Intramolecular Dimerizations of Cyclopentadienones

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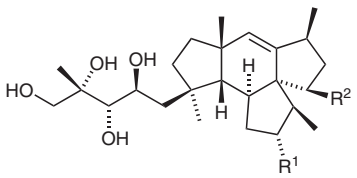
This paper is dedicated to Professor Paul A. Wender on the occasion of his 60th birthday.

Abstract: The generation of bis-cyclopentadienones joined by a tether results in the stereoselective, intramolecular dimerization of these reactive intermediates. This cycloaddition leads to structures of high molecular complexity from relatively simple starting materials.

Key words: cycloadditions, cyclopentadienones, intramolecular, dimerizations, antiaromaticity

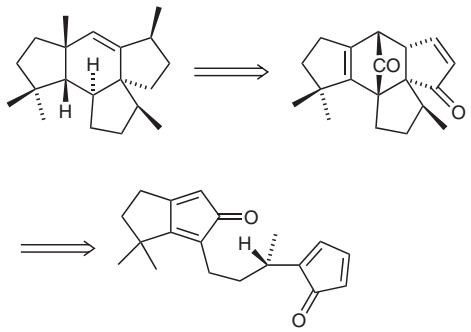
In considering possible synthetic routes to mangicols **1**–**3** (Figure 1), compounds with cytotoxic and anti-inflammatory activities,[1] we wondered whether the carbocyclic skeleton could be assembled by an intramolecular cyclopentadienone dimerization as illustrated in Scheme 1. Such a process might involve the reaction of two 'stable' cyclopentadienones that could be induced to react intramolecularly, the reaction of a 'stable' cyclopentadienone with one that would dimerize rapidly under normal circumstances, or the intramolecular reaction of two reactive cyclopentadienones. To the best of our knowledge, there are no examples of intramolecular cyclopentadienone dimerizations in the literature. Initially, we chose to examine the most difficult of the scenarios presented above, the intramolecular cycloaddition of two reactive cyclopentadienones.



1, R^1 = H, R^2 = OH; mangicol A
2, R^1 = OH, R^2 = H; mangicol B
3, R^1 = R^2 = H; mangicol C

Figure 1

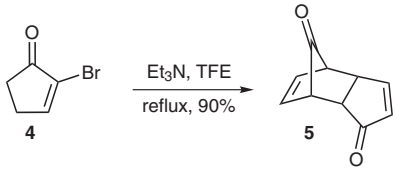
Cyclopentadienones are antiaromatic species. As such, they are generally quite reactive and undergo dimerization very rapidly, unless stabilized through substitution with bulky or electron-donating substituents. Such 'stable' cyclopentadienones have been used productively both as dienes and dienophiles, and offer great potential in synthesis.[2] Though not generally recognized, except in the synthesis of cubane and related caged hydrocarbons,[3] cyclopentadienone dimerization represents a profound increase in molecular complexity as the monomer proceeds to a dimer. We speculated that it would be possible to generate two reactive species that were joined by a tether and have them react intramolecularly rather than intermolecularly. Among other things, we reasoned that it would be important to generate these reactive species contemporaneously, lest two molecules with one reactive fragment collide and begin the process of oligomerization. This paper reports the success of what we view as principle studies that presage and justify further synthetic efforts.



Scheme 1 Retrosynthesis of the carbocyclic core of the mangicols

In 2001, we reported the generation of cyclopentadienones via dehydrobromination of 2-bromocyclopent-2-enones giving various cyclopentadienone dimers. Treatment of 2-bromo-substituted compound **4** with triethylamine in refluxing 2,2,2-trifluoroethanol (TFE) gave the cyclopentadienone dimer **5** in 90% yield (Scheme 2).[4] This work was extended to develop the first examples of an electrocyclic reaction involving an antiaromatic species (Scheme 3)[5] and a new method for generating a reactive cyclopentadienone that served as an excellent dienophile in the Diels–Alder reaction (Scheme 4).[6]

We began our study by preparing molecules that had two bromocyclopentenone units, to be used as bis-cyclopenta-



Scheme 2 Formation of the cyclopentadienone dimer

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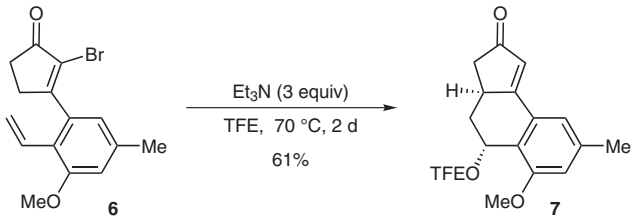
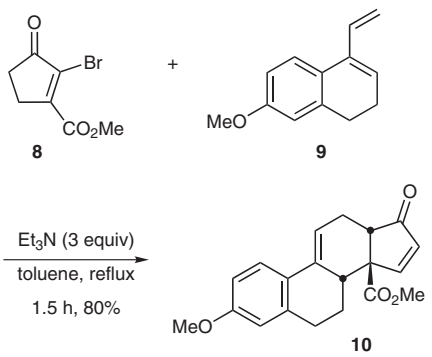
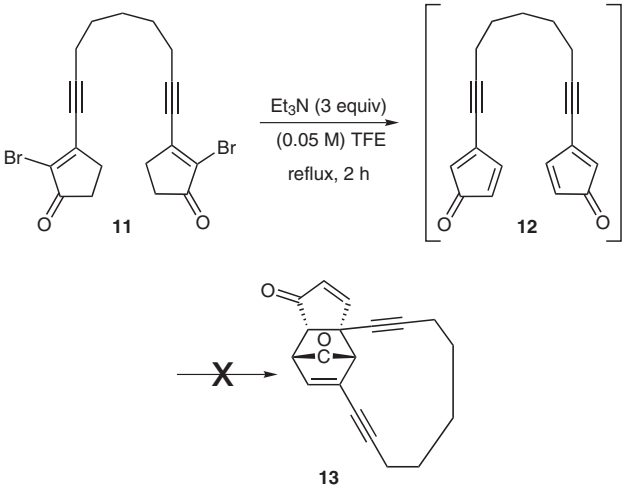


Scheme 3 Cyclopentadienone electrocyclization



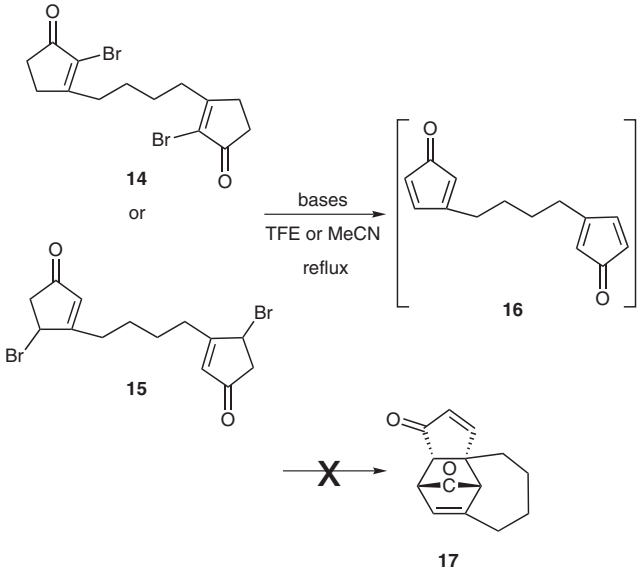
Scheme 4 Diels–Alder reaction via the generation of a reactive cyclopentadienone

dienone precursors. The preparation of these compounds was straightforward and will not be further discussed here. To evaluate our proposed intramolecular dimerization, compound **11** was treated with three equivalents of triethylamine in refluxing TFE (Scheme 5). However, no evidence of cycloadduct **13** was observed. The reaction led to the formation of a complex mixture.



Scheme 5 Attempted cyclization of **11**

Our attempts to generate bis-cyclopentadienone intermediate **16** from precursors **14** or **15** by using different types of base [Et_3N, DBU, 2,2,6,6-tetramethylpiperidine (TMP), 2,6-lutidine] in refluxing TFE or acetonitrile also did not provide the corresponding cycloadduct **17** (Scheme 6). As before, polymerization and decomposition appeared to occur.

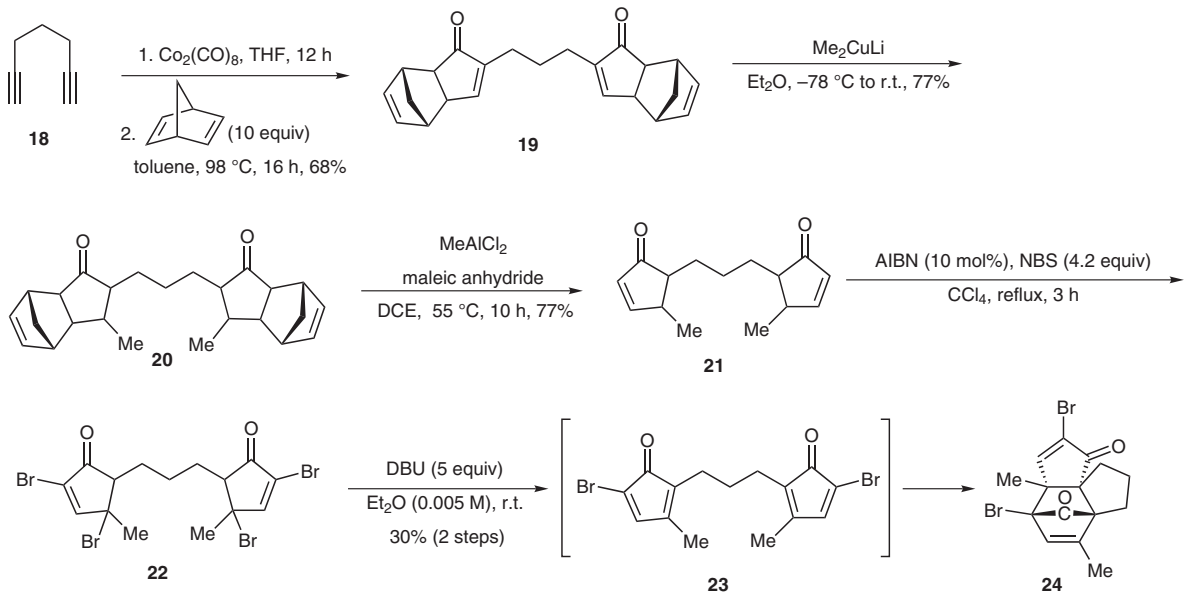


Scheme 6 Attempted cyclization of **14** and **15**

We were forced to find a better bis-cyclopentadienone precursor and decided to pursue the sequence shown in Scheme 7. We synthesized bis-cyclopentenone compound **19** using the Pauson–Khand reaction of hepta-1,6-diyne (**18**) and norbornadiene according to the procedure reported by Krafft.[7] Introduction of a nucleophile into **19** using lithium dimethylcuprate gave **20** in 75% yield.[8] A Lewis acid induced retro-Diels–Alder reaction of **20** using methylaluminum dichloride and an excess of maleic anhydride as a cyclopentadiene trap afforded **21** in 77% yield.[9] Bromination of **21** with 4.2 equivalents of *N*-bromosuccinimide (NBS) in the presence of 10 mol% 2,2′-azobis(isobutyronitrile) (AIBN) in refluxing carbon tetrachloride presumably introduced four bromine atoms at both α- and γ-positions. We used excess reagent to add mass to the material. However, this process was not clean, as indicated in the ^1H and ^{13}C NMR spectra of the crude product. Because of the complexity of the mixture containing **22**, the crude product was directly subjected to the next step without any purification. An ethereal solution of crude **22** was slowly added to an ethereal solution of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) at room temperature and the mixture stirred for five hours. Happily, the polycyclic cycloadduct **24** was isolated in 30% yield.[10] The structure of **24** was based on ^1H and ^{13}C NMR spectroscopy and the precedent that dimerizations of cyclopentadienones typically take place in an *endo* fashion.[11]

Excited by the result, we wanted to see if an analogue of **22**, namely **25** (Figure 2), would undergo cycloaddition at room temperature upon treatment with base; the hope being that if that base was strong enough, rapid formation of cyclopentadienones and intramolecular cycloaddition would ensue.

Compound **25** was treated with five equivalents of DBU in a mixture of diethyl ether and dichloromethane under reflux. Another experiment was also performed using triethylamine as base in refluxing TFE. Both experiments



Scheme 7 The first example of an intramolecular cyclopentadienone dimerization

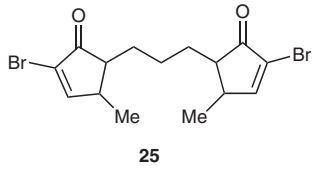


Figure 2

led to complex mixtures with no evidence of cycloadduct formation.

We then decided to turn our attention to investigating more examples of the cycloaddition process that gave cycloadduct **24** (Scheme 7), in spite of the low yield observed. We began with the synthesis of norbornene derivatives **20** from 1,4-addition to compounds **19** and **26** using organocopper reagents (Table 1). The Michael adducts **20** were obtained in moderate to good yields.

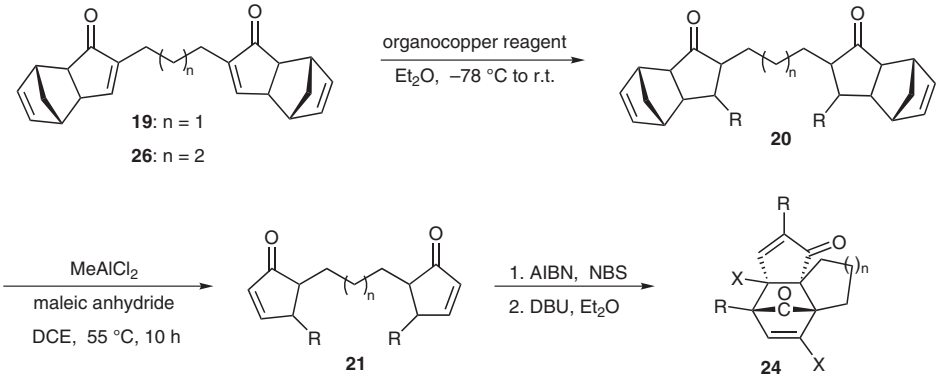
We then subjected the norbornene derivatives **20** to the Lewis acid induced retro-Diels–Alder reaction described above. The corresponding bis-cyclopentenones **21** were obtained in reasonable yields.

Finally, investigations on the bromination and intramolecular dimerization of the different bis-cyclopentenone substrates were conducted. The cyclizations were performed at room temperature, given that higher temperatures did not improve the results and lower temperatures might slow the formation of the cyclopentadienones, a circumstance we did not desire.[10] All of the dimers were produced in moderate yields, at around 45% per step (bromination and cyclization, Table 1). We believe the main cause of such moderate yields is that the bromination reaction was never clean, regardless of the amount of brominating agent or the conditions used. Though we could not isolate any clean side products, it is likely that radicals formed during the bromination process could react inter- or intramolecularly to form byproducts. Polybromination and non-regioselective bromination could also be a problem. However, even with lower amounts of brominating agent, as used in the formation of **24f**, the crude product was still not clean.

All of the cycloadducts isolated were single compounds and structural assignments were made using ^{1}H and ^{13}C NMR spectroscopy; *endo* selectivity was assumed,[11] but supported by the X-ray crystal structure of another cycloadduct (see below).

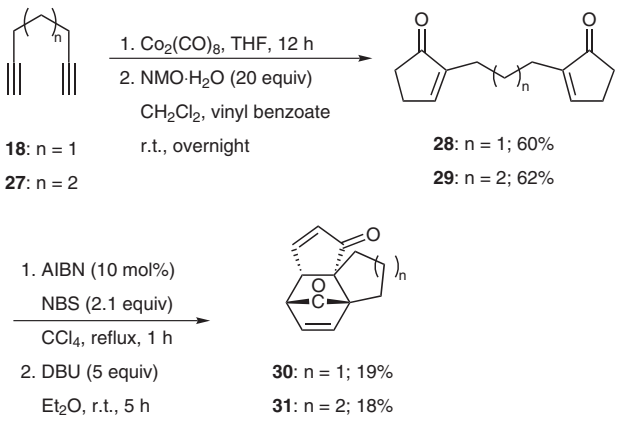
From the results shown in Table 1, we wondered if a different substrate might afford a bis-cyclopentadienone so that cyclization yields could be evaluated for products derived from clean, characterized precursors. To explore this, we synthesized bis-cyclopentenones **28** and **29** from the Pauson–Khand reaction using vinyl benzoate as an ethene equivalent in the presence of hydrated *N*-methylmorpholine *N*-oxide as shown in Scheme 8.[12] The reactions afforded adducts **28** and **29** in 60 and 62% yield, respectively. Allylic bromination of these compounds resulted in the formation of complex mixtures of dibromosubstituted enones, as determined by NMR spectroscopic examination of the crude products. As before, we nonetheless proceeded to take the unstable crude products through the dimerization step by treatment with DBU in diethyl ether solution. Cycloadducts **30** and **31** were isolated in 19 and 18% yield, respectively. The X-ray crystal structure of **30** confirmed the *endo* nature of the cycloadduct, as illustrated in Figure 3.[13]

Table 1 Intramolecular Cyclopentadienone Dimerizations



Entry	n	R[a]	Product	Yield (%)	Product[c]	Yield (%)	X	Product[e,f]	Yield (%)
1	1	Me	**20**	77	**21**	77	Br	**24**	30
2	1	Et[b]	**20a**	53	**21a**	56	Br	**24a**	21
3	1	*n*-Pr[b]	**20b**	55	**21b**	72	Br	**24b**	23
4	1	*n*-Bu	**20c**	66	**21c**	93	Br	**24c**	26
5	1	*n*-Hex	**20d**	82	**21d**	63	Br	**24d**	19
6	1	Ph	**20e**	83	**21e**	62	Br	**24e**	21
7	2	Me	**20f**	64	**21f**	59	H[d]	**24f**	29
8	2	*n*-Bu	**20g**	67	**21g**	64	Br	**24g**	23
9	2	*n*-Hex	**20h**	68	**21h**	61	Br	**24h**	21

[a] All organocopper reagents were prepared at –20 °C from the corresponding organolithium (10 equiv) and CuI (5 equiv).
[b] Ethyl- and propyllithium reagents were freshly prepared from EtI and PrI with *t*-BuLi at –78 °C.
[c] All reactions were conducted at 55 °C in the presence of $MeAlCl_2$ (5 equiv) and maleic anhydride (10 equiv) in 0.1 M DCE.
[d] In this case, 2.1 equiv of NBS were used in the bromination step.
[e] Bromination reactions were performed in the presence of 10 mol% AIBN and NBS (4.2 equiv) in 0.1 M CCl_4 under reflux conditions.
[f] All cyclization reactions were conducted at r.t. with DBU (5 equiv) in 0.005 M Et_2O.



Scheme 8 Cyclization of simple bis-cyclopentadienone precursors

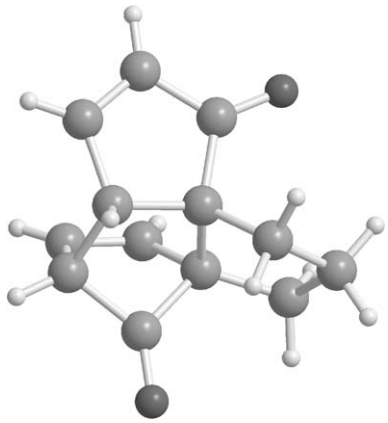


Figure 3 Crystal structure of **30**

In summary, we have demonstrated for the first time that cycloaddition between cyclopentadienones can occur to diastereoselectively generate cycloadducts that are the result of intramolecular dimerization. At this stage, the yields are too low, but we believe that clean cyclopentadienone precursors will give the products in much higher yields. Thus, our future work will involve the synthesis of new cyclopentadienone precursors and studying the intramolecular dimerizations of cyclopentadienones that have a lower reactivity profile, as will be necessary for a synthetic approach to the mangicols. Results will be reported in due course.

All reactions were carried out under an atmosphere of N_2 in oven-dried glassware and with a magnetic stir bar. THF was distilled from Na/benzophenone. Chromatographic separations were carried out using Silicycle ultrapure silica gel (230–400 mesh). Analytical TLC was performed on EM Reagent 0.25-nm silica gel 60-F plates. Visualization of the developed chromatogram was performed by phosphomolybdic acid stain solution followed by heating. Infrared spectra were recorded on a Perkin Elmer 1600 series FT-IR spectrometer. NMR spectra were recorded on a Bruker ARX-250 (250 MHz), DRX-300 (300 MHz), and DRX-500 (500 MHz) spectrometer using TMS as an internal standard. High-resolution mass spectrometry was carried out on a Waters Quattro II instrument using electrospray ionization (ESI).

2,2′-Propane-1,3-diylbis(3a,4,7,7a-tetrahydro-4,7-methano-1*H*-inden-1-one) (19); Typical Procedure

A 200-mL, round-bottomed flask was charged with hepta-1,6-diyne (**18**; 0.32 g, 1.628 mmol) and $Co_2(CO)_8$ (2.62 g, 4.640 mmol) in THF (34 mL) under an Ar atmosphere. The red-brown solution was stirred at r.t. until complex formation was completed, as judged by TLC. The excess solvent was removed under reduce pressure and the dicobalt–diyne complex was purified by filtration through a short plug of silica gel.

A 30-mL sealed tube was charged with the hepta-1,6-diynedicobalt complex (0.540 g, 0.8132 mmol), norbornadiene (0.749 g, 8.133 mmol), and toluene (8.1 mL). The mixture was heated at 98 °C for 16 h. After the mixture was cooled to r.t., it was filtered through a pad of Celite. The solvent was removed and the crude product was purified by flash column chromatography (silica gel, hexane–EtOAc, 4:1) to afford a colorless semisolid. Yield: 0.184 g (68%).

IR (film): 3052, 2970, 2938, 2868, 1695, 1626, 1569, 1324, 1213, 1139, 1008 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.20 (br, 2 H), 6.28 (dd, *J* = 3.2, 5.3 Hz, 2 H), 6.20 (dd, *J* = 3.2, 5.3 Hz, 2 H), 2.90 (s, 2 H), 2.71 (s, 2 H), 2.67 (s, 2 H), 2.27 (d, *J* = 7.0 Hz, 2 H), 2.19 (t, *J* = 7.0 Hz, 4 H), 1.72–1.62 (m, 2 H), 1.37 (d, *J* = 9.2 Hz, 2 H), 1.19 (d, *J* = 9.3 Hz, 2 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 209.9, 159.3, 150.0, 138.4, 137.0, 52.5, 47.7, 43.6, 42.9, 41.2, 25.6, 24.8.

HRMS: *m*/*z* [M + Na]$^+$ calcd for $C_{23}H_{24}O_2$: 355.1668; found: 355.1669.

2,2′-Butane-1,4-diylbis(3a,4,7,7a-tetrahydro-4,7-methano-1*H*-inden-1-one) (26)

IR (film): 3056, 2972, 2938, 1696, 1617, 1458, 1319, 1209, 1061 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.16 (d, *J* = 1.2 Hz, 2 H), 6.28 (dd, *J* = 3.0, 6.6 Hz, 2 H), 6.20 (dd, *J* = 3.0, 6.6 Hz, 2 H), 2.90 (s, 2 H), 2.71–2.70 (m, 2 H), 2.66 (s, 2 H), 2.29–2.26 (m, 2 H), 2.18 (t, *J* = 6.0 Hz, 4 H), 1.52–1.46 (m, 4 H), 1.38–1.35 (m, 2 H), 1.19 (d, *J* = 9.2 Hz, 2 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 209.7, 158.9, 150.4, 138.3, 137.0, 52.5, 47.6, 43.6, 42.9, 41.1, 27.5, 24.7.

HRMS: *m*/*z* [M + Na]$^+$ calcd for $C_{24}H_{26}O_2$: 369.1825; found: 369.1823.

Conjugate Addition (Method A): 2,2′-Propane-1,3-diylbis(3-methyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20); Typical Procedure

A 25-mL round-bottomed flask was charged with CuI (0.358 g, 1.89 mmol) and Et_2O (5.6 mL). The suspension was cooled to –20 °C for 10 min and then a 1.08 M soln of MeLi in THF–cumene (3.48 mL, 3.76 mmol) was added dropwise. The mixture was stirred at –20 °C for 30 min and then it was cooled to –78 °C for another 10 min. Compound **19** (0.125 g, 0.376 mmol) was added and the resulting mixture was slowly warmed to r.t. After the solution was stirred at r.t. for 5 h, it was poured into chilled H_2O (30 mL). The aqueous mixture was filtered over a pad of Celite and the ethereal layer was separated. The aqueous solution was further extracted with Et_2O (3 ×10 mL). The combined organic layers were dried ($MgSO_4$), filtered, and concentrated. The crude product was purified by flash chromatography (10% EtOAc–hexane) to provide a yellow oil. Yield: 0.106 g (77%).

IR (neat): 3056, 2962, 2868, 1723, 1458, 1372, 1266, 1050 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 6.16 (dd, *J* = 3.0, 5.4 Hz, 2 H), 6.11 (dd, *J* = 3.0, 5.4 Hz, 2 H), 3.09 (d, *J* = 1.0 Hz, 2 H), 2.72 (s, 2 H), 2.28 (d, *J* = 9.0 Hz, 2 H), 2.18–2.10 (m, 2 H), 1.81 (t, *J* = 8.0 Hz, 2 H), 1.63–1.49 (m, 2 H), 1.46–1.23 (m, 8 H), 1.21 (d, *J* = 6.4 Hz, 6 H), 1.03 (d, *J* = 9.4 Hz, 2 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 218.3, 138.2, 137.4, 60.5, 54.2, 48.7, 46.6, 44.9, 44.8, 44.4, 40.2, 40.0, 27.8, 27.7, 24.6, 24.4, 21.1, 21.0.

HRMS: *m*/*z* [M + Na]$^+$ calcd for $C_{25}H_{32}O_2$: 387.2294; found: 387.2298.

Conjugate Addition (Method B): 2,2′-Propane-1,3-diylbis(3-ethyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20a); Typical Procedure

To a solution of EtI (2.346 g, 15.04 mmol) in Et_2O (20 mL) at –78 °C was added dropwise a 0.89 M soln of *t*-BuLi in pentane (34 mL, 30.10 mmol) over 10 min. The resulting solution was stirred at –78 °C for 1 h and at r.t. for another 1 h.

Anhyd CuI (1.432 g, 7.52 mmol) and Et_2O (10 mL) were placed in a 200-mL round-bottomed flask fitted with a septum and a stir bar under an Ar atmosphere. The resulting suspension was stirred at –20 °C for 10 min before adding the EtLi soln prepared above. The mixture was stirred for 30 min at –20 °C and then was cooled to –78 °C. The mixture was added dropwise to a solution of **19** (0.500 g, 1.504 mmol) in THF (5 mL) and the resulting mixture was allowed to warm to r.t. After 6 h, the reaction was quenched with ice water and was extracted with Et_2O (3 × 20 mL). The combined organic layers were washed with brine, dried ($MgSO_4$), and concentrated. Purification of the yellow residue by column chromatography (10% EtOAc–hexane) provided a colorless oil. Yield: 0.310 g (53%).

IR (neat): 2958, 2925, 1728, 1454, 1324, 1217 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 6.19 (dd, *J* = 3.0, 5.6 Hz, 2 H), 6.13 (dd, *J* = 3.0, 5.6 Hz, 2 H), 3.11 (s, 2 H), 2.71 (s, 2 H), 2.28 (d, *J* = 9.0 Hz, 2 H), 2.25–2.15 (m, 2 H), 1.92–1.86 (m, 2 H), 1.83–1.73 (m, 2 H), 1.63–1.51 (m, 2 H), 1.47–1.18 (m, 10 H), 1.05 (t, *J* = 7.2 Hz, 8 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 218.9, 138.3, 137.6, 58.8, 54.4, 48.2, 46.6, 46.4, 44.7, 29.0, 28.3, 25.0, 11.8.

HRMS: *m*/*z* [M]$^+$ calcd for $C_{27}H_{36}O_2$: 392.2710; found: 392.2667.

2,2′-Propane-1,3-diylbis(3-propyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20b)

IR (neat): 3064, 2958, 1728, 1454, 1356, 1209 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 6.18 (dd, *J* = 3.0, 5.5 Hz, 2 H), 6.12 (dd, *J* = 3.0, 5.5 Hz, 2 H), 3.11 (s, 2 H), 2.70 (s, 2 H), 2.29 (d, *J* = 9.2 Hz, 2 H), 2.20 (br, 2 H), 1.91–1.86 (m, 2 H), 1.66–1.50 (m, 6 H), 1.44–1.26 (m, 12 H), 1.07–0.92 (m, 8 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 218.9, 138.3, 138.0, 137.6, 137.4, 59.2, 59.1, 54.4, 54.3, 48.2, 47.1, 46.9, 44.8, 44.8, 44.7, 44.6, 44.5, 39.1, 28.3, 28.2, 24.9, 24.6, 20.7, 14.5.

HRMS: *m*/*z* [M + Na]$^+$ calcd for $C_{29}H_{40}O_2$: 443.2921; found: 443.2921.

2,2′-Propane-1,3-diylbis(3-butyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20c)
IR (neat): 3060, 2962, 2917, 2868, 1732, 1458, 1319, 1217 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 6.19 (dd, *J* = 3.0, 5.5 Hz, 2 H), 6.12 (dd, *J* = 3.0, 5.5 Hz, 2 H), 3.11 (s, 2 H), 2.70 (s, 2 H), 2.29 (d, *J* = 9.0 Hz, 2 H), 2.22–2.11 (m, 2 H), 1.91–1.86 (m, 2 H), 1.69–1.64 (m, 2 H), 1.63–1.50 (m, 4 H), 1.47–1.22 (m, 16 H), 1.04 (d, *J* = 9.0 Hz, 2 H), 0.95 (t, *J* = 7.0 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 218.7, 138.3, 138.2, 137.3, 59.2, 59.1, 54.4, 54.3, 48.1, 47.0, 44.9, 44.7, 44.6, 36.4, 36.2, 29.6, 28.2, 28.1, 28.0, 24.8, 24.6, 23.0, 22.9, 14.0.

HRMS: *m*/*z* $[M]^+$ calcd for $C_{31}H_{44}O_2$: 448.3336; found: 448.3320.

2,2′-Propane-1,3-diylbis(3-hexyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20d)
IR (neat): 2925, 2855, 1732, 1459, 1325 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 6.20–6.11 (m, 4 H), 3.11 (s, 2 H), 2.70 (s, 2 H), 2.29 (d, *J* = 9.0 Hz, 2 H), 2.19–2.18 (m, 2 H), 1.91–1.86 (m, 2 H), 1.63–1.49 (m, 4 H), 1.46–1.20 (m, 26 H), 1.05 (d, *J* = 9.0 Hz, 2 H), 0.91 (t, *J* = 6.5 Hz, 6 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 218.8, 138.3, 137.3, 59.2, 59.1, 54.4, 48.1, 47.0, 45.0, 44.7, 36.7, 31.9, 29.7, 28.3, 28.2, 27.4, 22.7, 14.1.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{35}H_{52}O_2$: 527.3860; found: 527.3868.

2,2′-Propane-1,3-diylbis(3-phenyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20e)
IR (neat): 3060, 2958, 1728, 1601, 1491, 1454, 1323, 1209 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.36–7.30 (m, 4 H), 7.28–7.19 (m, 6 H), 6.12 (dd, *J* = 3.0, 5.4 Hz, 2 H), 6.06 (dd, *J* = 3.0, 5.4 Hz, 2 H), 3.16 (s, 2 H), 2.75 (s, 2 H), 2.44 (d, *J* = 9.0 Hz, 2 H), 2.38–2.34 (m, 1 H), 2.31–2.28 (m, 1 H), 2.26–2.18 (m, 2 H), 1.54–1.37 (m, 4 H), 1.30–1.23 (m, 2 H), 1.20–1.13 (m, 2 H), 1.07 (t, *J* = 8.9 Hz, 2 H), 0.98–0.86 (m, 2 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 217.1, 144.7, 144.6, 138.2, 137.5, 128.7, 127.5, 127.4, 126.6, 60.2, 54.1, 54.0, 52.2, 52.1, 49.9, 49.7, 46.7, 46.5, 44.7, 44.6, 27.7, 27.3, 23.7, 23.6.

HRMS: *m*/*z* $[M]^+$ calcd for $C_{35}H_{36}O_2$: 488.2709; found: 488.2726.

2,2′-Butane-1,4-diylbis(3-methyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20f)
IR (neat): 3030, 2956, 1732, 1460, 1325, 1213 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 6.17 (dd, *J* = 3.0, 5.5 Hz, 2 H), 6.12 (dd, *J* = 3.0, 5.5 Hz, 2 H), 3.10 (s, 2 H), 2.73 (s, 2 H), 2.29 (d, *J* = 9.0 Hz, 2 H), 2.17–2.11 (m, 2 H), 1.82 (t, *J* = 8.1 Hz, 2 H), 1.61–1.54 (m, 2 H), 1.46–1.32 (m, 10 H), 1.22 (d, *J* = 6.4 Hz, 6 H), 1.05 (d, *J* = 9.1 Hz, 2 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 218.3, 218.2, 138.2, 137.4, 60.6, 54.2, 48.7, 46.6, 44.8, 44.4, 40.0, 39.9, 27.3, 27.2, 27.1, 27.0, 21.0.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{26}H_{34}O_2$: 401.2457; found: 401.2452.

2,2′-Butane-1,4-diylbis(3-butyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20g)
IR (neat): 2957, 2925, 2855, 1732, 1460, 1319, 1217 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 6.20–6.18 (m, 2 H), 6.14–6.11 (m, 2 H), 3.11 (s, 2 H), 2.70 (s, 2 H), 2.29 (d, *J* = 8.8 Hz, 2 H), 2.18 (br s, 2 H), 1.89–1.86 (m, 2 H), 1.67–1.66 (m, 2 H), 1.55–1.20 (m, 22 H), 1.05 (d, *J* = 8.8 Hz, 2 H), 0.94 (t, *J* = 6.8 Hz, 6 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 218.9, 138.3, 137.4, 59.3, 54.4, 48.2, 47.0, 44.7, 44.6, 36.4, 29.7, 27.6, 27.5, 27.4, 27.3, 23.0, 14.1.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{32}H_{46}O_2$: 485.3390; found: 485.3391.

2,2′-Butane-1,4-diylbis(3-hexyl-2,3,3a,4,7,7a-hexahydro-4,7-methano-1*H*-inden-1-one) (20h)
IR (neat): 2957, 2925, 2855, 1732, 1460, 1217 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 6.20 (dd, *J* = 3.0, 5.6 Hz, 2 H), 6.13 (dd, *J* = 3.0, 5.6 Hz, 2 H), 3.11 (s, 2 H), 2.70 (s, 2 H), 2.29 (d, *J* = 8.9 Hz, 2 H), 2.23–2.12 (m, 2 H), 1.91–1.85 (m, 2 H), 1.71–1.61 (m, 2 H), 1.42–1.19 (m, 30 H), 1.06 (d, *J* = 9.1 Hz, 2 H), 0.90 (t, *J* = 6.6 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 218.8, 138.3, 137.4, 59.3, 54.4, 48.2, 47.0, 44.8, 44.7, 44.6, 36.7, 31.8, 29.7, 27.6, 27.5, 27.4, 27.3, 22.6, 14.1.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{36}H_{54}O_2$: 541.4016; found: 541.4027.

Retro-Diels–Alder Reaction: 5,5′-Propane-1,3-diylbis(4-methylcyclopent-2-en-1-one) (21); Typical Procedure
A 50-mL two-necked flask equipped with a reflux condenser was charged with compound **20** (0.374 g, 1.024 mmol), maleic anhydride (1.004 g, 10.24 mmol), and 0.1 M DCE (10.24 mL) under an Ar atmosphere. A 1 M soln of $MeAlCl_2$ in hexane (4.30 mL, 4.30 mmol) was added at r.t. and the resulting mixture was heated in an oil bath at 55 °C for 10 h. The mixture was cooled to r.t. and the solvent was removed in vacuo. The residue was dissolved in EtOAc (20 mL) and washed with sat. aq $NaHCO_3$. The aqueous layer was extracted with EtOAc (3×10 mL). The combined organic layers were dried ($MgSO_4$) and concentrated. The crude product was purified by flash column chromatography (30% EtOAc–hexane) to afford a colorless oil. Yield: 0.225 g (77%).

IR (neat): 2970, 2933, 1760, 1728, 1585, 1450 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.56 (dd, *J* = 2.4, 5.6 Hz, 2 H), 6.10 (d, *J* = 2.0 Hz, 1 H), 6.08 (d, *J* = 2.0 Hz, 1 H), 2.71–2.61 (m, 2 H), 1.90–1.84 (m, 2 H), 1.81–1.74 (m, 2 H), 1.59–1.43 (m, 4 H), 1.26–1.21 (m, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.0, 211.9, 168.5, 168.3, 132.5, 132.4, 55.3, 53.2, 42.8, 42.7, 30.6, 30.4, 24.9, 24.7, 19.6.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{15}H_{20}O_2$: 255.1355; found: 255.1361.

5,5′-Propane-1,3-diylbis(4-ethylcyclopent-2-en-1-one) (21a)
IR (neat): 2962, 2925, 2851, 1777, 1691, 1589, 1458, 1176 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.62–7.59 (m, 2 H), 6.11 (d, *J* = 1.9 Hz, 1 H), 6.09 (d, *J* = 1.9 Hz, 1 H), 2.57–2.51 (m, 2 H), 1.97–1.94 (m, 2 H), 1.72–1.67 (m, 2 H), 1.63–1.53 (m, 4 H), 1.52–1.44 (m, 4 H), 0.99 (dt, *J* = 1.9, 7.6 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.0, 211.9, 166.8, 132.8, 132.7, 50.7, 50.6, 49.3, 49.1, 31.2, 31.0, 27.1, 24.5, 24.2, 11.5.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{17}H_{24}O_2$: 283.1669; found: 283.1662.

5,5′-Propane-1,3-diylbis(4-propylcyclopent-2-en-1-one) (21b)
IR (neat): 2954, 2864, 1703, 1589, 1462, 1364 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.62–7.58 (m, 2 H), 6.10–6.07 (m, 2 H), 2.62–2.56 (m, 2 H), 1.97–1.93 (m, 2 H), 1.74–1.66 (m, 2 H), 1.58–1.33 (m, 12 H), 1.00–0.88 (m, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.1, 167.2, 132.7, 132.6, 51.4, 51.3, 47.8, 47.7, 36.7, 31.3, 31.2, 24.5, 24.2, 20.7, 14.2.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{19}H_{28}O_2$: 311.1982; found: 311.1975.

5,5′-Propane-1,3-diylbis(4-butylcyclopent-2-en-1-one) (21c)
IR (neat): 2953, 2929, 1704, 1589, 1485 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.62–7.57 (m, 2 H), 6.10–6.08 (m, 2 H), 2.63–2.52 (m, 2 H), 2.00–1.92 (m, 2 H), 1.70–1.66 (m, 2 H), 1.52–1.25 (m, 16 H), 0.92 (t, *J* = 6.1 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.0, 167.2, 132.7, 132.6, 51.3, 51.2, 47.9, 47.8, 34.1, 31.2, 31.1, 29.5, 24.4, 24.2, 22.7, 13.8.

HRMS: *m*/*z* $[M]^+$ calcd for $C_{21}H_{32}O_2$: 316.2397; found: 316.2418.

5,5′-Propane-1,3-diylbis(4-hexylcyclopent-2-en-1-one) (21d)
IR (neat): 2954, 2926, 2856, 1707, 1585, 1458, 1348, 1172 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.61–7.59 (m, 2 H), 6.10–6.08 (m, 2 H), 2.63–2.56 (m, 2 H), 1.97–1.93 (m, 2 H), 1.73–1.67 (m, 2 H), 1.53–1.48 (m, 6 H), 1.39–1.29 (m, 18), 0.89 (t, *J* = 7.1 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.1, 212.0, 167.2, 132.7, 132.6, 51.3, 51.2, 48.0, 47.9, 34.5, 31.6, 31.3, 31.2, 29.4, 27.3, 24.5, 24.3, 22.5, 14.0.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{25}H_{40}O_2$: 395.2921; found: 395.2917.

5,5′-Propane-1,3-diylbis(4-phenylcyclopent-2-en-1-one) (21e)
IR (neat): 3027, 2933, 2856, 1773, 1703, 1589, 1491, 1450, 1331, 1176, 1082 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.55–7.53 (m, 2 H), 7.32–7.30 (m, 4 H), 7.27–7.23 (m, 2 H), 7.13–7.08 (m, 4 H), 6.26 (dd, *J* = 2.1, 5.6 Hz, 2 H), 3.71–3.67 (m, 2 H), 2.62–2.21 (m, 2 H), 1.80–1.76 (m, 2 H), 1.60–1.43 (m, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 212.6, 165.3, 165.2, 141.3, 133.1, 133.0, 129.0, 127.3 (2 C), 127.2, 54.9, 54.7, 53.7 (2 C), 30.7, 30.6, 24.5, 24.3.

HRMS: *m*/*z* $[M]^+$ calcd for $C_{25}H_{24}O_2$: 356.1771; found: 356.1739.

5,5′-Butane-1,4-diylbis(4-methylcyclopent-2-en-1-one) (21f)
IR (neat): 2925, 2856, 1700, 1593, 1454, 1344 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.52 (dd, *J* = 2.4, 10.7 Hz, 2 H), 6.10 (d, *J* = 1.9 Hz, 1 H), 6.07 (d, *J* = 1.9 Hz, 1 H), 2.67–2.62 (m, 2 H), 1.85–1.76 (m, 4 H), 1.43–1.42 (m, 6 H), 1.23 (d, *J* = 7.2 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.0, 168.2, 132.4 (2 C), 53.4, 53.3, 42.7, 42.6, 30.4, 30.3, 27.4, 27.3, 19.6, 19.5.

HRMS: *m*/*z* $[M + H]^+$ calcd for $C_{16}H_{22}O_2$: 247.1698; found: 247.1704.

5,5′-Butane-1,4-diylbis(4-butylcyclopent-2-en-1-one) (21g)
IR (neat): 2928, 2858, 1708, 1589, 1462, 1348 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.52 (dd, *J* = 2.4, 5.4 Hz, 2 H), 6.10 (d, *J* = 1.3 Hz, 1 H), 6.08 (d, *J* = 1.3 Hz, 1 H), 2.60–2.54 (m, 2 H), 1.94–1.91 (m, 2 H), 1.71–1.67 (m, 2 H), 1.52–1.35 (m, 18 H), 0.92 (t, *J* = 7.0 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.0, 167.0, 132.6, 51.4, 51.3, 47.8, 47.7, 34.1, 30.9, 30.8, 29.4, 27.1, 27.0, 22.6, 13.8.

Anal. Calcd for $C_{22}H_{34}O_2$: C, 79.95; H, 10.37. Found: C, 79.79; H, 10.27.

5,5′-Butane-1,4-diylbis(4-hexylcyclopent-2-en-1-one] (21h)
IR (neat): 2926, 2856, 1706, 1589, 1461, 1348 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.52 (dd, *J* = 2.5, 5.6 Hz, 2 H), 6.10 (d, *J* = 1.4 Hz, 1 H), 6.08 (d, *J* = 1.4 Hz, 1 H), 2.60–2.54 (m, 2 H), 1.95–1.90 (m, 2 H), 1.71–1.66 (m, 2 H), 1.49–1.29 (m, 26 H), 0.92 (t, *J* = 7.0 Hz, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 212.0, 167.0, 132.6, 51.4, 51.3, 47.8, 47.7, 34.4, 31.9, 30.9, 30.8, 29.2, 27.3, 27.1, 27.0, 22.4, 13.9.

Anal. Calcd for $C_{26}H_{42}O_2$: C, 80.77; H, 10.95. Found: C, 80.59; H, 10.73.

Pauson–Khand Reaction Using a Vinyl Ester as an Ethene Equivalent: 2,2′-Propane-1,3-diylbis(cyclopent-2-en-1-one) (28); Typical Procedure
To a stirred solution of hepta-1,6-diynedicobalt complex (1.00 g, 1.506 mmol) formed from **18** (see above) in CH_2Cl_2 (8 mL) was added vinyl benzoate (8.0 mL) at r.t. The mixture was slowly added to a solution of NMO·H_2O (5.34 g, 30.12 mmol) in CH_2Cl_2 (15 mL) over 3 h and stirring was continued overnight at r.t. The mixture was filtered through a short pad of Celite and the solvent was removed in vacuo. The crude product was purified by flash column chromatography (30% EtOAc–hexane) to give a colorless semisolid. Yield: 0.183 g (60%).

IR (film): 2933, 2884, 1691, 1617, 1442, 1331, 1262, 1200 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.35–7.34 (m, 2 H), 2.58–2.56 (m, 4 H), 2.40–2.38 (m, 4 H), 2.21–2.17 (m, 4 H), 1.73–1.66 (m, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 209.9, 157.8, 145.7, 34.5, 26.4, 25.5, 24.4.

HRMS: *m*/*z* $[M + Na]^+$ calcd for $C_{13}H_{16}O_2$: 227.1048; found: 227.1043.

2,2′-Butane-1,4-diylbis(cyclopent-2-en-1-one) (29)
IR (film): 2924, 2848, 1691, 1617, 1646, 1626, 1462, 1356, 1258, 1127 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.36–7.30 (m, 2 H), 2.59–2.53 (m, 4 H), 2.42–2.38 (m, 4 H), 2.23–2.15 (m, 4 H), 1.53–1.47 (m, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 210.1, 157.8, 146.0, 34.4, 27.4, 26.3, 24.4.

Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 77.69; H, 8.45.

Intramolecular Dimerization of Bis-cyclopentenone 21; Typical Procedure
A 10-mL round-bottomed flask equipped with a reflux condenser was charged with **21** (0.0622 g, 0.268 mmol), AIBN (4.4 mg, 0.0268 mmol), NBS (0.1906 g, 1.071 mmol), and CCl_4 (2.7 mL). The mixture was refluxed in an oil bath for 1 h. The mixture was then cooled, diluted with CCl_4, and filtered through a pad of Celite. The solution was washed with 10% aq $Na_2S_2O_3$, H_2O, and brine. The organic layer was dried ($MgSO_4$), filtered, and concentrated. The crude product was used in the next step without any purification.

To a stirred solution of DBU (0.2025 g, 1.33 mmol) in Et_2O (34 mL) at r.t. was slowly added the crude product solution in Et_2O (20 mL). The mixture was stirred for 5 h at r.t. and it was quenched with sat. aq NH_4Cl. The ethereal layer was separated and the aqueous layer was further extracted with Et_2O (3 × 10 mL). The combined ethereal solution was dried ($MgSO_4$), filtered, and concentrated. The crude product was purified by flash column chromatography (10% EtOAc–hexane) to provide the dimer product **24**. Yield: 0.0301 g (30%).

IR (film): 2959, 2872, 1798, 1720, 1687, 1668, 1589, 1430, 1263 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 7.43 (s, 1 H), 5.92 (q, *J* = 1.6 Hz, 1 H), 2.53–2.36 (m, 1 H), 2.25–2.15 (m, 1 H), 2.10–1.99 (m, 2 H), 1.88–1.78 (m, 1 H), 1.73 (d, *J* = 3.2 Hz, 3 H), 1.54–1.45 (m, 1 H), 1.27 (s, 3 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 200.4, 193.7, 160.7, 142.5, 130.4, 127.9, 69.7, 68.7, 63.1, 53.6, 28.9, 25.8, 19.4, 18.5, 15.4.

HRMS: *m/z* [M]$^+$ calcd for $C_{15}H_{14}Br_2O_2$: 385.9335; found: 385.9365.

24a

IR (film): 2964, 1796, 1716, 1588, 1460, 1282 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.37 (s, 1 H), 5.91–5.90 (m, 1 H), 2.50–2.38 (m, 1 H), 2.31–2.13 (m, 2 H), 2.11–1.94 (m, 6 H), 1.43–1.33 (m, 1 H), 0.96 (t, *J* = 7.4 Hz, 3 H), 0.88–0.79 (m, 3 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 200.8, 193.6, 160.7, 147.2, 130.5, 126.4, 70.6, 69.1, 62.0, 58.7, 29.1, 25.4, 24.1, 22.1, 18.7, 10.7, 10.0.

HRMS: *m/z* [M + Na]$^+$ calcd for $C_{17}H_{18}Br_2O_2$: 434.5966; found: 434.5965.

24b

IR (neat): 2954, 2864, 1798, 1712, 1585, 1458 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 7.38 (s, 1 H), 5.88 (t, *J* = 1.9 Hz, 1 H), 2.47–2.30 (m, 1 H), 2.21–2.05 (m, 2 H), 2.02–1.90 (m, 5 H), 1.47–1.22 (m, 3 H), 1.17–1.10 (m, 2 H), 0.94–0.85 (m, 7 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 200.8, 193.6, 160.7, 147.2, 130.5, 126.4, 70.6, 69.1, 62.0, 58.7, 29.1, 25.4, 24.1, 22.1, 18.7, 10.7, 10.0.

HRMS: *m/z* [M + Na]$^+$ calcd for $C_{19}H_{22}Br_2O_2$: 462.9879; found: 462.9872.

24c

IR (neat): 2962, 2925, 1802, 1716, 1585, 1462 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.37 (s, 1 H), 5.89 (t, *J* = 1.8 Hz, 1 H), 2.49–2.35 (m, 1 H), 2.20–2.09 (m, 2 H), 2.07–1.93 (m, 5 H), 1.35–1.25 (m, 8 H), 1.09–1.02 (m, 2 H), 0.89 (t, *J* = 7.4 Hz, 6 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 200.8, 193.7, 160.2, 146.0, 130.3, 127.0, 70.6, 69.2, 62.2, 58.1, 31.0, 29.2, 28.7, 27.8, 25.3, 23.2, 22.2, 19.0, 13.8.

HRMS: *m/z* [M]$^+$ calcd for $C_{21}H_{26}Br_2O_2$: 470.0274; found: 470.0274.

24d

IR (neat): 2955, 2929, 2858, 1796, 1718, 1585 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 7.37 (s, 1 H), 5.88 (t, *J* = 1.8 Hz, 1 H), 2.15–1.97 (m, 6 H), 1.25–1.24 (m, 20 H), 0.91–0.84 (m, 6 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 200.8, 193.7, 160.2, 146.1, 130.3, 126.9, 70.6, 69.2, 62.2, 58.1, 31.4, 31.3, 29.8, 29.2, 28.9, 28.8, 26.6, 25.7, 25.3, 23.2, 22.5, 22.4, 19.0, 14.0, 13.9.

HRMS: *m/z* [M + Na]$^+$ calcd for $C_{25}H_{34}Br_2O_2$: 547.0818; found: 547.0851.

24e

IR (neat): 3064, 2958, 1797, 1716, 1589, 1491 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 7.83 (s, 1 H), 7.40–7.30 (m, 7 H), 7.25–7.17 (m, 3 H), 6.48 (s, 1 H), 2.41–2.25 (m, 3 H), 1.94–1.89 (m, 1 H), 1.59–1.50 (m, 1 H), 1.11–1.00 (m, 1 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 201.1, 193.2, 158.8, 145.3, 136.7, 132.6, 131.4, 130.6, 129.1, 128.9, 128.7, 128.6, 128.4, 128.3, 128.1, 128.0, 127.7, 71.9, 66.1, 65.6, 63.2, 31.0, 25.7, 21.3.

HRMS: *m/z* [M]$^+$ calcd for $C_{25}H_{18}Br_2O_2$: 509.9648; found: 509.9616.

24f

IR (film): 2917, 1789, 1683, 1430 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.20 (d, *J* = 6.0 Hz, 1 H), 6.34 (d, *J* = 6.0 Hz, 1 H), 5.86 (d, *J* = 1.5 Hz, 1 H), 3.11–3.10 (m, 1 H), 2.08–1.99 (m, 3 H), 1.82–1.80 (m, 1 H), 1.74–1.71 (m, 1 H), 1.66 (d, *J* = 1.5 Hz, 3 H), 1.63–1.59 (m, 1 H), 1.42 (t, *J* = 1.5 Hz, 1 H), 1.25 (dd, *J* = 3.5, 13.5 Hz, 1 H), 1.21 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 207.9, 195.1, 163.1, 143.6, 138.5, 129.0, 56.2, 55.3, 51.5, 45.8, 27.5, 21.8, 21.2, 20.1, 18.9, 15.3.

HRMS: *m/z* [M + Na]$^+$ calcd for $C_{16}H_{18}O_2$: 265.1204; found: 265.1205.

24g

IR (neat): 2957, 2931, 2870, 1790, 1714, 1590 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 7.35 (s, 1 H), 5.88 (t, *J* = 2.0 Hz, 1 H), 2.12–1.92 (m, 8 H), 1.43–1.25 (m, 10 H), 0.92–0.87 (m, 8 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 200.1, 194.2, 160.3, 147.5, 130.3, 128.3, 69.6, 58.2, 57.4, 51.7, 31.8, 29.3, 27.8, 27.6, 27.3, 23.5, 22.2, 21.5, 21.3, 20.4, 13.9, 13.8.

HRMS: *m/z* [M + H]$^+$ calcd for $C_{22}H_{28}Br_2O_2$: 483.0534; found: 483.0518.

30

IR (film): 2958, 2925, 2855, 1773, 1683, 1580, 1348, 1176 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.32 (dd, *J* = 2.7, 5.7 Hz, 1 H), 6.35–6.29 (m, 2 H), 6.15 (dd, *J* = 3.5, 6.9 Hz, 1 H), 3.31 (t, *J* = 4 Hz, 1 H), 3.21 (br s, 1 H), 2.41–2.31 (m, 1 H), 2.21–2.16 (m, 1 H), 2.05–1.95 (m, 4 H).

^{13}C NMR (62.5 MHz, $CDCl_3$): δ = 209.6, 201.3, 159.9, 140.0, 133.8, 127.8, 69.9, 68.1, 51.6, 48.7, 29.9, 25.6, 20.5.

HRMS: *m/z* [M]$^+$ calcd for $C_{13}H_{12}O_2$: 200.0832; found: 200.0837.

31

IR (film): 2959, 2929, 1729, 1462, 1274, 1123 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.26 (dd, *J* = 2.7, 5.7 Hz, 1 H), 6.28 (dd, *J* = 1.2, 6.0 Hz, 1 H), 6.13 (dd, *J* = 3.9, 6.6 Hz, 1 H), 6.01 (dd, *J* = 1.5, 6.6 Hz, 1 H), 3.19–3.16 (m, 1 H), 2.99–2.96 (m, 1 H), 2.12–2.01 (m, 3 H), 1.99–1.94 (m, 1 H), 1.79–1.72 (m, 1 H), 1.65–1.15 (m, 2 H), 1.33 (td, *J* = 3.6, 13.8 Hz, 1 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 209.1, 201.8, 159.2, 140.0, 136.6, 128.9, 56.6, 51.5, 50.3, 48.2, 29.8, 22.5, 22.2, 20.5.

HRMS: *m/z* [M + H]$^+$ calcd for $C_{14}H_{14}O_2$: 215.1072; found: 215.1066.

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