 mmol) in THF (3 mL), and the mixture was stirred for 5 h at room temperature. The reaction mixture was directly passed through a pad of silica gel with EtOAc. After removal of the solvent under vacuum, the residue was chromatographed on silica gel with hexane/EtOAc = 25/1 to afford compound **2a** as a pale yellow oil (535 mg, 2.87 mmol; 96% yield). ^1H NMR ($CDCl_3$, 400 MHz): δ 7.66 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.49 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.40 (td, *J* = 7.6, 1.4 Hz, 1H), 7.32 (td, *J* = 7.6, 1.4 Hz, 1H), 2.72 (s, 3H), 2.44 (t, *J* = 7.1 Hz, 2H), 1.66 (sext, *J* = 7.2 Hz, 2H), 1.06 (t, *J* = 7.3 Hz, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 201.0, 141.2, 134.1, 131.1, 128.4, 127.6, 122.5, 96.8, 79.9, 30.1, 22.0, 21.8, 13.7.

1-(2-(1-Propynyl)phenyl)ethanone (2b) (CAS no. 171258-00-7). Iodomethane (191 μL, 3.00 mmol) was added dropwise to a stirring suspension of Mg turnings (80.2 mg, 3.30 mmol) in Et_2O (1.0 mL), and the mixture was stirred for 20 min at room temperature. This was then added dropwise with the aid of additional Et_2O (1.0 mL) to a solution of 2-(1-propynyl)benzaldehyde[15] (288 mg, 2.00 mmol) in Et_2O (3.0 mL) at 0 °C, and the mixture was stirred for 4 h at 0 °C. The reaction was quenched with saturated NH_4Claq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was dissolved in CH_2Cl_2 (6.0 mL) and pyridinium chlorochromate (647 mg, 3.00 mmol) was added to it, and the mixture was stirred for 4 h at room temperature. The reaction mixture was directly passed through a pad of silica gel with CH_2Cl_2. After removal of the solvent under vacuum, the residue was chromatographed on silica gel with hexane/EtOAc = 15/1 to afford compound **2b** as a pale yellow oil (291 mg, 1.84 mmol; 92% yield). ^1H NMR ($CDCl_3$, 400 MHz): δ 7.66 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.48

(dd, J = 7.8, 1.4 Hz, 1H), 7.40 (td, J = 7.6, 1.4 Hz, 1H), 7.32 (td, J = 7.6, 1.4 Hz, 1H), 2.71 (s, 3H), 2.10 (s, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 201.0, 141.1, 134.0, 131.2, 128.4, 127.6, 122.5, 92.3, 78.9, 30.0, 4.7.

1-(2-(Trimethylsilylethynyl)phenyl)ethanone (2c) (CAS no. 202871-98-5). This was synthesized following the procedure for compound **2a**. 96% yield (529 mg). ^1H NMR ($CDCl_3$, 498 MHz): δ 7.68 (dd, J = 7.8, 1.4 Hz, 1H), 7.55 (dd, J = 7.6, 1.4 Hz, 1H), 7.42 (td, J = 7.4, 1.5 Hz, 1H), 7.38 (td, J = 7.5, 1.4 Hz, 1H), 2.74 (s, 3H), 0.26 (s, 9H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 200.6, 141.7, 134.3, 131.1, 128.6, 128.5, 121.5, 104.0, 101.1, 30.2, –0.2.

(2-(1-Pentynyl)phenyl)(phenyl)methanone (2d) (CAS no. 1006056-21-8). This was synthesized following the procedure for compound **2a**. 78% yield (486 mg). ^1H NMR ($CDCl_3$, 400 MHz): δ 7.85-7.79 (m, 2H), 7.56 (tt, J = 7.3, 1.4 Hz, 1H), 7.51-7.33 (m, 6H), 2.08 (t, J = 6.9 Hz, 2H), 1.26 (sext, J = 7.2 Hz, 2H), 0.78 (t, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 197.4, 141.8, 137.4, 133.0, 132.6, 130.2, 130.0, 128.3, 128.1, 127.4, 122.6, 96.5, 78.8, 21.7, 21.3, 13.4.

1-(4-Methoxy-2-(1-pentynyl)phenyl)ethanone (2g). This was synthesized following the procedure for compound **2b**. 88% yield (177 mg). ^1H NMR ($CDCl_3$, 400 MHz): δ 7.75 (d, J = 8.7 Hz, 1H), 6.97 (d, J = 2.8 Hz, 1H), 6.85 (dd, J = 8.7, 2.8 Hz, 1H), 3.84 (s, 3H), 2.70 (s, 3H), 2.45 (t, J = 7.1 Hz, 2H), 1.67 (sext, J = 7.2 Hz, 2H), 1.07 (t, J = 7.3 Hz, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 198.8, 161.9, 133.4, 131.3, 125.1, 118.6, 114.1, 96.9, 80.4, 55.6, 30.0, 22.0, 21.8, 13.8. HRMS (FAB, sector) calcd for $C_{14}H_{17}O_2$ ($M+H^+$) 217.1223, found 217.1229.

1-(5-Nitro-2-(1-pentynyl)phenyl)ethanone (2h). This was synthesized following the procedure for compound **2a**. 64% yield (148 mg). ^1H NMR ($CDCl_3$, 400 MHz): δ 8.51 (d, J = 2.3 Hz, 1H), 8.23 (dd, J = 8.7, 2.3 Hz, 1H), 7.64 (d, J = 8.7 Hz, 1H), 2.76 (s, 3H), 2.50 (t, J = 7.1 Hz, 2H), 1.69 (sext, J = 7.2 Hz, 2H), 1.07 (t, J = 7.3 Hz, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 198.5, 146.6, 141.9, 135.2, 129.0, 125.3, 123.7, 103.3, 79.0, 29.9, 22.0, 21.8, 13.7. HRMS (FAB, sector) calcd for $C_{13}H_{14}NO_3$ ($M+H^+$) 232.0968, found 232.0971.

1-(1-Methyl-2-(1-pentynyl)-1*H*-3-indolyl)ethanone (2i). Iodomethane (210 μL, 3.30 mmol) was added dropwise to a stirring suspension of Mg turnings (88.2 mg, 3.63 mmol) in Et_2O (2.0 mL), and the mixture was stirred for 20 min at room temperature. This was then added dropwise with the aid of additional Et_2O (1.0 mL) to a solution of 1-methyl-2-(1-pentynyl)-1*H*-indole-3-carbaldehyde[15] (495 mg, 2.20 mmol) in Et_2O (12 mL) at 0 °C, and the mixture was stirred for 6 h at 0 °C. The reaction was quenched with saturated NH_4Claq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was dissolved in CH_2Cl_2 (10

mL) and 4-methylmorpholine *N*-oxide (531 mg, 4.40 mmol) and tetrapropylammonium perruthenate (39.9 mg, 0.110 mmol) were added to it at 0 °C, and the mixture was stirred for 3 h at 0 °C. The reaction mixture was directly passed through a pad of silica gel with EtOAc. After removal of the solvent under vacuum, the residue was chromatographed on silica gel with hexane/EtOAc = 5/1, and the solid thus obtained was washed with pentane to afford compound **2i** as a white solid (328 mg, 1.37 mmol; 62% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.47-8.42 (m, 1H), 7.35-7.25 (m, 3H), 3.83 (s, 3H), 2.73 (s, 3H), 2.61 (t, *J* = 7.1 Hz, 2H), 1.75 (sext, *J* = 7.2 Hz, 2H), 1.12 (t, *J* = 7.3 Hz, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 193.9, 136.7, 127.9, 125.9, 124.1, 123.1, 122.9, 119.0, 109.3, 104.6, 72.6, 31.0, 29.8, 22.0, 21.9, 13.8. Mp: 103–104 °C. HRMS (FAB, sector) calcd for $C_{16}H_{18}NO$ ($M+H^+$) 240.1383, found 240.1387.

1-(2-(4-(3,5-Dimethoxyphenyl)-1-butynyl)phenyl)ethanone (2j). $HgCl_2$ (11.3 mg, 41.6 μmol) was added to a stirring suspension of Mg turnings (128 mg, 5.28 mmol) in Et_2O (2.0 mL), and the mixture was stirred for 30 min at room temperature. This was cooled to 0 °C and propargyl bromide (361 μL, 4.80 mmol) was added slowly over 1 h and the mixture was stirred for 30 min at 0 °C. This was then added dropwise with the aid of THF (1.5 mL) to a solution of 3,5-dimethoxybenzyl bromide (739 mg, 3.20 mmol) in THF (2.0 mL) at 0 °C, and the mixture was stirred for 30 min at 0 °C and for 24 h at 40 °C. The reaction was quenched with saturated NH_4Claq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 20/1 to afford 1-(3-butynyl)-3,5-dimethoxybenzene as a colorless oil (577 mg, 3.03 mmol; 95% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 6.39 (d, *J* = 2.3 Hz, 2H), 6.33 (t, *J* = 2.3 Hz, 1H), 3.78 (s, 6H), 2.79 (t, *J* = 7.8 Hz, 2H), 2.48 (td, *J* = 7.8, 2.8 Hz, 2H), 1.99 (t, *J* = 2.8 Hz, 1H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 160.9, 142.9, 106.6, 98.4, 83.9, 69.0, 55.3, 35.2, 20.4.

1-(3-Butynyl)-3,5-dimethoxybenzene (457 mg, 2.40 mmol) was added to a mixture of 1-(2-iodophenyl)ethanone (492 mg, 2.00 mmol), $Pd(PPh_3)_4$ (46.2 mg, 40.0 μmol), CuI (15.2 mg, 80.0 μmol), and Et_3N (834 μL, 6.00 mmol) in THF (2 mL), and the mixture was stirred for 12 h at room temperature and for 24 h at 40 °C. The reaction mixture was directly passed through a pad of silica gel with EtOAc. After removal of the solvent under vacuum, the residue was chromatographed on silica gel with hexane/EtOAc = 8/1 to afford compound **2j** as a red oil (477 mg, 1.55 mmol; 77% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.65 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.46 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.39 (td, *J* = 7.6, 1.4 Hz, 1H), 7.33 (td, *J* = 7.6, 1.4 Hz, 1H), 6.43 (d, *J* = 2.3 Hz, 2H), 6.34 (t, *J* = 2.3 Hz, 1H), 3.78 (s, 6H), 2.89 (t, *J* = 7.3 Hz, 2H), 2.76 (t, *J* = 7.3 Hz, 2H), 2.63 (s, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 200.8, 160.9, 142.8, 141.1,

134.1, 131.1, 128.4, 127.7, 122.2, 106.6, 98.4, 95.8, 80.5, 55.3, 35.1, 29.9, 21.7. HRMS (FAB, sector) calcd for $C_{20}H_{21}O_3$ ($M+H^+$) 309.1485, found 309.1489.

(2-(1-Pentynyl)phenyl)(1*H*-1-pyrrolyl)methanone (2k). *n*BuLi (4.62 mL, 7.35 mmol; 1.59 M solution in hexane) was added slowly over 8 min to a solution of 1-bromo-2-(1-pentynyl)benzene[38] (1.56 g, 7.00 mmol) in THF (35 mL) at –78 °C, and the mixture was stirred for 30 min at –78 °C. CO_2 was then bubbled through the mixture for 30 min while gradually raising the temperature to room temperature. The reaction was quenched with 1 M HClaq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum to afford 2-(1-pentynyl)benzoic acid as a red oil. This was dissolved in CH_2Cl_2 (30 mL), and DMF (12.0 μL, 0.156 mmol) and oxalyl chloride (1.20 mL, 14.0 mmol) were added to it, and the mixture was stirred for 3 h at room temperature. The volatiles were removed under vacuum to afford 2-(1-pentynyl)benzoyl chloride as a purple oil. Separately, NaH (267 mg, 6.68 mmol; 60 wt% in mineral oil) was added to a solution of pyrrole (440 μL, 6.36 mmol) in THF (20 mL) at 0 °C, and the mixture was stirred for 30 min at 0 °C and for 30 min at room temperature. After cooled to 0 °C, a solution of 2-(1-pentynyl)benzoyl chloride obtained above in THF (10 mL) was added to it and the mixture was stirred for 20 h at room temperature. The reaction was quenched with 1 M HClaq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 20/1 to afford compound **2k** as a yellow oil (1.25 g, 5.27 mmol; 83% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.53-7.42 (m, 3H), 7.41-7.34 (m, 1H), 7.15 (bs, 2H), 6.33-6.26 (m, 2H), 2.21 (t, J = 6.9 Hz, 2H), 1.40 (sext, J = 7.2 Hz, 2H), 0.87 (t, J = 7.3 Hz, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 167.3, 136.8, 132.5, 130.4, 127.8, 127.5, 122.7, 120.7, 113.3, 96.2, 77.4, 21.8, 21.4, 13.4. HRMS (FAB, sector) calcd for $C_{16}H_{16}NO$ ($M+H^+$) 238.1226, found 238.1231.

Procedure for Equation 1. 1,5-Cyclooctadiene (24.5 μL, 0.200 mmol), H_2O (11.7 μL, 0.649 mmol), and THF (0.5 mL) were added to a solution of $[Rh(OH)(cod)]_2$ (9.1 mg, 40 μmol Rh), compound **1a** (189 mg, 0.650 mmol), and compound **2a** (93.1 mg, 0.500 mmol) in THF (4.5 mL), and the mixture was stirred for 16 h at 40 °C. After cooled to room temperature, H_2O (0.50 mL) and conc. H_2SO_4 (2.8 μL, 50 μmol) were added to it and the mixture was stirred for 2 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 10/1, and the solid thus obtained was washed with cold pentane to afford 5-

methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (**4aa**) as a white solid (149 mg, 0.409 mmol; 82% yield). The reaction on a 3.00 mmol scale of **2a** gave compound **4aa** in 78% yield (848 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.62 (dd, *J* = 7.3, 1.8 Hz, 1H), 8.14 (dd, *J* = 7.8, 1.8 Hz, 1H), 7.65-7.48 (m, 6H), 7.39-7.29 (m, 2H), 7.18 (td, *J* = 7.3, 0.9 Hz, 1H), 6.96 (td, *J* = 7.6, 0.9 Hz, 1H), 6.03 (d, *J* = 7.8 Hz, 1H), 2.56 (ddd, *J* = 12.4, 10.0, 4.6 Hz, 1H), 2.47 (s, 3H), 2.46-2.35 (m, 1H), 2.15 (s, 1H), 0.81-0.59 (m, 5H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 150.9, 141.2, 140.9, 140.4, 135.6, 135.0, 133.6, 132.8, 129.8, 129.6, 129.3, 129.0, 128.9, 128.4, 127.6, 127.0, 126.1, 125.9, 125.6, 125.2, 122.8, 122.6, 84.2, 42.4, 17.4, 16.3, 14.3. Mp: 132–134 °C. HRMS (FAB, sector) calcd for $C_{27}H_{24}O$ (M^+) 364.1822, found 364.1832.

General Procedure for Scheme 2. 1,5-Cyclooctadiene (4.9–9.8 μL, 40–80 μmol), H_2O (4.7 μL, 0.26 mmol), and THF (0.5 mL) were added to a solution of $[Rh(OH)(cod)]_2$ (1.8–3.6 mg, 7.9–16 μmol Rh), compound **1** (0.260 mmol), and compound **2** (0.200 mmol) in THF (1.5 mL), and the mixture was stirred for 16 h at 40 °C. After cooled to room temperature, H_2O (0.20 mL) and conc. H_2SO_4 (5.0 μL, 90 μmol) were added to it and the mixture was stirred for 1–5 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel to afford compound **4**.

5,11-Dimethyl-6-phenyl-11*H*-benzo[*a*]fluoren-11-ol (4ab). 8 mol% Rh and 40 mol% cod were used. The crude material was purified by silica gel chromatography with hexane/EtOAc = 9/1, and the solid thus obtained was washed with cold pentane. Pale orange solid. 81% yield (54.4 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.62 (dd, *J* = 7.8, 1.4 Hz, 1H), 8.16 (dd, *J* = 8.2, 1.4 Hz, 1H), 7.67-7.48 (m, 6H), 7.38-7.29 (m, 2H), 7.21 (td, *J* = 7.3, 0.9 Hz, 1H), 6.98 (td, *J* = 7.6, 1.4 Hz, 1H), 6.06 (d, *J* = 7.8 Hz, 1H), 2.47 (s, 3H), 2.07 (s, 1H), 1.97 (s, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 152.3, 142.2, 140.8, 139.3, 135.2, 134.5, 133.7, 132.9, 129.7, 129.6, 129.03, 128.95, 128.4, 127.7, 127.1, 126.1, 125.9, 125.6, 125.4, 123.0, 122.4, 81.0, 27.2, 16.2. Mp: 113–115 °C. HRMS (FAB, sector) calcd for $C_{25}H_{20}O$ (M^+) 336.1509, found 336.1516.

6-(*tert*-Butyl)-5-methyl-11*H*-benzo[*a*]fluoren-11-ol (4bc). 8 mol% Rh and 40 mol% cod were used. After rhodium catalysis, the reaction mixture was passed through a pad of silica gel with EtOAc and concentrated under vacuum. This was dissolved in Et_2O, washed with H_2O, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was dissolved in THF (0.6 mL) and nBu$_4$NF•3H_2O (63.1 mg, 0.200 mmol) in THF (0.4 mL) was added to it at 0 °C, and the mixture was stirred for 24 h at 30 °C. After cooled to room temperature, THF (1.0 mL), H_2O (0.20 mL) and conc. H_2SO_4 (0.20 mL, 3.6 mmol) were added to it and the mixture was

stirred for 2 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 10/1, and the solid thus obtained was washed with cold pentane. Pale yellow solid. 68% yield (41.3 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.38-8.32 (m, 1H), 8.10-8.03 (m, 1H), 8.01 (d, *J* = 7.8 Hz, 1H), 7.70 (d, *J* = 7.4 Hz, 1H), 7.57-7.47 (m, 2H), 7.38 (td, *J* = 7.8, 1.4 Hz, 1H), 7.28 (td, *J* = 7.3, 0.9 Hz, 1H), 5.91 (d, *J* = 10.5 Hz, 1H), 2.87 (s, 3H), 1.767 (d, *J* = 10.1 Hz, 1H), 1.765 (s, 9H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 146.9, 143.9, 143.0, 141.0, 137.5, 134.5, 134.3, 128.1, 128.0, 127.3, 126.3, 126.1, 125.8, 125.2, 124.6, 124.5, 74.6, 37.9, 32.8, 20.6. Mp: 149–150 °C. HRMS (FAB, sector) calcd for $C_{22}H_{22}O$ (M^+) 302.1665, found 302.1673.

6-(*tert*-Butyl)-5-phenyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4bd). 4 mol% Rh and 20 mol% cod were used. 3.60 mmol of conc. H_2SO_4 was used in the subsequent step. The crude material was purified by silica gel chromatography with hexane/CH_2Cl_2 = 1/1. White solid. 87% yield (70.6 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.66 (d, *J* = 8.3 Hz, 1H), 8.08 (d, *J* = 7.8 Hz, 1H), 7.65 (dd, *J* = 7.3, 1.4 Hz, 1H), 7.51-7.36 (m, 6H), 7.36-7.21 (m, 4H), 2.65-2.54 (m, 1H), 2.48-2.36 (m, 1H), 2.13 (s, 1H), 1.43 (s, 9H), 0.87-0.62 (m, 5H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 151.3, 145.5, 142.5, 142.3, 141.6, 139.2, 137.0, 134.5, 132.5, 131.6, 128.2, 127.81, 127.78, 127.7, 127.5, 127.4, 127.2, 126.5, 125.8, 125.5, 124.6, 122.4, 83.9, 42.9, 37.6, 34.3, 17.4, 14.3. Mp: 218–219 °C. HRMS (FAB, sector) calcd for $C_{30}H_{30}O$ (M^+) 406.2291, found 406.2300.

6-Phenyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4ae). 8 mol% Rh and 40 mol% cod were used and conducted for 20 h at 20 °C. The crude material was purified by silica gel chromatography with hexane/EtOAc = 12/1. Pale yellow solid. 83% yield (58.3 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.57 (d, *J* = 8.2 Hz, 1H), 7.89 (d, *J* = 8.2 Hz, 1H), 7.71 (s, 1H), 7.65-7.45 (m, 8H), 7.23 (t, *J* = 7.3 Hz, 1H), 7.06 (t, *J* = 7.6 Hz, 1H), 6.73 (d, *J* = 7.8 Hz, 1H), 2.66-2.52 (m, 1H), 2.51-2.37 (m, 1H), 2.15 (bs, 1H), 0.92-0.61 (m, 5H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 150.9, 144.1, 140.9, 139.9, 136.1, 135.0, 133.5, 130.7, 129.7, 129.2, 129.0, 128.9, 128.6, 128.44, 128.35, 127.8, 127.2, 126.5, 126.0, 124.6, 122.9, 122.8, 84.2, 42.3, 17.4, 14.3. Mp: 134–136 °C. HRMS (FAB, sector) calcd for $C_{26}H_{22}O$ (M^+) 350.1665, found 350.1671.

2-Chloro-6-phenyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4af). 8 mol% Rh and 40 mol% cod were used and conducted for 20 h at 20 °C. The crude material was purified by silica gel chromatography with hexane/EtOAc = 10/1, and the solid thus obtained was washed with cold pentane. Yellow solid. 78% yield (60.3 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.55 (s, 1H),

7.81 (d, *J* = 8.7 Hz, 1H), 7.68 (s, 1H), 7.56 (d, *J* = 7.4 Hz, 1H), 7.55-7.46 (m, 5H), 7.44 (dd, *J* = 8.7, 2.3 Hz, 1H), 7.25 (t, *J* = 7.6 Hz, 1H), 7.06 (t, *J* = 7.6 Hz, 1H), 6.73 (d, *J* = 7.8 Hz, 1H), 2.58-2.33 (m, 2H), 2.19 (d, *J* = 5.5 Hz, 1H), 0.93-0.61 (m, 5H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 101 MHz, 60 °C): δ 151.0, 143.6, 140.7, 139.6, 136.5, 136.2, 132.6, 131.8, 130.6, 130.5, 129.7, 129.4, 128.7, 128.6, 128.0, 127.6, 127.0, 123.6, 123.2, 122.9, 84.3, 42.6, 17.5, 14.2. Mp: 110–112 °C. HRMS (FAB, sector) calcd for $C_{26}H_{21}ClO$ (M^+) 384.1275, found 384.1281.

2-Methoxy-5-methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4ag). 8 mol% Rh and 40 mol% cod were used. The crude material was purified by silica gel chromatography with hexane/EtOAc = 7/1, and the solid thus obtained was washed with cold pentane. Pale yellow solid. 83% yield (65.3 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.04 (d, *J* = 9.6 Hz, 1H), 7.94 (d, *J* = 2.8 Hz, 1H), 7.58-7.47 (m, 4H), 7.36-7.27 (m, 2H), 7.22 (dd, *J* = 9.4, 2.7 Hz, 1H), 7.18 (td, *J* = 7.3, 0.9 Hz, 1H), 6.96 (td, *J* = 7.6, 0.9 Hz, 1H), 6.04 (d, *J* = 7.8 Hz, 1H), 4.03 (s, 3H), 2.65-2.51 (m, 1H), 2.47-2.32 (m, 1H), 2.43 (s, 3H), 2.12 (s, 1H), 0.79-0.60 (m, 5H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 101 MHz): δ 157.5, 150.9, 140.9, 140.4, 139.8, 136.0, 133.5, 132.9, 130.4, 130.0, 129.8, 129.0, 128.8, 128.3, 128.2, 127.5, 127.1, 126.9, 122.8, 122.5, 118.3, 103.5, 84.1, 55.5, 41.8, 17.4, 16.3, 14.3. Mp: 195–197 °C. HRMS (FAB, sector) calcd for $C_{28}H_{26}O_2$ (M^+) 394.1927, found 394.1931.

5-Methyl-3-nitro-6-phenyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4ah). 8 mol% Rh and 40 mol% cod were used. 0.45 mmol of conc. H_2SO_4 was used in the subsequent step. The crude material was purified by silica gel chromatography with hexane/CH_2Cl_2 = 1/2, and the solid thus obtained was washed with pentane. Yellow solid. 86% yield (70.5 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 9.12 (d, *J* = 2.3 Hz, 1H), 8.74 (d, *J* = 9.2 Hz, 1H), 8.34 (dd, *J* = 9.2, 2.3 Hz, 1H), 7.63-7.51 (m, 4H), 7.38-7.23 (m, 3H), 7.01 (td, *J* = 7.6, 0.9 Hz, 1H), 6.08 (d, *J* = 7.8 Hz, 1H), 2.56 (s, 3H), 2.55-2.35 (m, 2H), 2.18 (s, 1H), 0.79-0.55 (m, 5H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 101 MHz): δ 151.1, 145.2, 141.4, 139.7, 139.6, 139.4, 137.1, 136.6, 131.83, 131.76, 129.5, 129.4, 129.28, 129.26, 128.8, 128.24, 128.22, 126.7, 123.6, 122.8, 122.7, 119.5, 84.1, 42.7, 17.4, 16.5, 14.2. Mp: 252–255 °C (dec). HRMS (FAB, sector) calcd for $C_{27}H_{24}NO_3$ ($M+H^+$) 410.1751, found 410.1755.

6,11-Dimethyl-5-phenyl-12-propyl-11,12-dihydroindeno[2,1-*a*]carbazol-12-ol (4ai). 8 mol% Rh and 40 mol% cod were used. The crude material was purified by silica gel chromatography with hexane/EtOAc = 8/1, and the solid thus obtained was washed with pentane. White solid. 82% yield (68.4 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.25 (d, *J* = 7.8 Hz, 1H), 7.59-7.45 (m, 6H), 7.39-7.31 (m, 2H), 7.31-7.24 (m, 1H), 7.16 (td, *J* = 7.6, 0.9 Hz, 1H), 6.94 (td, *J* = 7.8, 1.4 Hz, 1H), 6.03 (d, *J* = 7.8 Hz, 1H), 4.46 (s, 3H), 2.63 (s, 3H), 2.57-2.46 (m,

1H), 2.46-2.35 (m, 1H), 2.35 (s, 1H), 0.89-0.60 (m, 5H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 149.8, 143.1, 140.8, 140.7, 137.9, 136.4, 132.8, 130.8, 130.4, 129.3, 129.0, 128.9, 128.5, 127.4, 127.0, 126.9, 125.5, 124.2, 122.9, 122.8, 122.4, 119.4, 108.9, 83.3, 42.8, 33.8, 18.0, 17.5, 14.3. Mp: 122–125 °C. HRMS (FAB, sector) calcd for $C_{30}H_{27}NO$ (M^+) 417.2087, found 417.2093.

6-(*tert*-Butyl)-5-methyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4ba). 4 mol% Rh and 20 mol% cod were used. 0.45 mmol of conc. H_2SO_4 was used in the subsequent step. The crude material was purified by silica gel chromatography with hexane/EtOAc = 14/1. White solid. 88% yield (60.7 mg). ^1H NMR ($CDCl_3$, 400 MHz): δ 8.56-8.49 (m, 1H), 8.12-8.05 (m, 1H), 7.93 (d, *J* = 7.8 Hz, 1H), 7.58 (dd, *J* = 7.4, 1.4 Hz, 1H), 7.53-7.45 (m, 2H), 7.33 (td, *J* = 7.6, 1.4 Hz, 1H), 7.25 (t, *J* = 7.3 Hz, 1H), 2.86 (s, 3H), 2.54 (td, *J* = 12.4, 4.6 Hz, 1H), 2.40 (ddd, *J* = 12.8, 11.4, 4.6 Hz, 1H), 1.97 (bs, 1H), 1.75 (s, 9H), 0.95-0.70 (m, 2H), 0.68 (t, *J* = 7.1 Hz, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 151.0, 143.8, 143.5, 142.8, 136.9, 134.20, 134.16, 127.5, 127.2, 126.8, 126.1, 125.6, 125.2, 125.0, 124.5, 122.5, 84.4, 42.6, 37.7, 32.6, 20.5, 17.5, 14.3. Mp: 181–182 °C. HRMS (FAB, sector) calcd for $C_{25}H_{28}O$ (M^+) 344.2135, found 344.2147.

6-(*tert*-Butyldimethylsilyl)-5-methyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4ca). 4 mol% Rh and 20 mol% cod were used. 0.40 mL of H_2O and 0.45 mmol of conc. H_2SO_4 were used in the subsequent step. The crude material was purified by silica gel chromatography with hexane/EtOAc = 14/1. White solid. 82% yield (66.1 mg). ^1H NMR ($CDCl_3$, 400 MHz): δ 8.56 (d, *J* = 8.2 Hz, 1H), 8.11 (d, *J* = 7.8 Hz, 1H), 7.85 (d, *J* = 7.4 Hz, 1H), 7.61-7.48 (m, 3H), 7.32 (td, *J* = 7.4, 0.9 Hz, 1H), 7.28 (dd, *J* = 7.3, 1.4 Hz, 1H), 2.92 (s, 3H), 2.57-2.46 (m, 1H), 2.46-2.35 (m, 1H), 2.03 (s, 1H), 1.33 (s, 9H), 0.93-0.61 (m, 5H), 0.354 (s, 3H), 0.346 (s, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 151.0, 144.6, 142.5, 142.2, 141.9, 132.34, 132.32, 129.5, 127.0, 126.8, 126.7, 125.7, 125.11, 125.06, 124.6, 122.5, 84.4, 42.5, 30.6, 24.2, 18.3, 17.5, 14.3, 2.9, 2.4. Mp: 186–188 °C. HRMS (FAB, sector) calcd for $C_{27}H_{34}OSi$ (M^+) 402.2373, found 402.2376.

6-Cyclohexyl-5-methyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4da). 8 mol% Rh and 40 mol% cod were used on a 0.400 mmol scale. 0.90 mmol of conc. H_2SO_4 was used in the subsequent step. The crude material was purified by silica gel chromatography with hexane/CH_2Cl_2 = 1/1 and further purified by silica gel preparative TLC with hexane/EtOAc = 10/1. Yellow amorphous. 30% yield (44.0 mg). ^1H NMR ($CDCl_3$, 400 MHz): δ 8.60-8.53 (m, 1H), 8.13-8.07 (m, 1H), 7.84 (d, *J* = 7.8 Hz, 1H), 7.63 (dd, *J* = 7.4, 1.4 Hz, 1H), 7.55-7.46 (m, 2H), 7.40 (td, *J* = 7.6, 1.4 Hz, 1H), 7.33 (t, *J* = 7.3, 1H), 3.84 (tt, *J* = 12.6, 3.0, 1H), 2.86 (s, 3H), 2.57-2.44 (m, 1H), 2.43-2.32 (m, 1H), 2.30-2.15 (m, 2H), 2.09 (s, 1H), 2.06-1.84 (m, 5H),

1.68-1.38 (m, 3H), 0.78-0.50 (m, 5H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 101 MHz): δ 151.5, 142.0, 141.1, 138.8, 136.6, 134.0, 133.8, 128.8, 128.2, 126.9, 125.7, 125.3, 125.1, 124.6, 123.5, 123.1, 83.9, 42.5, 41.7, 31.1, 30.7, 27.8, 27.6, 26.4, 17.8, 17.4, 14.2. HRMS (FAB, sector) calcd for $C_{27}H_{30}O$ (M^+) 370.2291, found 370.2295.

9-(Dimethylamino)-5-methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4ea). 8 mol% Rh and 40 mol% cod were used and conducted for 20 h at 20 °C. The crude material was purified by silica gel chromatography with hexane/EtOAc = 5/1, and further purified by GPC with $CHCl_3$. White solid. 75% yield (61.2 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.56 (d, *J* = 7.8 Hz, 1H), 8.11 (d, *J* = 8.2 Hz, 1H), 7.60-7.45 (m, 5H), 7.38-7.27 (m, 2H), 6.97 (s, 1H), 6.34 (d, *J* = 7.3 Hz, 1H), 5.89 (d, *J* = 8.7 Hz, 1H), 2.96 (s, 6H), 2.63-2.51 (m, 1H), 2.45 (s, 3H), 2.39-2.27 (m, 1H), 2.19 (s, 1H), 0.86-0.60 (m, 5H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 101 MHz): δ 152.8, 150.0, 141.2, 139.5, 136.5, 134.5, 133.2, 131.9, 129.9, 129.7, 129.4, 128.9, 128.8, 127.4, 125.8, 125.6, 124.9, 124.7, 123.3, 112.2, 107.4, 84.2, 42.8, 41.0, 17.4, 16.2, 14.3. Mp: 162–164 °C (dec). HRMS (FAB, sector) calcd for $C_{29}H_{29}NO$ (M^+) 407.2244, found 407.2250.

6-(*tert*-Butyl)-8-methoxy-5-methyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4fa). 8 mol% Rh and 40 mol% cod were used. 0.45 mmol of conc. H_2SO_4 were used in the subsequent step. The crude material was purified by silica gel chromatography with hexane/EtOAc = 6/1, and the solid thus obtained was washed with cold pentane. White solid. 77% yield (57.5 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.55-8.48 (m, 1H), 8.12-8.04 (m, 1H), 7.54-7.43 (m, 4H), 6.80 (dd, *J* = 8.2, 2.3 Hz, 1H), 3.88 (s, 3H), 2.86 (s, 3H), 2.52 (ddd, *J* = 12.4, 11.4, 4.2 Hz, 1H), 2.37 (ddd, *J* = 12.8, 11.0, 4.6 Hz, 1H), 1.92 (s, 1H), 1.75 (s, 9H), 0.95-0.63 (m 5H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 101 MHz): δ 159.2, 144.2, 144.0, 143.7, 143.1, 136.4, 134.2, 134.0, 127.0, 125.6, 125.1, 124.9, 124.4, 122.6, 113.9, 110.5, 83.7, 55.5, 42.7, 37.5, 32.5, 20.4, 17.5, 14.2. Mp: 154–156 °C. HRMS (FAB, sector) calcd for $C_{26}H_{30}O_2$ (M^+) 374.2240, found 374.2244.

6-(*tert*-Butyl)-8,9-difluoro-5-methyl-11-propyl-11*H*-benzo[*a*]fluoren-11-ol (4ga). 4 mol% Rh and 20 mol% cod were used. 1.80 mmol of conc. H_2SO_4 was used in the subsequent step. The crude material was purified by silica gel chromatography with hexane/EtOAc = 11/1, and the solid thus obtained was washed with cold pentane. White solid. 86% yield (65.7 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.51-8.44 (m, 1H), 8.12-8.05 (m, 1H), 7.72 (dd, *J* = 12.4, 7.3 Hz, 1H), 7.55-7.47 (m, 2H), 7.35 (dd, *J* = 9.2, 7.8 Hz, 1H), 2.86 (s, 3H), 2.58-2.45 (m, 1H), 2.39-2.26 (m, 1H), 1.98 (s, 1H), 1.72 (s, 9H), 0.91-0.63 (m, 5H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 101 MHz): δ 149.7 (dd, *J* = 244, 13.4 Hz), 149.0 (dd, *J* = 249, 13.4 Hz), 147.5 (dd, *J* = 4.8, 2.9 Hz), 143.84, 143.82, 143.3, 138.7 (dd, *J* = 6.7, 2.9 Hz), 135.2, 134.7, 134.2, 126.9, 126.1, 125.6,

124.7, 115.8 (d, J = 21.1 Hz), 111.3 (d, J = 18.2 Hz), 83.9, 42.5, 37.6, 32.6, 20.5, 17.4, 14.2. Mp: 208–209 °C. HRMS (FAB, sector) calcd for $C_{25}H_{26}F_2O$ (M^+) 380.1946, found 380.1942.

Procedure for Table 1, Entry 1. 1,5-Cyclooctadiene (24.5 μL, 0.200 mmol), MeOH (410 μL, 10.1 mmol), and THF (1.0 mL) were added to a solution of $[Rh(OH)(cod)]_2$ (9.1 mg, 40 μmol Rh), compound **1a** (189 mg, 0.650 mmol), and compound **2a** (93.1 mg, 0.500 mmol) in THF (4.0 mL), and the mixture was stirred for 16 h at 40 °C. After cooled to room temperature, conc. H_2SO_4 (2.8 μL, 50 μmol) was added to it and the mixture was stirred for 2 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 50/1, and the solid thus obtained was washed with cold pentane to afford 11-methoxy-5-methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluorene (**5**) as a pale yellow solid (147 mg, 0.388 mmol; 78% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.60-8.52 (m, 1H), 8.15 (dd, J = 7.4, 1.8 Hz, 1H), 7.64-7.49 (m, 5H), 7.47 (d, J = 7.3 Hz, 1H), 7.40-7.29 (m, 2H), 7.19 (td, J = 7.6, 1.4 Hz, 1H), 6.98 (td, J = 7.6, 1.4 Hz, 1H), 6.07 (d, J = 7.3 Hz, 1H), 2.83 (s, 3H), 2.48 (s, 3H), 2.48-2.37 (m, 1H), 2.37-2.27 (m, 1H), 0.81-0.56 (m, 5H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 147.6, 141.6, 140.9, 138.4, 137.0, 135.1, 133.5, 132.4, 129.9, 129.7, 129.6, 129.0, 128.9, 128.3, 127.6, 126.7, 126.3, 126.0, 125.6, 124.7, 123.0, 122.7, 90.3, 51.8, 42.9, 17.1, 16.3, 14.3. Mp: 143–145 °C. HRMS (FAB, sector) calcd for $C_{28}H_{26}O$ (M^+) 378.1978, found 378.1988.

General Procedure for Table 1, Entries 2–6 and Equation 2. 1,5-Cyclooctadiene (98.1 μL, 0.800 mmol), H_2O (46.9 μL, 2.60 mmol), and THF (2.0 mL) were added to a solution of $[Rh(OH)(cod)]_2$ (36.5 mg, 0.160 mmol Rh), compound **1a** (754 mg, 2.60 mmol), and compound **2a** (373 mg, 2.00 mmol) in THF (18 mL), and the mixture was stirred for 16 h at 40 °C. The reaction mixture was directly passed through a pad of silica gel with EtOAc and concentrated under vacuum. The residue was dissolved in Et_2O, washed with H_2O, dried over $MgSO_4$, filtered, and concentrated under vacuum. The solid thus obtained was washed with cold pentane to afford compound **3aa** as a crude product (749 mg). 1/10 of this material (74.9 mg) was used for each subsequent step.

Entry 2 (11-Benzylthio-5-methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluorene (6)). Trifluoroacetic acid (15.3 μL, 0.200 mmol) was added dropwise to a solution of crude product **3aa** (74.9 mg) and benzyl mercaptan (23.5 μL, 0.200 mmol) in CH_2Cl_2 (1.0 mL) at 0 °C, and the mixture was stirred for 3 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with CH_2Cl_2. The organic layer was washed with saturated

NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 50/1 to afford compound **6** as a white solid (73.2 mg, 0.156 mmol; 78% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.84 (d, *J* = 8.2 Hz, 1H), 8.14 (d, *J* = 8.2 Hz, 1H), 7.66 (d, *J* = 6.8 Hz, 1H), 7.65-7.49 (m, 5H), 7.41-7.31 (m, 2H), 7.23 (t, *J* = 7.6 Hz, 1H), 7.01-6.88 (m, 4H), 6.76-6.65 (m, 2H), 6.07 (d, *J* = 7.8 Hz, 1H), 2.80 (d, *J* = 12.4 Hz, 1H), 2.76 (d, *J* = 12.4 Hz, 1H), 2.70-2.57 (m, 1H), 2.47 (s, 3H), 2.43-2.32 (m, 1H), 0.69-0.53 (m, 5H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 150.6, 141.12, 141.09, 139.0, 137.5, 136.9, 134.8, 133.1, 132.7, 129.9, 129.7, 129.3, 129.03, 128.96, 128.7, 127.8, 127.6, 127.3, 126.9, 126.3, 125.74, 125.66, 125.6, 125.0, 123.4, 122.4, 61.2, 41.2, 33.7, 17.4, 16.3, 14.2. Mp: 166–168 °C. HRMS (FAB, sector) calcd for $C_{34}H_{30}S$ (M^+) 470.2063, found 470.2064.

Entry 3 (11-Azido-5-methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluorene (7)). HCl (50.0 μL, 0.200 mmol; 4.0 M solution in 1,4-dioxane) was added to a solution of crude product **3aa** (74.9 mg) in 1,4-dioxane (1.0 mL), and the mixture was stirred for 3 h. The volatiles were then removed under vacuum. $ZnCl_2$ (27.3 mg, 0.200 mmol) and DMF (1.0 mL) were added to it, and NaN_3 (26.0 mg, 0.400 mmol) was added to this mixture. After stirring for 24 h at 40 °C, the reaction was quenched with saturated $NaHCO_3$aq and this was extracted with EtOAc. The organic layer was washed with H_2O, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 50/1 to afford compound **7** as a pale yellow solid (55.5 mg, 0.142 mmol; 71% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.45 (dd, *J* = 7.8, 1.4 Hz, 1H), 8.17 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.68-7.49 (m, 6H), 7.41-7.30 (m, 2H), 7.24 (td, *J* = 7.6, 0.9 Hz, 1H), 7.02 (td, *J* = 7.6, 0.9 Hz, 1H), 6.09 (d, *J* = 7.8 Hz, 1H), 2.55-2.40 (m, 1H), 2.49 (s, 3H), 2.37-2.25 (m, 1H), 0.82-0.58 (m, 5H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 146.9, 141.3, 140.6, 137.7, 136.8, 135.0, 134.3, 132.9, 129.8, 129.7, 129.04, 129.02, 128.9, 128.8, 127.8, 127.1, 126.5, 126.1, 125.9, 124.6, 123.1, 122.9, 75.2, 41.3, 17.1, 16.4, 14.1. Mp: 149–151 °C. HRMS (FAB, sector) calcd for $C_{27}H_{23}N_3$ (M^+) 389.1887, found 389.1888.

Entry 4 (11-Chloro-5-methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluorene (8)). Crude product **3aa** (74.9 mg) was further washed with hexane and the resulting solid was dissolved in toluene (1.0 mL). Conc. HCl (360 μL, 4.32 mmol) was then added to it, and the mixture was stirred for 1 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over Na_2SO_4, filtered, and concentrated under vacuum to afford compound **8** as an orange solid (67.2 mg, 0.175 mmol; 88% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.57 (d, *J* = 8.2 Hz, 1H), 8.18 (d, *J* = 8.2 Hz, 1H), 7.70-7.47 (m, 6H), 7.39-7.29 (m, 2H), 7.23 (t, *J* = 7.6 Hz, 1H), 6.98

(t, J = 7.8 Hz, 1H), 6.05 (d, $^3J_{HH}$ = 7.8 Hz, 1H), 3.01-2.86 (m, 1H), 2.77-2.63 (m, 1H), 2.48 (s, 3H), 0.75-0.56 (m, 5H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 149.4, 140.6, 139.9, 138.6, 136.0, 135.0, 134.7, 133.0, 129.74, 129.70, 129.1, 129.0, 128.8, 128.6, 127.8, 127.3, 126.3, 126.0, 125.9, 124.8, 123.3, 122.9, 73.8, 45.2, 18.2, 16.4, 13.9. Mp: 74–76 °C. HRMS (FAB, sector) calcd for $C_{27}H_{23}$ ($M–Cl^–$) 347.1794, found 347.1798.

Entry 5 (11-Allyl-5-methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluorene (9)). Trifluoroacetic acid (45.9 μL, 0.600 mmol) was added dropwise to a solution of crude product **3aa** (74.9 mg) and allyltrimethylsilane (63.7 μL, 0.400 mmol) in CH_2Cl_2 (0.5 mL) at 0 °C, and the mixture was stirred for 2 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with CH_2Cl_2. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane to afford compound **9** as a white solid (59.6 mg, 0.153 mmol; 77% yield). ^1H NMR ($CDCl_3$, 400 MHz): δ 8.32 (d, J = 8.7 Hz, 1H), 8.19 (dd, J = 7.8, 1.4 Hz, 1H), 7.65-7.48 (m, 5H), 7.42 (d, J = 7.8 Hz, 1H), 7.38-7.31 (m, 2H), 7.19 (td, J = 7.3, 0.9 Hz, 1H), 6.94 (td, J = 7.6, 0.9 Hz, 1H), 6.10 (d, J = 7.8 Hz, 1H), 5.06-4.89 (m, 1H), 4.64 (dd, J = 17.0, 2.3 Hz, 1H), 4.51 (dd, J = 10.1, 2.3 Hz, 1H), 3.16 (dd, J = 14.2, 7.3 Hz, 1H), 3.03 (dd, J = 13.8, 6.9 Hz, 1H), 2.62-2.42 (m, 1H), 2.48 (s, 3H), 2.31-2.16 (m, 1H), 0.68-0.38 (m, 5H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 152.1, 141.94, 141.93, 141.4, 137.5, 135.3, 133.7, 132.5, 131.8, 129.9, 129.8, 128.92, 128.90, 127.5, 126.5, 126.1, 125.6, 125.2, 124.3, 122.6, 122.1, 116.6, 56.5, 44.6, 42.2, 17.3, 16.3, 14.5. Mp: 139–141 °C. HRMS (FAB, sector) calcd for $C_{30}H_{28}$ (M^+) 388.2186, found 388.2192.

Entry 6 (5-Methyl-6-phenyl-11-propyl-11*H*-benzo[*a*]fluorene (10)). Trifluoroacetic acid (45.9 μL, 0.600 mmol) was added dropwise to a solution of crude product **3aa** (74.9 mg) and triethylsilane (63.5 μL, 0.400 mmol) in CH_2Cl_2 (1.0 mL) at 0 °C, and the mixture was stirred for 2 h at room temperature. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with CH_2Cl_2. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane to afford compound **10** as a white solid (54.2 mg, 0.156 mmol; 78% yield). ^1H NMR ($CDCl_3$, 400 MHz): δ 8.25-8.13 (m, 2H), 7.66-7.49 (m, 6H), 7.44-7.37 (m, 1H), 7.36-7.30 (m, 1H), 7.18 (td, J = 7.6, 0.9 Hz, 1H), 6.97 (td, J = 7.6, 0.9 Hz, 1H), 6.18 (d, J = 7.8 Hz, 1H), 4.44 (dd, J = 6.9, 3.7 Hz, 1H), 2.49 (s, 3H), 2.43-2.28 (m, 1H), 2.23-2.08 (m, 1H), 1.03 (sext, J = 7.6 Hz, 2H), 0.79 (t, J = 7.3 Hz, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 101 MHz): δ 149.3, 142.4, 141.7, 141.3, 137.0, 135.4, 132.3, 131.5, 129.9, 129.73, 129.71, 129.0, 128.9,

127.5, 126.5, 125.84, 125.81, 125.77, 125.5, 124.9, 123.8, 122.7, 46.7, 36.6, 18.2, 16.1, 14.5. Mp: 114–116 °C. HRMS (FAB, sector) calcd for $C_{27}H_{24}$ (M^+) 348.1873, found 348.1878.

Equation 2 ((*E*)-5-Methyl-6-phenyl-11-propylidene-11*H*-benzo[*a*]fluorene (11)). A solution of crude product **3aa** (74.9 mg) and *p*-toluenesulfonic acid (38.0 mg, 0.200 mmol; monohydrate) in toluene (2.0 mL) was stirred for 12 h at 80 °C. The reaction was quenched with saturated $NaHCO_3$aq and this was extracted with Et_2O. The organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 100/1 to afford compound **11** as a yellow solid (51.4 mg, 0.148 mmol; 74% yield, *E*/*Z* = 97/3). The major structure of **11** was determined by X-ray crystallographic analysis after recrystallizations from hexane. *E*-isomer: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.62 (d, *J* = 7.8 Hz, 1H), 8.15 (dd, *J* = 8.7, 0.9 Hz, 1H), 7.80 (d, *J* = 7.8 Hz, 1H), 7.63-7.47 (m, 5H), 7.37-7.31 (m, 2H), 7.28 (t, *J* = 7.3 Hz, 1H), 7.16 (td, *J* = 7.6, 0.9 Hz, 1H), 6.93 (td, *J* = 7.6, 0.9 Hz, 1H), 6.14 (d, *J* = 7.8 Hz, 1H), 2.98 (quint, *J* = 7.4 Hz, 2H), 2.45 (s, 3H), 1.37 (t, *J* = 7.6 Hz, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 141.3, 140.9, 139.2, 138.8, 137.8, 135.7, 135.1, 132.9, 132.8, 132.2, 129.8, 129.0, 128.9, 127.5, 127.1, 126.5, 126.0, 125.9, 125.3, 125.2, 124.5, 122.8, 24.1, 16.4, 14.7. Mp: 110–112 °C. HRMS (FAB, sector) calcd for $C_{27}H_{22}$ (M^+) 346.1716, found 346.1723.

Procedure for Equation 3. 1,5-Cyclooctadiene (9.8 μL, 80 μmol), H_2O (4.7 μL, 0.26 mmol), and THF (0.5 mL) were added to a solution of $[Rh(OH)(cod)]_2$ (3.6 mg, 16 μmol Rh), compound **1a** (75.4 mg, 0.260 mmol), and compound **2j** (61.7 mg, 0.200 mmol) in THF (1.5 mL), and the mixture was stirred for 16 h at 40 °C. The reaction mixture was directly passed through a pad of silica gel with EtOAc and concentrated under vacuum. The residue was dissolved in CH_2Cl_2 (2.0 mL) and boron trifluoride diethyl etherate (25.1μL, 0.200 mmol) was added to it at 0 °C. The mixture was stirred for 1 h at 0 °C, and the reaction was quenched with saturated $NaHCO_3$aq. After extraction with CH_2Cl_2, the organic layer was washed with saturated NaClaq, dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/EtOAc = 14/1 to afford 5',7'-dimethoxy-5-methyl-6-phenyl-2',3'-dihydrospiro[benzo[*a*]fluorene-11,1'-indene] (**12**) as a white solid (72.5 mg, 0.155 mmol; 77% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.14 (d, *J* = 8.3 Hz, 1H), 7.62 (d, *J* = 8.7 Hz, 1H), 7.60-7.50 (m, 3H), 7.49-7.36 (m, 3H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.09 (d, *J* = 7.3 Hz, 1H), 7.03 (t, *J* = 7.1 Hz, 1H), 6.91 (t, *J* = 7.6 Hz, 1H), 6.65 (d, *J* = 1.8 Hz, 1H), 6.15 (d, *J* = 7.8 Hz, 1H), 6.11 (d, *J* = 1.8 Hz, 1H), 3.85 (s, 3H), 3.55 (dt, *J* = 16.0, 9.6 Hz, 1H), 3.41 (ddd, *J* = 16.5, 9.6, 2.3 Hz, 1H), 3.07-2.95 (m, 1H), 3.01 (s, 3H), 2.50 (s, 3H), 2.31 (ddd, *J* = 13.3, 9.2, 2.3 Hz, 1H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 161.3, 157.0, 154.8, 147.1, 145.2,

141.6, 140.1, 136.0, 135.2, 132.6, 131.3, 129.91, 129.86, 129.0, 128.9, 128.8, 128.1, 127.4, 126.3, 126.2, 125.7, 125.3, 125.1, 124.3, 122.4, 122.0, 101.4, 98.1, 61.7, 55.6, 55.5, 39.8, 32.7, 16.2. Mp: 254–256 °C (dec). HRMS (FAB, sector) calcd for $C_{34}H_{28}O_2$ (M^+) 468.2084, found 468.2085.

General Procedure for Equation 4. 1,5-Cyclooctadiene (7.4 μL, 60 μmol), H_2O (7.0 μL, 0.39 mmol), and THF (0.6 mL) were added to a solution of $[Rh(OH)(cod)]_2$ (2.7 mg, 12 μmol Rh), compound **1** (0.390 mmol), and compound **2k** (71.1 mg, 0.300 mmol) in THF (2.4 mL), and the mixture was stirred for 16 h at 40 °C. The reaction mixture was directly passed through a pad of silica gel with EtOAc and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/CH_2Cl_2 to afford compound **13**.

6-(*tert*-Butyl)-11-propyl-5*H*-benzo[*a*]fluoren-5-one (13bk). The crude material was purified by silica gel chromatography with hexane/CH_2Cl_2 = 5/4. Red solid. 95% yield (93.4 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.88 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.75 (d, *J* = 7.3 Hz, 1H), 7.69 (d, *J* = 7.8 Hz, 1H), 7.50 (td, *J* = 7.6, 1.4 Hz, 1H), 7.31 (t, *J* = 7.3 Hz, 1H), 7.23-7.13 (m, 3H), 2.92-2.83 (m, 2H), 1.85-1.72 (m, 2H), 1.60 (s, 9H), 1.16 (t, *J* = 7.3 Hz, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 190.5, 151.1, 147.4, 146.6, 146.2, 135.9, 133.4, 132.5, 132.2, 129.3, 129.0, 127.3, 127.1, 126.8, 124.4, 120.3, 35.6, 30.9, 29.1, 21.4, 14.8. Mp: 173–175 °C. HRMS (FAB, sector) calcd for $C_{24}H_{25}O$ ($M+H^+$) 329.1900, found 329.1903.

6-(*tert*-Butyldimethylsilyl)-11-propyl-5*H*-benzo[*a*]fluoren-5-one (13ck). The crude material was purified by silica gel chromatography with hexane/CH_2Cl_2 = 3/2. Red solid. 93% yield (108 mg). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.05 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.75 (d, *J* = 7.8 Hz, 1H), 7.71 (d, *J* = 7.8 Hz, 1H), 7.52 (td, *J* = 7.8, 1.8 Hz, 1H), 7.32 (t, *J* = 7.6 Hz, 1H), 7.25-7.17 (m, 2H), 7.11 (td, *J* = 7.3, 1.8 Hz, 1H), 2.96-2.87 (m, 2H), 1.87-1.72 (m, 2H), 1.18 (t, *J* = 7.3 Hz, 3H), 1.16 (s, 9H), 0.33 (s, 6H). ^{13}C{^{1}H} NMR ($CDCl_3$, 101 MHz): δ 191.1, 160.7, 149.7, 146.1, 140.5, 136.8, 134.2, 132.5, 130.6, 130.1, 128.1, 127.7, 127.2, 126.8, 125.9, 124.6, 120.4, 29.2, 28.9, 21.1, 19.3, 14.9, 0.1. Mp: 180–181 °C. HRMS (FAB, sector) calcd for $C_{26}H_{31}OSi$ ($M+H^+$) 387.2139, found 387.2146.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Crystallographic data, NMR spectra (PDF)

Accession Codes

CCDC 1992334 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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References

1. For reviews: (a) Shirini, F.; Abedini, M. Application of Nanocatalysts in Multi-component Reactions. *J. Nanosci. Nanotechnol.* **2013**, *13*, 4838–4860. (b) Smith, A. B., III; Wuest, W. M. Evolution of multi-component anion relay chemistry (ARC): construction of architecturally complex natural and unnatural products. *Chem. Commun.* **2008**, 5883–5895. (c) Hulme, C.; Gore, V. "Multi-component Reactions: Emerging Chemistry in Drug Discovery" 'From Xylocain to Crixivan'. *Curr. Med. Chem.* **2003**, *10*, 51–80. (d) Weber, L.; Illgen, K.; Almstetter, M. Discovery of New Multi Component Reactions with Combinatorial Methods. *Synlett* **1999**, 366–374.
2. For reviews: (a) Hu, B.; Lu, P.; Wang, Y. Fluorescent chemosensors based on 9-cycloheptatrienylidene fluorenes (9-CHFs). *New J. Chem.* **2013**, *37*, 1645–1653. (b) Abbel, R.; Schenning, A. P. H. J.; Meijer, E. W. Fluorene-Based Materials and Their Supramolecular Properties. *J. Polym. Sci. Part A: Polym. Chem.* **2009**, *47*, 4215–4233. (c) Grimsdale, A. C.; Müllen, K. Oligomers and Polymers Based on Bridged Phenylenes as Electronic Materials. *Macromol. Rapid Commun.* **2007**, *28*, 1676–1702. (d) Scherf, U.; List, E. J. W. Semiconducting Polyfluorenes−Towards Reliable Structure−Property Relationships. *Adv. Mater.* **2002**, *14*, 477–487. (e) Leclerc, M. Polyfluorenes: Twenty Years of Progress. *J. Polym. Sci. Part A: Polym. Chem.* **2001**, *39*, 2867–2873. (f) Neher, D. Polyfluorene Homopolymers: Conjugated Liquid-Crystalline Polymers for Bright Blue Emission and Polarized Electroluminescence. *Macromol. Rapid Commun.* **2001**, *22*, 1365–1385. (g) Bernius, M.; Inbasekaran, M.; Woo, E.; Wu, W.; Wujkowski, L. Fluorene-based polymers-preparation and applications. *J. Mater. Sci.: Materials in Electronics* **2000**, *11*, 111–116. See also: (h) Goubard, F.; Dumur, F. Truxene: a promising scaffold for future

materials. *RSC Adv.* **2015**, *5*, 3521–3551. (i) Wong, W.-Y. Metallated molecular materials of fluorene derivatives and their analogues. *Coord. Chem. Rev.* **2005**, *249*, 971–997.

3. For reviews: (a) Kirillov, E.; Saillard, J.-Y.; Carpentier, J.-F. Groups 2 and 3 metal complexes incorporating fluorenyl ligands. *Coord. Chem. Rev.* **2005**, *249*, 1221–1248. (b) Alt, H. G.; Samuel, E. Fluorenyl complexes of zirconium and hafnium as catalysts for olefin polymerization. *Chem. Soc. Rev.* **1998**, *27*, 323–329.
4. (a) Kuo, M. R.; Morbidoni, H. R.; Alland, D.; Sneddon, S. F.; Gourlie, B. B.;Staveski, M. M.; Leonard, M.; Gregory, J. S.; Janjigian, A. D.; Yee, C.; Musser, J. M.; Kreiswirth, B.; Iwamoto, H.; Perozzo, R.; Jacobs, W. R., Jr.; Sacchettini, J. C.; Fidock, D. A. Targeting Tuberculosis and Malaria through Inhibition of Enoyl Reductase. *J. Biol. Chem.* **2003**, *278*, 20851–20859. (b) Dunn, D.; Hostetler, G.; Iqbal, M.; Marcy, V. R.; Lin, Y. G.; Jones, B.; Animone, L. D.; Gruner, J.; Ator, M. A.; Bacon, E. R.; Chatterjee, S. Wake promoting agents: Search for next generation modafinil, lessons learned: Part III. *Bioorg. Med. Chem. Lett.* **2012**, *22*, 3751–3753. (c) Moritomo, A.; Yamada, H.; Watanabe, T.; Itahana, H.; Koga, Y.; Akuzawa, S.; Okada, M. Synthesis and structure–activity relationships of new carbonyl guanidine derivatives as novel dual 5-HT_{2B} and 5-HT_7 receptor antagonists. Part 2. *Bioorg. Med. Chem.* **2014**, *22*, 4323–4337. (d) Suresh, A.; Srinivasarao, S.; Agnieszka, N.; Ewa, A.-K.; Alvala, M.; Lherbet, C.; Sekhar, K. V. G. C. Design and synthesis of 9*H*-fluorenone based 1,2,3-triazole analogues as *Mycobacterium tuberculosis* InhA inhibitors. *Chem. Biol. Drug Des.* **2018**, *91*, 1078–1086.
5. For reviews: (a) Kaiser, R. P.; Caivano, I.; Kotora, M. Transition-metal-catalyzed methods for synthesis of fluorenes. *Tetrahedron* **2019**, *75*, 2981–2992. (b) Zhou, A.-H.; Pan, F.; Zhu, C.; Ye, L.-W. Recent Progress towards Transition-Metal-Catalyzed Synthesis of Fluorenes. *Chem. Eur. J.* **2015**, *21*, 10278–10288.
6. For recent examples: (a) Li, G.; Wang, E.; Chen, H.; Li, H.; Liu, Y.; Wang, P. G. A general and efficient synthesis of substituted fluorenes and hetrocyclic-fused indenes containing thiophene or indole rings utilizing a Suzuki–Miyaura coupling and acid-catalyzed Friedel–Crafts reactions as key steps. *Tetrahedron* **2008**, *64*, 9033–9043. (b) Sun, F.-L.; Zeng, M.; Gu, Q.; You, S.-L. Enantioselective Synthesis of Fluorene Derivatives by Chiral Phosphoric Acid Catalyzed Tandem Double Friedel–Crafts Reaction. *Chem. Eur. J.* **2009**, *15*, 8709–8712. (c) Rose, B. D.; Santa Maria, P. J.; Fix, A. G.; Vonnegut, C. L.; Zakharov, L. N.; Parkin, S. R.; Haley, M. M. Scalable synthesis of 5,11-diethynylated indeno[1,2-*b*]fluorene-6,12-diones and exploration of their solid state packing. *Beilstein J. Org. Chem.* **2014**, *10*, 2122–2130. (d) Killander, D.; Sterner, O. Reagent-Controlled Cyclization–Deprotection Reaction to Yield either Fluorenes or Benzochromenes. *Eur. J. Org. Chem.* **2014**, 6507–6512. (e) Xu, L.; Yang, W.; Zhang, L.; Miao, M.; Yang, Z.; Xu, X.; Ren, H. Brönsted Acid-Mediated Intramolecular Cyclization of Biaryl Triazenes for the Synthesis of Fluorenes and 9,10-Dihydro-Phenanthrenes. *J. Org. Chem.* **2014**, *79*, 9206–9221. (f) Hacker, A. S.; Pavano, M.; Wood, J. E., II; Immoos, C. E.; Hashimoto, H.; Genis, S. P.; Frantz, D. K. Synthesis and Electronic Properties of Fluoreno[2,1-*a*]fluorenedione and Fluoreno[1,2-*a*]fluorenedione. *J. Org. Chem.* **2018**, *83*, 510–515.
7. For recent examples: (a) Lockner, J. W.; Dixon, D. D.; Risgaard, R.; Baran, P. S. Practical Radical Cyclizations with Arylboronic Acids and Trifluoroborates. *Org. Lett.* **2011**, *13*, 5628–5631. (b) Seo, S.; Slater, M.; Greaney, M. F. Decarboxylative C–H Arylation of Benzoic Acids under Radical Conditions. *Org. Lett.* **2012**, *14*, 2650–2653. (c) Shi, Z.; Glorius, F. Synthesis of fluorenones *via* quaternary ammonium salt-promoted intramolecular dehydrogenative arylation of aldehydes. *Chem. Sci.* **2013**, *4*, 829–833. (d) Wertz, S.; Leifert, D.; Studer, A. Cross Dehydrogenative Coupling via Base-Promoted Homolytic Aromatic Substitution (BHAS): Synthesis of Fluorenones and Xanthones. *Org. Lett.* **2013**, *15*, 928–931. (e) Zhang, Y.; Xu, J.; Guo, H. Light-Induced Intramolecular

Iodine-Atom Transfer Radical Addition of Alkyne: An Approach from Aryl Iodide to Alkenyl Iodide. *Org. Lett.* **2019**, *21*, 9133–9137.

8. For selected examples: (a) Hwang, S. J.; Kim, H. J.; Chang, S. Highly Efficient and Versatile Synthesis of Polyarylfluorenes via Pd-Catalyzed C–H Bond Activation. *Org. Lett.* **2009**, *11*, 4588–4591. (b) Hsiao, C.-C.; Lin, Y.-K.; Liu, C.-J.; Wu, T.-C.; Wu, Y.-T. Synthesis of Methylene-Bridge Polyarenes through Palladium-Catalyzed Activation of Benzylic Carbon-Hydrogen Bond. *Adv. Synth. Catal.* **2010**, *352*, 3267–3274. (c) Morimoto, K.; Itoh, M.; Hirano, K.; Satoh, T.; Shibata, Y.; Tanaka, K.; Miura, M. Synthesis of Fluorene Derivatives through Rhodium-Catalyzed Dehydrogenative Cyclization. *Angew. Chem., Int. Ed.* **2012**, *51*, 5359–5362. (d) Itoh, M.; Hirano, K.; Satoh, T.; Shibata, Y.; Tanaka, K.; Miura, M. Rhodium- and Iridium-Catalyzed Dehydrogenative Cyclization through Double C−H Bond Cleavages To Produce Fluorene Derivatives. *J. Org. Chem.* **2013**, *78*, 1365–1370. (e) Fukuyama, T.; Maetani, S.; Miyagawa, K.; Ryu, I. Synthesis of Fluorenones through Rhodium-Catalyzed Intramolecular Acylation of Biarylcarboxylic Acids. *Org. Lett.* **2014**, *16*, 3216–3219. (f) Song, J.; Li, Y.; Sun, W.; Yi, C.; Wu, H.; Wang, H.; Ding, K.; Xiao, K.; Liu, C. Efficient palladium-catalyzed C(sp^2)–H activation towards the synthesis of fluorenes. *New. J. Chem.* **2016**, *40*, 9030–9033.
9. Wan, J.-C.; Huang, J.-M.; Jhan, Y.-H.; Hsieh, J.-C. Novel Syntheses of Fluorenones via Nitrile-Directed Palladium-Catalyzed C–H and Dual C–H Bond Activation. *Org. Lett.* **2013**, *15*, 2742–2745.
10. (a) Dong, C.-G.; Hu, Q.-S. Annulative Tandem Reactions Based on Pd^0/$t$$Bu_3$P-Catalyzed Cross-Coupling and C(sp^3)–H Bond Activation. *Angew. Chem., Int. Ed.* **2006**, *45*, 2289–2292. (b) Liu, T.-P.; Xing, C.-H.; Hu, Q.-S. Synthesis of Fluorene and Indenofluorene Compounds: Tandem Palladium-Catalyzed Suzuki Cross-Coupling and Cyclization. *Angew. Chem., Int. Ed.* **2010**, *49*, 2909–2912. (c) Song, J.; Sun, W.; Li, Y.; Wei, F.; Liu, C.; Qian, Y.; Chen, S. Halogen-Adjusted Chemoselective Synthesis of Fluorene Derivatives with Position-Controlled Substituents. *Chem. Asian J.* **2016**, *11*, 211–215.
11. (a) Shi, G.; Chen, D.; Jiang, H.; Zhang, Y.; Zhang, Y. Synthesis of Fluorenes Starting from 2-Iodobiphenyls and CH_2Br_2 through Palladium-Catalyzed Dual C–C Bond Formation. *Org. Lett.* **2016**, *18*, 2958–2961. (b) Xu, S.; Chen, R.; Fu, Z.; Zhou, Q.; Zhang, Y.; Wang, J. Palladium-Catalyzed Formal [4 + 1] Annulation via Metal Carbene Migratory Insertion and C(sp^2)–H Bond Functionalization. *ACS Catal.* **2017**, *7*, 1993–1997.
12. Ma, D.; Shi, G.; Wu, Z.; Ji, X.; Zhang, Y. Synthesis of 9,9-Disubstituted Fluorenes from 2-Iodobiphenyls and α-Diazoesters under Palladium Catalysis. *J. Org. Chem.* **2018**, *83*, 1065–1072.
13. Manojveer, S.; Balamurugan, R. A facile access to substituted benzo[*a*]fluorenes from *o*-alkynylbenzaldehydes *via in situ* formed acetals. *Chem. Commun.* **2014**, *50*, 9925–9928.
14. For other examples of intermolecular processes: (a) Gorin, D. J.; Watson, I. D. G.; Toste, F. D. Fluorenes and Styrenes by Au(I)-Catalyzed Annulation of Enynes and Alkynes. *J. Am. Chem. Soc.* **2008**, *130*, 3736–3737. (b) Wang, X.-C.; Yan, R.-L.; Zhong, M.-J.; Liang, Y.-M. Bi(III)-Catalyzed Intermolecular Reactions of (*Z*)-Pent-2-en-4-yl Acetates with Ethynylarenes for the Construction of Multisubstituted Fluorene Skeletons through a Cascade Electrophilic Addition/Cycloisomerization Sequence. *J. Org. Chem.* **2012**, *77*, 2064–2068. (c) Lee, C.-W.; Liu, E.-C.; Wu, Y.-T. Palladium-Catalyzed Reaction of Haloarenes with Diarylethynes: Synthesis, Structural Analysis, and Properties of Methylene-Bridged Arenes. *J. Org. Chem.* **2015**, *80*, 10446–10456. (d) Kaiser, R. P.; Hessler, F.; Mosinger, J.; Císařová, I.; Kotora, M. A [2+2+2]-Cyclotrimerization Approach to Selectively Substituted Fluorenes and Fluorenols, and Their Conversion to 9,9'-Spirobifluorenes. *Chem. Eur. J.* **2015**, *21*, 13577–13582. (e) Sun, Z.; Huang, Q.; Han, J.; He, W.; Chen, J.; Xu, Y.; Deng, H.; Shao, M.; Zhang, H.; Cao, W. Facile synthesis of

perfluoroalkylated fluorenes *via* a one-pot two-step three-component process. *Tetrahedron* **2018**, *74*, 2073–2078.

15. Nishida, M.; Shintani, R. Convergent Synthesis of Fluorene Derivatives by a Rhodium-Catalyzed Stitching Reaction/Alkene Isomerization Sequence. *Chem. Eur. J.* **2019**, *25*, 7475–7479.
16. (a) Shintani, R.; Iino, R.; Nozaki, K. Rhodium-Catalyzed Stitching Reaction: Convergent Synthesis of Quinoidal Fused Oligosiloles. *J. Am. Chem. Soc.* **2016**, *138*, 3635–3638. (b) Takahashi, K.; Ito, S.; Shintani, R.; Nozaki, K. Selective synthesis of unsymmetric dibenzo[*a*,*e*]pentalenes by a rhodium-catalysed stitching reaction. *Chem. Sci.* **2017**, *8*, 101–107. (c) Shintani, R.; Misawa, N.; Tsuda, T.; Iino, R.; Fujii, M.; Yamashita, K.; Nozaki, K. Synthesis of Quinoidal Fused Oligosiloles by Rhodium-Catalyzed Stitching Reaction and Theoretical Investigation of Their Properties. *J. Am. Chem. Soc.* **2017**, *139*, 3861–3867. (d) Shintani, R.; Kishikawa, S.; Nakamura, K.; Tsuda, T.; Nozaki, K. Synthesis of carbonyl-bridged dibenzofulvalenes and related compounds by rhodium-catalyzed stitching reaction. *Chem. Commun.* **2019**, *55*, 1072–1075.
17. (a) Rappoport, Z.; Greenblatt, J.; Apeloig, Y. 1,10-, 1,4-, and 1,2-Eliminations and 1,5- and 1,7-Rearrangements in the Reactions of Substituted 9-Anisylidene-9,10-dihydroanthracenes and Anthrones in Acetic Acid. *J. Org. Chem.* **1979**, *44*, 3687–3694. (b) Ogata, F.; Takagi, M.; Nojima, M.; Kusabayashi, S. Reactions of (9-Anthryl)arylmethyl Chloride and Its Homologues with Nucleophiles under Solvolytic Conditions. Notable Effects of Reaction Conditions and Substituents on the Reaction Sites. *J. Am. Chem. Soc.* **1981**, *103*, 1145–1153.
18. For synthetic methods of 9*H*-fluoren-9-ols: (a) Abert, K.; Rieker, A. Zur innermolekularen Beweglichkeit in 9-Arylfluorenen, I. Die Natur des Austauschprozesses magnetisch nichtäquivalenter Atompaare. *Chem. Ber.* **1977**, *110*, 1804–1822. (b) Hayashi, N.; Mazaki, Y.; Kobayashi, K. Clathrate Formations with Isomeric Host Compounds Based on Thieno[3,2-*b*]thiophene and Thieno[2,3-*b*]thiophene: Inclusion Modes and Crystal Structures. *J. Org. Chem.* **1995**, *60*, 6342–6347. (c) Hu, C.; Hong, G.; Nahide, P. D.; He, Y.; Zhou, C.; Kozlowski, M. C.; Wang, L. C(sp^3)–H hydroxylation of fluorenes, oxindoles and benzofuranones with a $Mg(NO_3)_2$–$HP(O)Ph_2$ oxidation system. *Org. Chem. Front.* **2019**, *6*, 3167–3171. (d) Shaikh, M. A.; Agalave, S. G.; Ubale, A. S.; Gnanaprakasam, B. Ligand-Free Ru-Catalyzed Direct sp^3 C–H Alkylation of Fluorene Using Alcohols. *J. Org. Chem.* **2020**, *85*, 2277–2290.
19. Substrates with a terminal alkyne cannot be directly employed in the present reaction.
20. For synthetic methods of 9-alkoxy-9*H*-fluorenes: (a) Reference 17a. (b) Becker, H.-D.; Gustafsson, K. Preparation and Reactions of 2,6-Di-*tert*-butyl-4-(9-fluorenylidene)-1,4-benzoquinone. *J. Org. Chem.* **1976**, *41*, 214–221. (c) Hou, Y.; Meyers, C. Y. Stereochemistry of Reactions Involving Rotationally Restricted, Sterically Hindered Cations, Radicals, and Anions: 9-Fluorenyl Systems. *J. Org. Chem.* **2004**, *69*, 1186–1195. (d) Wu, Y.; Zhang, J.; Fei, Z.; Bo, Z. Spiro-Bridged Ladder-Type Poly(*p*-phenylene)s: Towards Structurally Perfect Light-Emitting Materials. *J. Am. Chem. Soc.* **2008**, *130*, 7192–7193. (e) Reference 12. (f) Soley, J.; Taylor, S. D. Mild, Rapid, and Chemoselective Procedure for the Introduction of the 9-Phenyl-9-fluorenyl Protecting Group into Amines, Acids, Alcohols, Sulfonamides, Amides, and Thiols. *J. Org. Chem.* **2020**, *85*, 2068–2081.
21. For synthetic methods of 9-thio-9*H*-fluorenes: (a) Reference 17a. (b) Ikehira, H.; Tanimoto, S.; Oida, T. n-Butyl-lithium-induced Cleavage of Several Dithioacetals Derived from Diaryl Ketones. *J. Chem. Soc., Perkin Trans. I* **1984**, 1223–1226. (c) Breu, J.; Höcht, P.; Rohr, U.; Schatz, J.; Sauer, J. Thiocarbonyl Compounds in [4+2] Cycloadditions: Preparative Aspects. *Eur. J. Org. Chem.* **1998**, 2861–2873. (d) Feldman, K. S.; Eastman, K. J. Studies on the Mechanism of Action of Prekinamycin, a Member of the

Diazoparaquinone Family of Natural Products: Evidence for Both sp^2 Radical and Orthoquinonemethide Intermediates. *J. Am. Chem. Soc.* **2006**, *128*, 12562–12573. (e) Reference 18f.

22. For synthetic methods of 9-amino- or 9-azido-9*H*-fluorenes: (a) Reference 18b. (b) Reddy, K. S.; Solà, L.; Moyano, A.; Rericàs, M. A.; Riera, A. Synthesis of a 9-Fluorenone Derived β-Amino Alcohol Ligand Depicting High Catalytic Activity and Pronounced Non-linear Stereochemical Effects. *Synthesis* **2000**, 165–176. (c) Reference 7c. (d) Reference 18f.
23. For synthetic methods of 9-chloro-9*H*-fluorenes: (a) Reference 17a. (b) Reference 18f.
24. (a) Deore, P. S.; Argade, N. P. Base-Stimulated 1,2-, 1,4-, and 1,6-Eliminations in Suitably Substituted Alkylidenesuccinates Leading to Natural and Unnatural Conjugated Alkenyl(methyl)maleic Anhydrides. *J. Org. Chem.* **2014**, *79*, 2538–2546. See also: (b) Werner, C.; Hopf, H.; Dix, I.; Bubenitschek, P.; Jones, P. G. 1,*x*-Elimination Reactions: Extending the Limits of a Classical Organic Reaction. *Chem. Eur. J.* **2007**, *13*, 9462–9477.
25. (a) Wu, R.; Schumm, J. S.; Pearson, D. L.; Tour, J. M. Convergent Synthetic Routes to Orthogonally Fused Conjugated Oligomers Directed toward Molecular Scale Electronic Device Applications. *J. Org. Chem.* **1996**, *61*, 6906–6921. (b) Cocherel, N.; Poriel, C.; Rault-Berthelot, J.; Barrière, F.; Audebrand, N.; Slawin, A. M. Z.; Vignau, L. New 3π-2Spiro Ladder-Type Phenylene Materials: Synthesis, Physicochemical Properties and Applications in OLEDs. *Chem. Eur. J.* **2008**, *14*, 11328–11342. (c) Romain, M.; Quinton, C.; Tondelier, D.; Geffroy, B.; Jeannin, O.; Rault-Berthelot, J.; Poriel, C. Thioxanthene and dioxothioxanthene dihydroindeno[2,1-*b*]fluorenes: synthesis, properties and applications in green and sky blue phosphorescent OLEDs. *J. Mater. Chem. C* **2016**, *4*, 1692–1703.
26. No efficient synthesis of this structure has been reported: (a) Harrington, L. E.; Britten, J. F.; Casey, M.; Grealis, J.; Ortin, Y.; Müller-Bunz, H.; McGlinchey, M. J. Protonation of Tetraphenyl- and 2,3,4-Triphenylcyclopentadienone – An NMR and X-ray Crystallographic Study. *Eur. J. Org. Chem.* **2017**, 3249–3255. (b) Mandal, M.; Balamurugan, R. Triflic acid-Mediated Expedient Synthesis of Benzo[*a*]fluorenes and Fluorescent Benzo[*a*]fluorenones. *Adv. Synth. Catal.* **2018**, *360*, 1453–1465.
27. Palladium- and nickel-catalyzed processes have been reported via mechanistically different pathways: (a) Meng, G.; Szostak, R.; Szostak, M. Suzuki–Miyaura Cross-Coupling of *N*-Acylpyrroles and Pyrazoles: Planar, Electronically Activated Amides in Catalytic N–C Cleavage. *Org. Lett.* **2017**, *19*, 3596–3599. (b) Huang, P.-Q.; Chen, H. Ni-Catalyzed coss-coupling reactions of *N*-acylpyrrole-type amides with organoboron reagents. *Chem. Commun.* **2017**, *53*, 12584–12587.
28. Evans, D. A.; Borg, G.; Scheidt, K. A. Remarkably Stable Tetrahedral Intermediates: Carbinols from Nucleophlic Additions to *N*-Acylpyrroles. *Angew. Chem., Int. Ed.* **2002**, *41*, 3188–3192.
29. For reviews: (a) Youn, S. W. Rhodium-Catalyzed Tandem Transformations with Organoboron Reagents: Sequential Multiple C–C Bond Formations. *Eur. J. Org. Chem.* **2009**, 2597–2605. (b) Yoshida, K.; Hayashi, T. Rhodium-Catalyzed Addition of Boronic Acids to Alkenes and Carbonyl Compounds. In *Boronic Acids*; Hall, D. G., Ed.; Wiley-VCH: Weinheim, Germany, 2005, Chapter 4. (c) Fagnou, K.; Lautens, M. Rhodium-Catalyzed Carbon–Carbon Bond Forming Reactions of Organometallic Compounds. *Chem. Rev.* **2003**, *103*, 169–196.
30. Formation of pyrrole was confirmed by ^{1}H NMR analysis of the crude mixture.
31. Yoo, W.-J.; Nguyen, T. V. Q.; Kobayashi, S. Synthesis of Isocoumarins through Three-Component Couplings of Arynes, Terminal Alkynes, and Carbon Dioxide Catalyzed by an NHC-Copper Complex. *Angew. Chem., Int. Ed.* **2014**, *53*, 10213–10217.
32. Liu, Y.; Zhen, W.; Dai, W.; Wang, F.; Li, X. Silver(I)-Catalyzed Addition-Cyclization of Alkyne-Functionalized Azomethines. *Org. Lett.* **2013**, *15*, 874–877.

33. Mason, M. R.; Verkade, J. G. Fluoride-Induced Reduction of Palladium(II) and Platinum(II) Phosphine Complexes. *Organometallics* **1992**, *11*, 2212–2220.
34. Coulson, D. R.; Satek, L. C.; Grim, S. O. Tetrakis(triphenylphosphine)palladium(0). *Inorg. Synth.* **1972**, *13*, 121–124.
35. Uson, R.; Oro, L. A.; Cabeza, J. A.; Bryndza, H. E.; Stepro, M. P. Dinuclear Methoxy, Cyclooctadiene, and Barrelene Complexes of Rhodium(I) and Iridium(I). *Inorg. Synth.* **1985**, *23*, 126–130.
36. Arndt, S.; Hansmann, M. M.; Motloch, P.; Rudolph, M.; Rominger, F.; Hashmi, A. S. K. Intramolecular *anti*-Phosphinoauration of Alkynes: An FLP-Motivated Approach to Stable Aurated Phosphindolium Complexes. *Chem. Eur. J.* **2017**, *23*, 2542–2547.
37. Yu, L.-Z.; Wei, Y.; Shi, M. Copper-catalyzed cascade cyclization of 1,5-enynes *via* consecutive trifluoromethylazidation/diazidation and click reaction: self-assembly of triazole fused isoindolines. *Chem. Commun.* **2016**, *52*, 13163–13166.
38. Shintani, R.; Misawa, N.; Takano, R.; Nozaki, K. Rhodium-Catalyzed Synthesis and Optical Properties of Silicon-Bridged Arylpyridines. *Chem. Eur. J.* **2017**, *23*, 2660–2665.