9

MULTIFOLD RING-CLOSING OLEFIN METATHESES IN SYNTHESES OF ORGANOMETALLIC MOLECULES WITH UNUSUAL CONNECTIVITIES

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9.1 INTRODUCTION

In 2003, one of the authors of this chapter noted that using a transition metal catalyst to carry out a reaction on a transition-metal-containing substrate might at first seem to be a risky proposition (1). However, strategies for directed syntheses of complex organometallic molecules are continually advancing, and nowadays nearly all of the transformations that can be applied to organic compounds see use in organometallic systems in some context.

In this regard, it is now well established that olefin metatheses can be carried out in diverse types of metal coordination spheres (e.g., metals, ligand sets, oxidation states, and charge states). This subject has been more generally reviewed earlier (1). In this chapter, the authors seek to focus on a more challenging subset of processes, namely, those involving *multifold* ring-closing metatheses and the generation of organometallic molecules with unusual connectivities. Transformations that may involve multiple olefin metatheses but do not yield multiple cycles—for example, ring-opening metathesis polymerizations—are excluded. Another exclusion, somewhat regrettable in the authors' opinion, involves metatheses that yield catenanes, knots, or direct precursors thereof. Assemblies with interlocked or threaded rings are derived from topologically more complicated processes than those outlined below, and may receive attention in a follow-up review.

Regardless of the exact scope of this chapter, to the authors' knowledge, the first olefin metatheses in metal coordination spheres were reported by Rudler in 1984 (2,3). These involved olefin-containing tungsten Fischer carbene complexes and the catalyst system $WOCl_4/Ph_2SiH_2$. However, turnover numbers did not exceed four. With regard to multifold ring-closing metatheses in metal coordination spheres, the first example the authors can locate comes from Sauvage and Grubbs (4–6), as depicted in Scheme 9.1 (4). However, this produces a catenane precursor with interlocked rings, **2**. As noted above, these types of cyclizations are not further treated.

The reader is cautioned that this is not intended to be a comprehensive review. Rather, the goal is to illustrate the various types of multifold ring-closing metatheses in a logical order, as opposed to exhaustively cataloging them. Nonetheless, the authors have attempted to make the reference list as complete as possible. All of the reported examples involve ruthenium catalysts, and "Grubbs' catalyst" will be taken to mean his first-generation system. However, Schrock-type catalysts continue to multiply and become increasingly available, and many of these have excellent activities as well as stereoselectivities in ring-closing processes (7).

9.2 STRATEGIC CONSIDERATIONS

A twofold ring-closing olefin metathesis requires four olefinic moieties. In Scheme 9.2, four representative acyclic arrays, designated A–D, are analyzed from the standpoint of possible products that lack interlocked rings. In order

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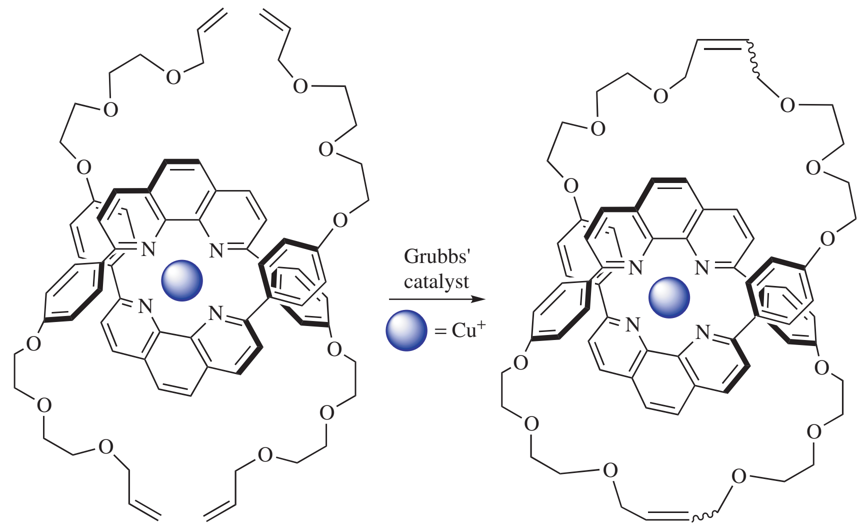
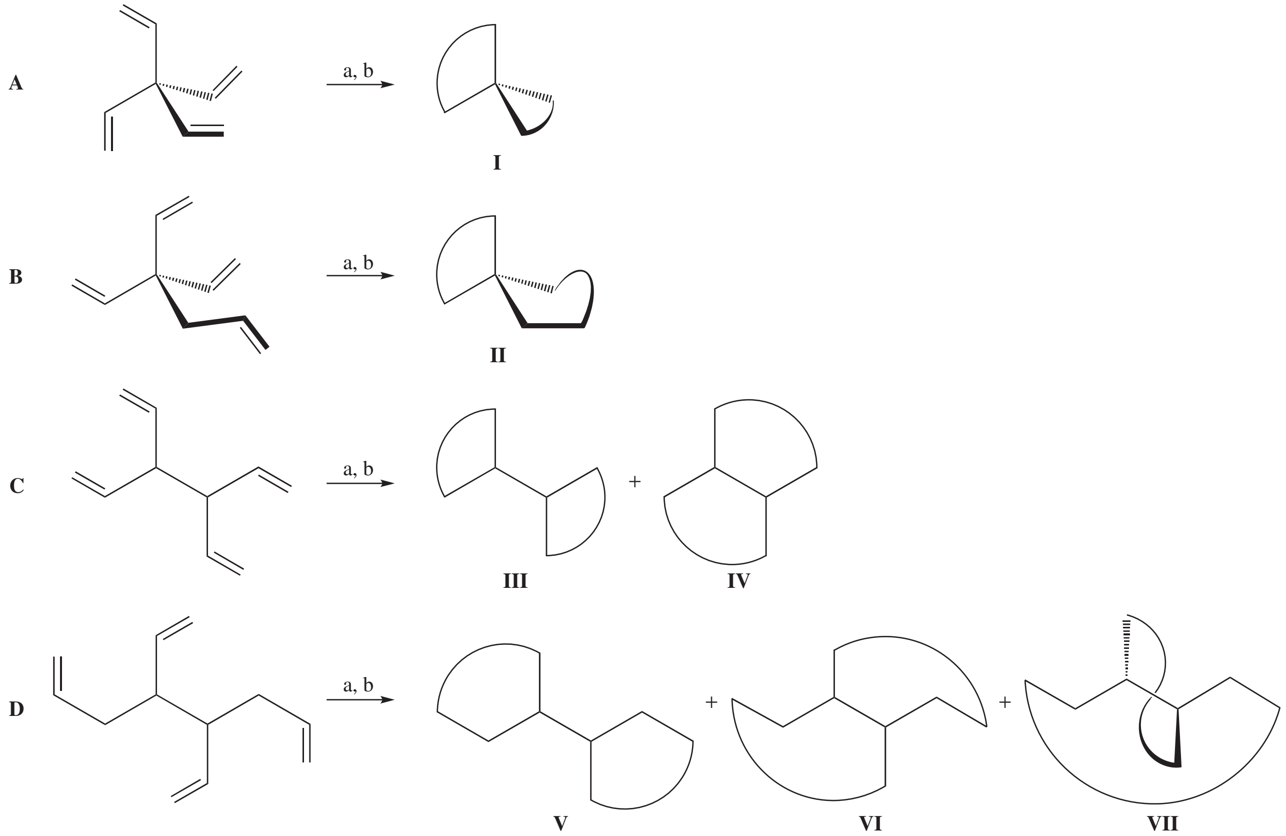
Olefin Metathesis: Theory and Practice, First Edition. Edited by Karol Grela.



1 **2**, 92%

Scheme 9.1



Scheme 9.2 Some types of twofold ring-closing metatheses: (a) C=C metathesis; (b) hydrogenation.

to minimize the number of stereoisomers and facilitate analyses, the C=C linkages have been hydrogenated.

Obviously, a substrate with tetrahedral symmetry such as A can only give rise to one product, **I**. The same holds when the substrate is desymmetrized by altering one of the four olefin-containing moieties, as illustrated by B and **II**. When the tetrahedral center in A is “elongated” to an axis as in C, two distinct cyclization modes are now possible.

The first product (**III**) is derived from metatheses of olefins on the same terminus of the axis or "*intra*ligand" in the case of a central metal. The second product (**IV**) results from metatheses of olefins on opposite termini of the axis or "*inter*ligand" for a suitable substrate. Many complexes described below can be viewed as analogs of C. When the four olefin moieties are arrayed along a chain as in D, three products are possible. These can be viewed as arising from [1,2 + 3,4] (**V**), [1,3 + 2,4] (**VI**), and [1,4 + 2,3] (**VII**) cyclization modes.

Possible cyclization modes become considerably more numerous and complex for substrates with six olefinic moieties. Three representative systems that can give threefold ring-closing metatheses are presented in Scheme 9.3, and obviously many others can be formulated. For the first, an octahedral substrate (E), three products that lack interlocked rings can be defined. These involve metatheses between olefin-containing substituents with cis/cis/cis (**VIII**), cis/cis/trans (**IX**), and trans/trans/trans relationships (**X**), respectively. The last two can also give rise to threaded systems, one of which is illustrated (**XI**).

The next substrate, F, is related to E in the same sense as C and A in Scheme 9.2. Such reactants feature two termini with three olefin-containing groups, and now only two cyclization modes are possible. In the first one depicted (**XII**), all metatheses involve olefinic groups on opposite termini. In the second (**XIII**), one metathesis takes place between groups on opposite termini, and the other two between groups on identical termini.

Substrate G represents an alternative deconstruction of E, resulting in three termini, each with two olefin-containing groups. Now three cyclization modes are possible. In the first one depicted (**XIV**), metatheses are restricted to olefinic groups on the same termini. In the second, all metatheses involve different termini (**XV**). In the third, one metathesis takes place between groups on the same terminus and the other two involve groups on different termini (**XVI**).

As will be seen below, organometallic molecules with even greater numbers of olefins have been subjected to ring-closing metatheses. In addition, the olefins can be arrayed about cyclic core units, as opposed to the acyclic substrates in Schemes 9.2 and 9.3. However, rather than abstractly diagramming even more possibilities, these will be analyzed as encountered.

9.3 EARLY SYSTEMATIC STUDIES WITH PHOSPHINE LIGANDS

Efforts to systematically probe some of the selectivity issues outlined in Schemes 9.2 and 9.3 were undertaken in the authors' group (8,9). One of these involved a series of *trans*-bis(phosphine) platinum complexes **3d**,**e**,**f**,**h** (Scheme 9.4, top; indices **a–h** are coded to the number of methylene groups throughout) (8). The phosphine ligands, $PhP((CH_2)_n(CH{=}CH_2))_2$ ($n = 4, 5, 6, 8$), featured two alkyl substituents terminating in vinyl groups. This allowed for either intraligand or interligand metathesis, akin to the generalized substrate C in Scheme 9.2. As shown in Scheme 9.4, only the latter pathway was observed, giving **4d**,**e**,**f**,**h** in 5–55% yields after workups. An authentic sample of the intraligand metathesis product was independently synthesized in the case of **3f** ($n = 6$). However, it could not be detected in the crude reaction mixture.

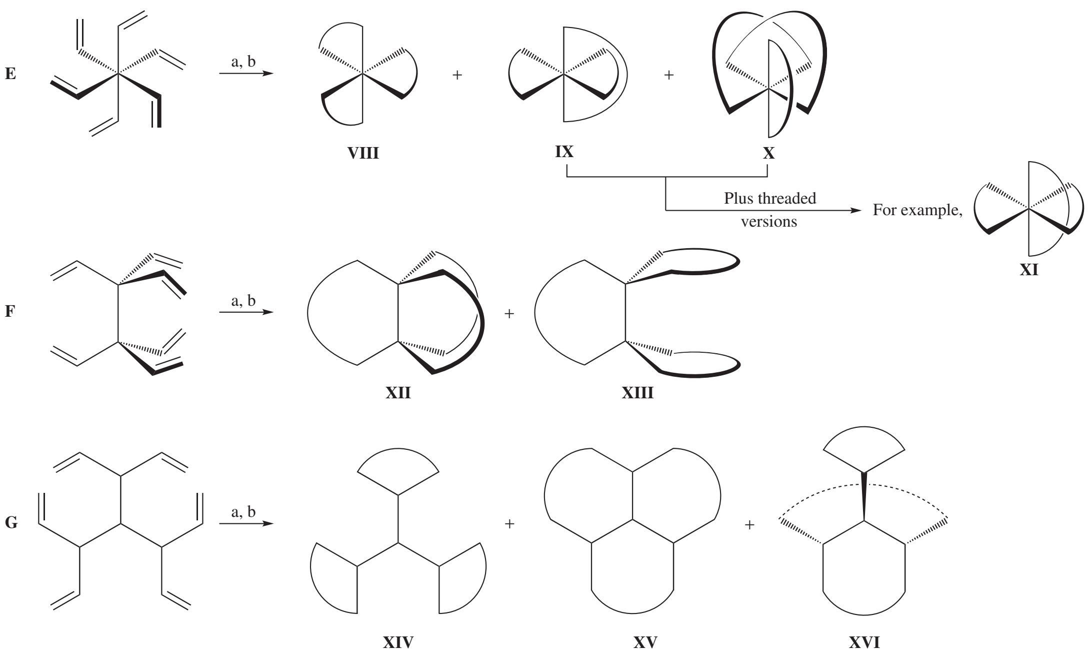
When the methylene chains were too short to allow for the formation of *trans*-spanning diphosphine ligands, intraligand metatheses were observed, as shown with **3b** and **4′b** in Scheme 9.4 (middle). Analogous bis(phosphine) complexes in which each phosphorus atom featured three olefin-containing substituents, allowing in principle for threefold intramolecular ring-closing metathesis, were also investigated. These are akin to the generalized substrate F in Scheme 9.3. However, as shown for **5** in Scheme 9.4 (bottom) only oligomeric and polymeric products were detected. As detailed below, when the pentafluorophenyl ligand is replaced by smaller ligands, monometallic products can be isolated.

Another substrate capable of threefold ring-closing metathesis, an octahedral tungsten complex with three facially disposed monophosphine ligands (**6**) (9), is shown in Scheme 9.5. This represents a model for G in Scheme 9.3. Reaction with Grubbs' catalyst gave a complex and almost intractable mixture of all three types of cyclization products, **7–9**, corresponding to **XIV–XVI** (Scheme 9.3). These formed as various C=C and/or P–Ph stereoisomers, as assayed by HPLC and mass spectrometry before hydrogenation. Crystal structures of two isomers of the threefold interligand metathesis product **8** were obtained.

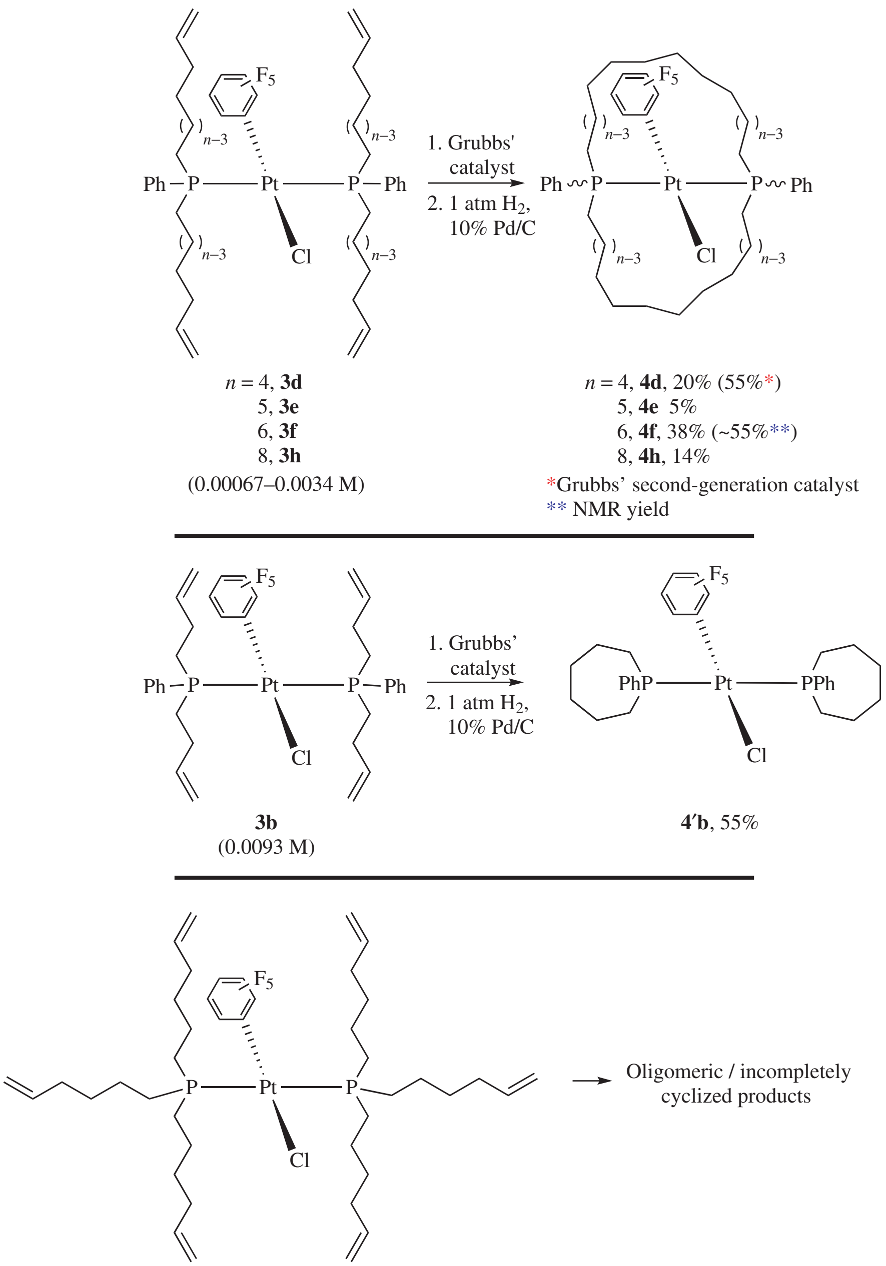
It should be noted in passing that threefold ring-closing metatheses of some organic hexaolefins of the type G give systems analogous to **XV** with high selectivities (no type **XIV** or **XVI** products detected) (10). Highly selective twofold ring-closing metatheses of organic tetraolefins of the type C have also been described (11).

9.4 APPLICATIONS OF TWOFOLD RING-CLOSING OLEFIN METATHESES USING PHOSPHINE LIGANDS

The authors' group has had a particular interest in complexes in which sp carbon or polyynediyl chains bridge two transition metals. For several reasons, it was sought to "insulate" the $-(C{\equiv}C)_n-$ linkages with two flexible sp^3 carbon chains. The diplatinum octatetraynediyl complexes **10f–i** in Scheme 9.6 feature four phosphine ligands with a single olefinic group, two with *trans* relationships on each terminus, and are closely related to the system C in Scheme 9.2. Interestingly,



Scheme 9.3 Some types of threefold ring-closing metatheses: (a) C=C metathesis; (b) hydrogenation.



n = 4, **3d**
5, **3e**
6, **3f**
8, **3h**
(0.00067–0.0034 M)

n = 4, **4d**, 20% (55%*)
5, **4e** 5%
6, **4f**, 38% (~55%**)
8, **4h**, 14%
*Grubbs' second-generation catalyst
** NMR yield

3b
(0.0093 M)

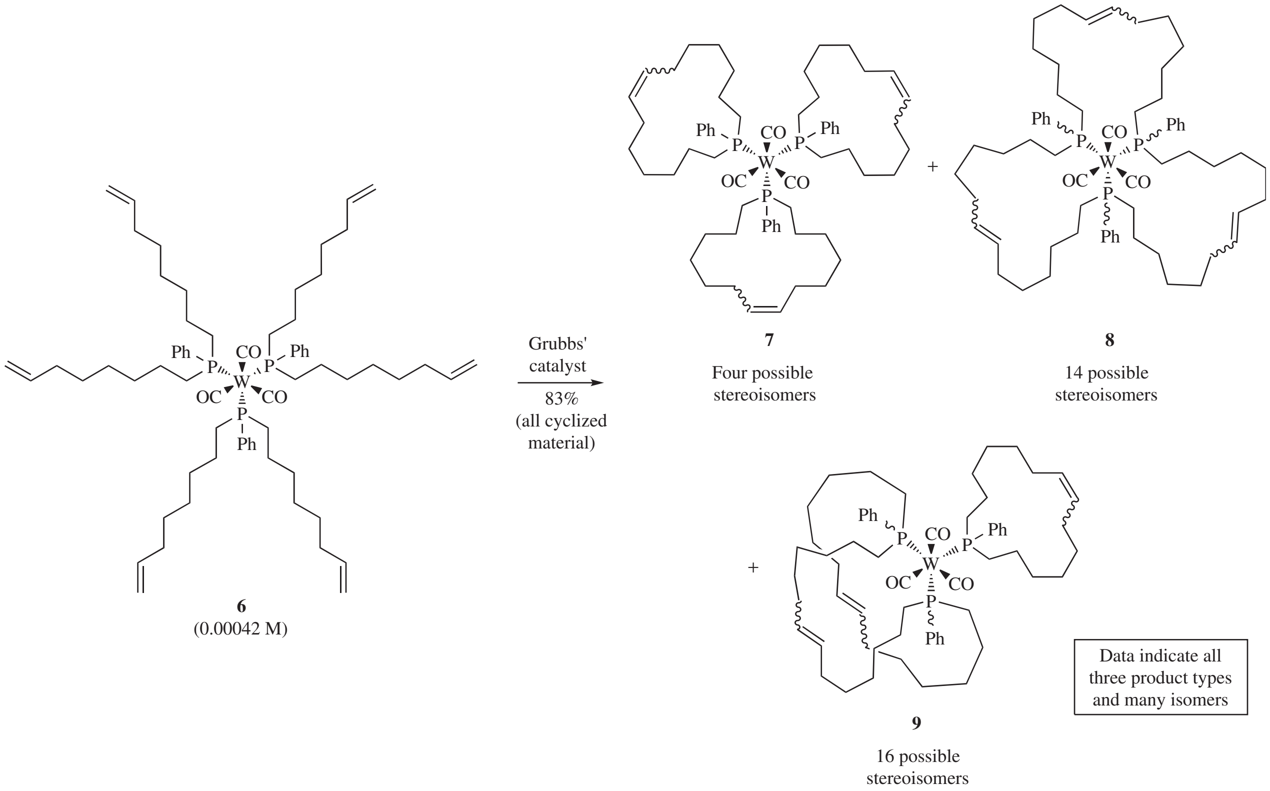
4′b, 55%

5

Scheme 9.4

twofold metathesis/hydrogenation sequences yield mainly the target complexes **11f–i**, derived from metatheses between phosphine ligands on opposite platinum termini (see **IV**, Scheme 9.2) (12). In three cases, lesser amounts of the alternative ring-closing products **12**, derived from metatheses between phosphine ligands on identical termini, also formed (see **III**).

Comparable reactions could be realized with diplatinum complexes with longer sp carbon chains. However, as shown in Scheme 9.7, substrate **13**, in which geminal dimethyl groups have been introduced on the sp^3 carbon segments, exhibited an opposite cyclization selectivity (13). Complex **15**, derived from metatheses between phosphine ligands on identical termini, greatly dominated. Possible contributing factors have been analyzed, but remain speculative. As shown in Scheme 9.8, substrate **16**, in which ether oxygen atoms have been inserted into the sp^3 carbon segments, cyclizes with the "normal" selectivity (13).



6
(0.00042 M)

7
Four possible stereoisomers

8
14 possible stereoisomers

9
16 possible stereoisomers

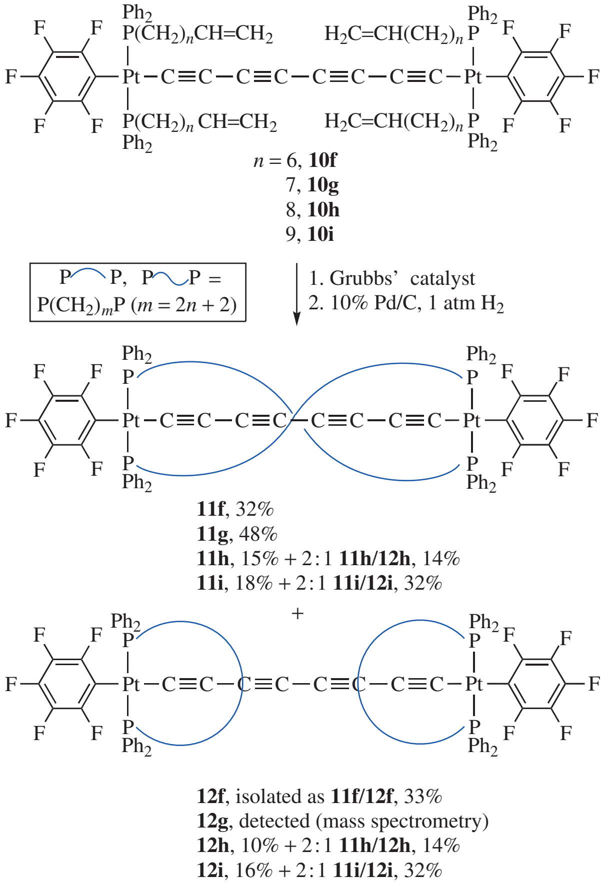
Data indicate all three product types and many isomers

Scheme 9.5

9.5 STUDIES WITH *TRANS* BIS(PYRIDINE) COMPLEXES

An early example of a twofold ring-closing metathesis in a metal coordination sphere is shown in Scheme 9.9 (top) (14). This features a *trans*-bis(pyridine) palladium complex **18** in which the 2,6 positions of the pyridine ligands are substituted with methylene chains that terminate in vinyl groups. As originally reported by Lambert (14,15) and later reinvestigated in the authors' laboratory, only interligand metathesis to give **19** is observed. One trans-spanning linkage extends above the coordination plane, and the other below. Although steric constraints would seem to strongly disfavor intraligand metathesis, this cyclization mode has been observed with similarly substituted monopyridine complexes (16,17). Analogous interligand metathesis products are obtained with the ethereal analogs **20a**,**b** in Scheme 9.9 (bottom), albeit in lower yields (15).

Monopyridine complexes have also been synthesized in which the 3,5-positions are substituted with methylene chains that terminate in vinyl groups. Here, ready intraligand metatheses have been observed. Accordingly, close relatives of the complexes in Scheme 9.9 with two 3,5-disubstituted pyridines should be capable of either intraligand or interligand metatheses (see **III** and **IV**, Scheme 9.2). As shown by **22d**,**e**,**f**,**h** and **24** in Scheme 9.10, only interligand metatheses to give **23d**,**e**,**f**,**h** and **25** are observed (15).

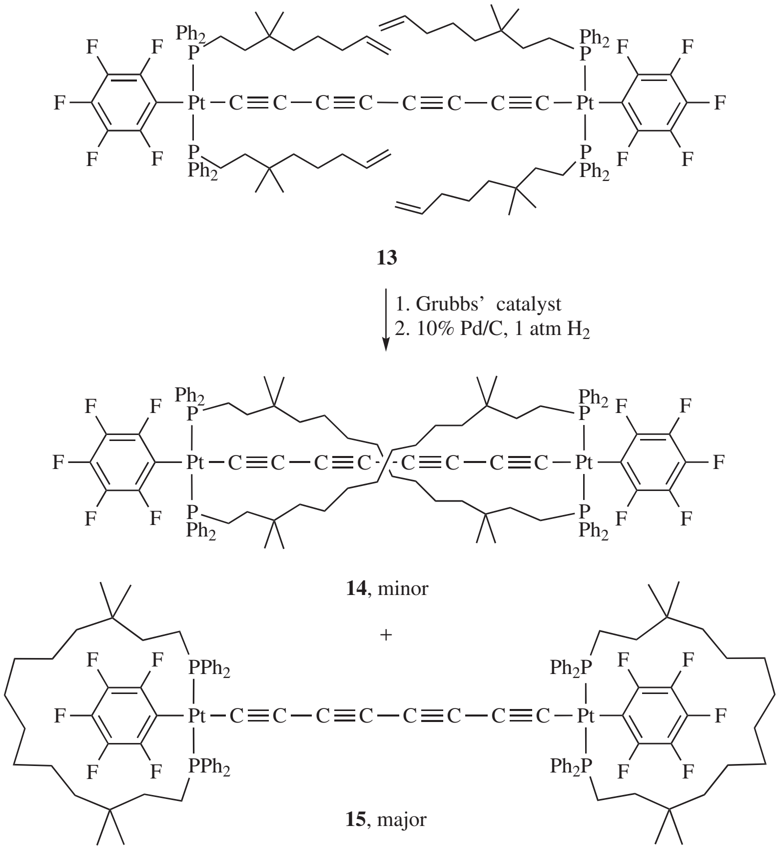


$n = 6$, **10f**
7, **10g**
8, **10h**
9, **10i**

11f, 32%
11g, 48%
11h, 15% + 2:1 **11h/12h**, 14%
11i, 18% + 2:1 **11i/12i**, 32%

12f, isolated as **11f/12f**, 33%
12g, detected (mass spectrometry)
12h, 10% + 2:1 **11h/12h**, 14%
12i, 16% + 2:1 **11i/12i**, 32%

Scheme 9.6



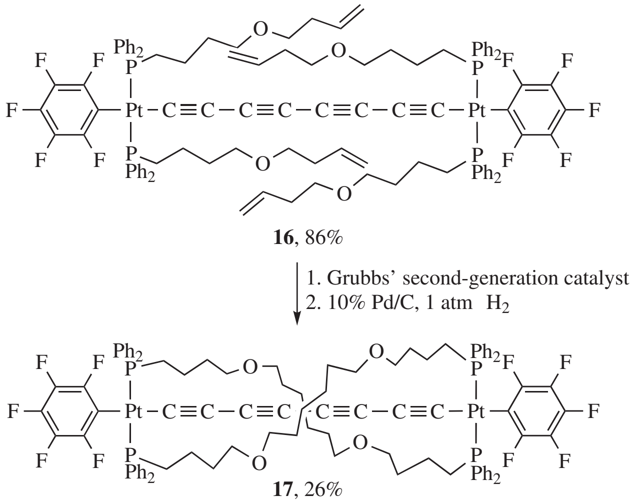
13

14, minor

15, major

Total yield **14**, **15**, and oligomers: 79%
15 after chromatography: 14–25%

Scheme 9.7



16, 86%

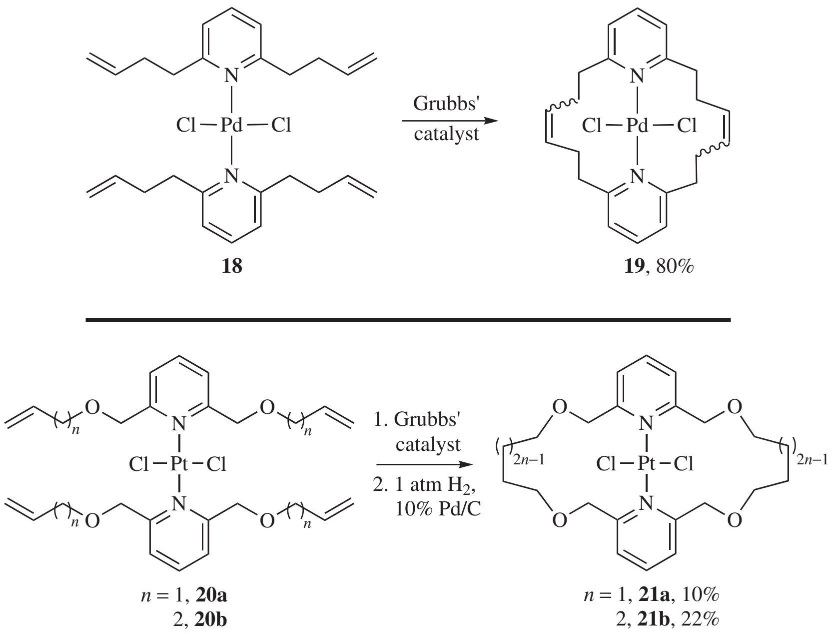
17, 26%

Scheme 9.8

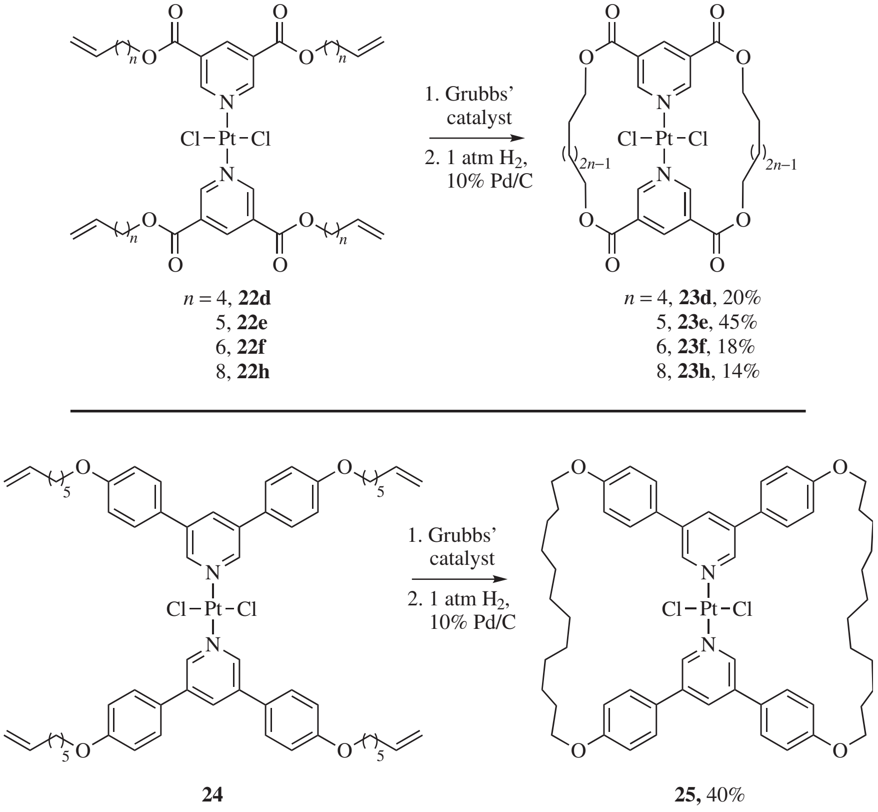
9.6 STUDIES WITH ARENE AND CYCLOPENTADIENYL LIGANDS

Various polyolefinated arene and cyclopentadienyl complexes have been investigated by Astruc (18) and provide a nice bridge from the twofold ring-closing metatheses that have dominated the previous sections to higher order metatheses. First, as shown in Scheme 9.11 (top), the metathesis of the tetraolefinic iron–arene complex **26** was examined. This substrate features two $H_2C{=}CHCH_2{-}C{-}CH_2CH{=}CH_2$ or "diallylmethane" segments, and gave only the twofold 1,1-ring-closing metathesis product **27** (76%), akin to cyclization mode **III** for C (Scheme 9.2). However, the alternative metathesis product involving allyl groups with 1,3-relationships, which could be viewed as a paddlane, would be highly strained.

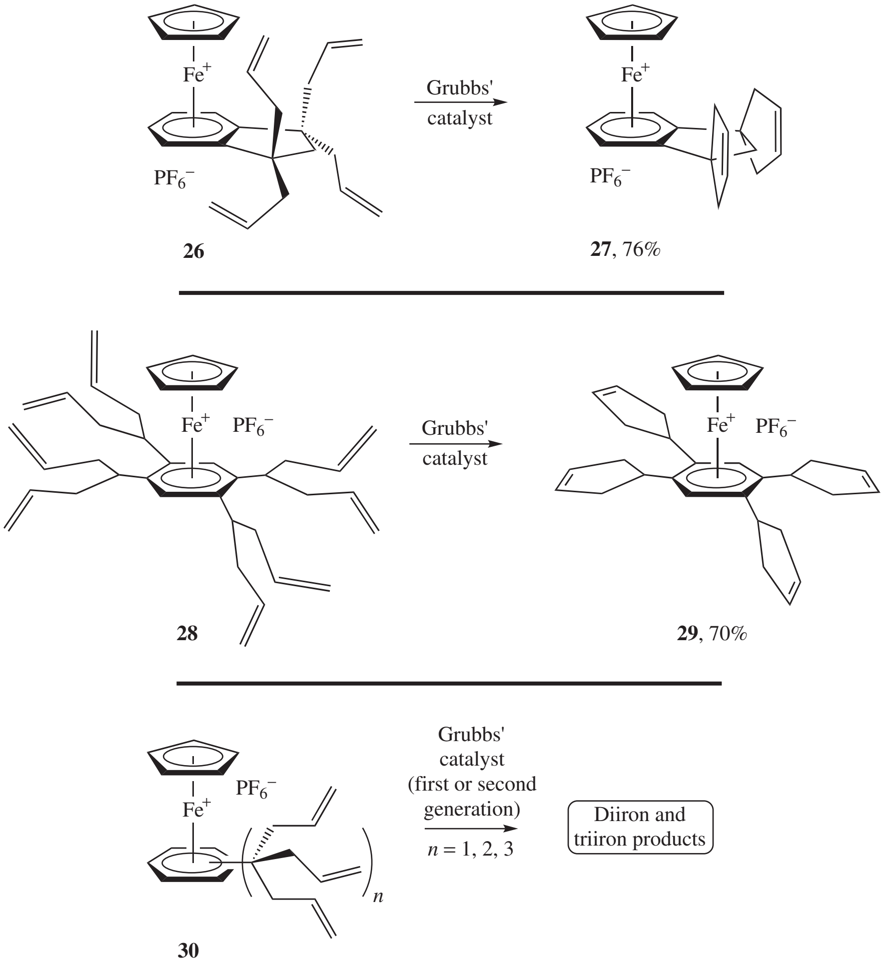
Next, Astruc investigated the octaolefinic arene complex **28** shown in Scheme 9.11 (middle), which features four $CH(CH_2CH{=}CH_2)_2$ substituents. This gave the fourfold ring-closing metathesis product **29** in 70% yield, again akin to cyclization mode **III** for C (Scheme 9.2). However, in this case, cyclization between adjacent diallylmethane segments (see **IV**) would not be prohibitively strained. Another series of substrates were synthesized in which the arene ligands featured one to three "triallylmethane" or $C(CH_2CH{=}CH_2)_3$ substituents (**30**; Scheme 9.11, bottom). However, in all cases, initial cyclopentene ring formation was followed by intermolecular metatheses to give diiron and triiron products.



Scheme 9.9



Scheme 9.10



Scheme 9.11

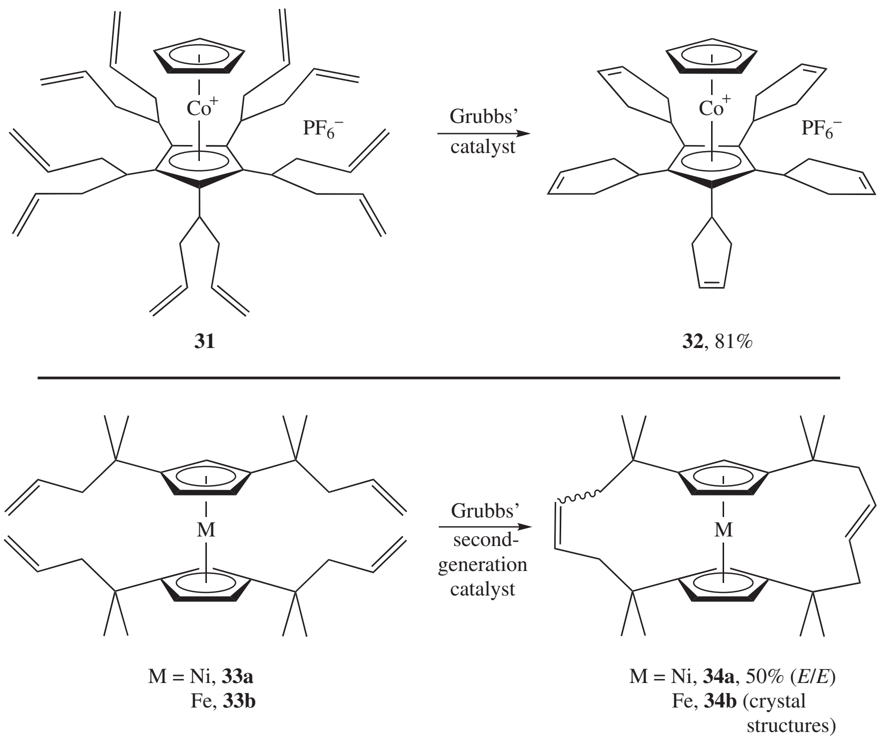
Attention was then turned to the cobaltocene **31** in Scheme 9.12 (top), in which one cyclopentadienyl ligand is completely substituted with five $CH(CH_2CH{=}CH_2)_2$ substituents. This decaolefin underwent a fivefold ring-closing metathesis to give the pentakis(cyclopentene) **32** in 81% yield. As with **28** in Scheme 9.11, cyclization took place within the substituents, as opposed to between them.

Some relevant work from the Buchowicz (19) laboratory is depicted in Scheme 9.12 (bottom). The nickel and iron metallocenes **33a**,**b** were prepared, in which each cyclopentadienyl ligand features two 1,3-disposed alkyl substituents that terminate in vinyl groups. With the nickelocene, Grubbs' second-generation catalyst afforded a single stereoisomer of a *diansa* product in 50% yield (**34a**; *E*/*E*). With the ferrocene, a mixture of *diansa* stereoisomers was isolated (**34b**), two of which could be crystallographically characterized (*E*/*E* and *E*/*Z*). These results are akin to cyclization mode **IV** of C (Scheme 9.2). Intraligand metathesis products analogous to **III** should be disfavored, as the resulting nine membered rings would include the equivalent of a *trans* C=C linkage, since they span the 1,3 positions of a cyclopentadienyl ligand.

9.7 STUDIES WITH POLYPYRIDINE AND POLY(TERPYRIDINE) COMPLEXES

Another series of higher order ring-closing metatheses involve pyridine adducts of platinum aryl complexes that are arrayed about a benzenoid core, such as the tricationic triplatinum pincer species **35** in Scheme 9.13 (16,20). Van Koten found that this hexaolefin underwent a threefold metathesis to give **36** as a mixture of *E*/*Z* isomers in 67% yield after workup. This corresponds to the cyclization mode **XV** for G in Scheme 9.3. The resulting tripyridine ligand, a 69-membered macrocycle, could be liberated from the triplatinum template upon addition of NaCl.

Kang and Ko (21) later extended this protocol to the hexametallic dodecaolefin **37** shown in Scheme 9.14. This



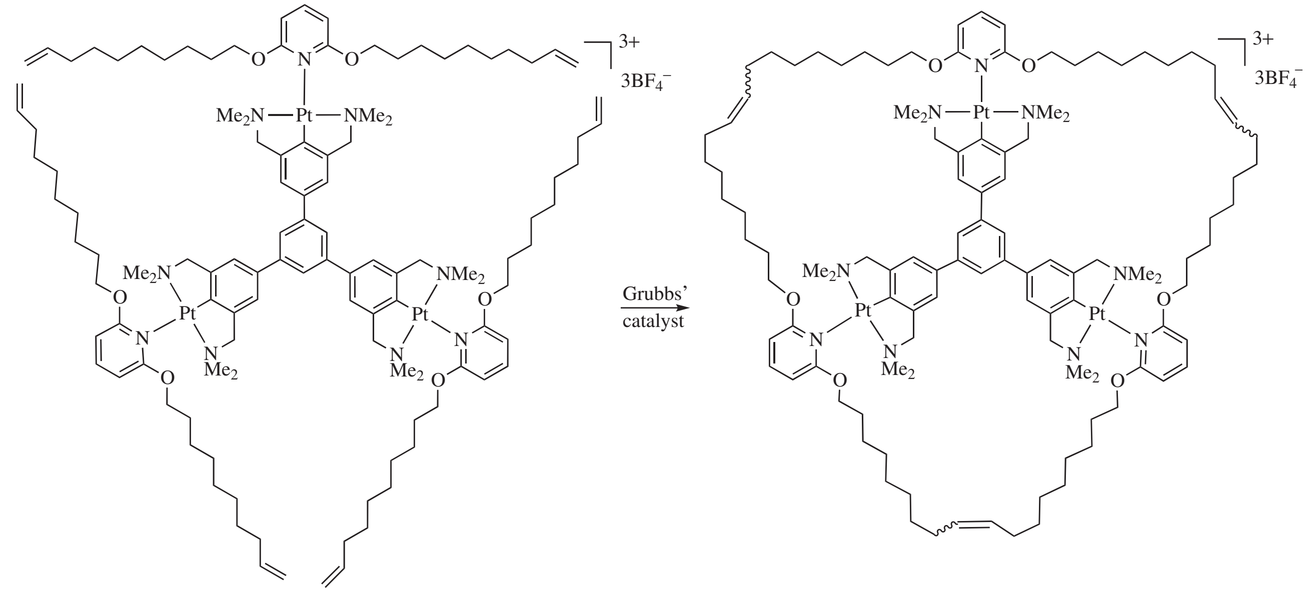
31

32, 81%

M = Ni, **33a**
Fe, **33b**

M = Ni, **34a**, 50% (*E*/*E*)
Fe, **34b** (crystal structures)

Scheme 9.12



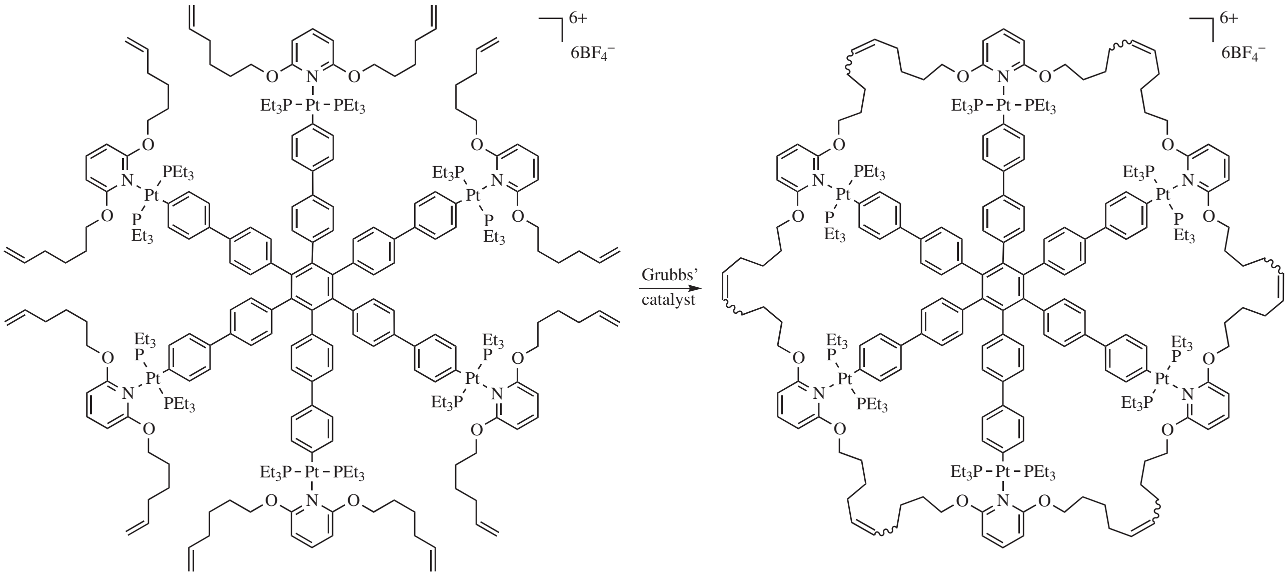
35

36, 67%

Scheme 9.13

underwent a related sixfold ring-closing metathesis to give **38** in 80% yield. To the authors' knowledge, this and the following example represent the highest order intramolecular ring-closing metatheses realized to date in metal coordination spheres, excepting three-dimensional capsule compounds (Section 9.9). The resulting hexapyridine ligand, a 90-membered macrocycle, could be liberated from the hexaplatinum template upon addition of NaI.

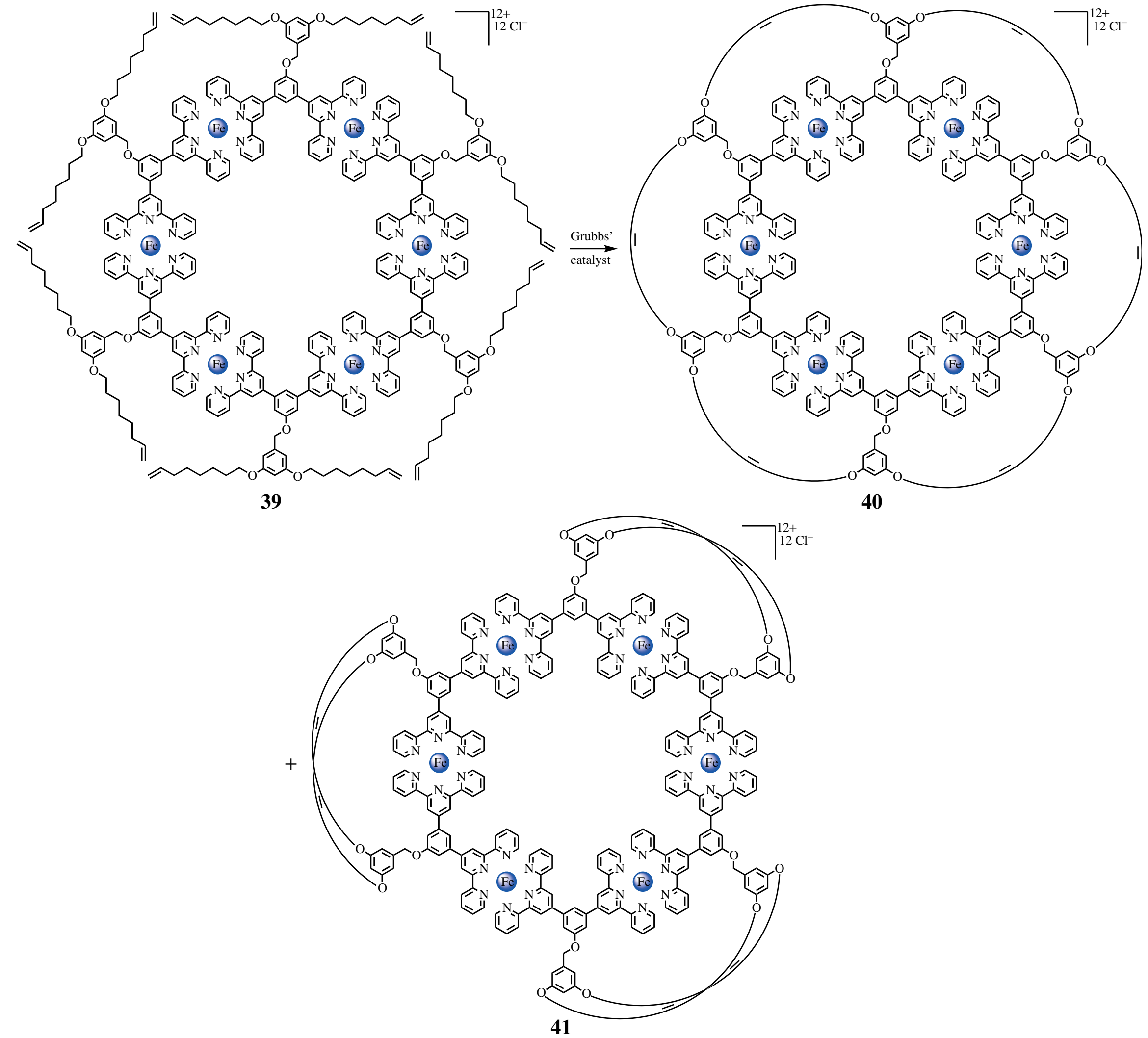
The largest macrocycle accessed by the preceding strategy is depicted in Scheme 9.15 (22). Newkome first showed that the hexairon dodeca(terpyridine) system **39** could easily be synthesized by self-assembly. Sixfold ring-closing



37

38, 80%

Scheme 9.14



39

40

41

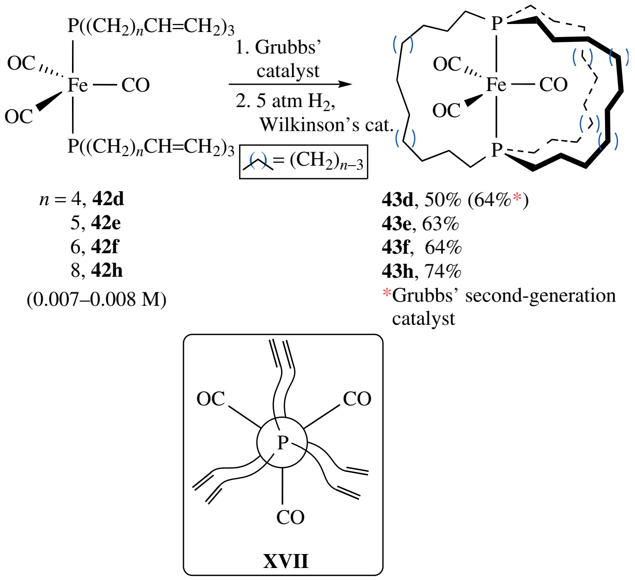
Scheme 9.15

metathesis then gave two products: (i) **40**, derived from reactions of the olefins on a given resorcinol moiety with those on two different resorcinol moieties, analogous to the products in Schemes 9.13 and 9.14, and (ii) **41**, derived from reactions of both olefins on a given resorcinol moiety with those on a single other resorcinol moiety. Here, both products represent interligand metatheses. The structures were established by decomplexing the ligands (K_2CO_3/DMF; good overall yields) and, after hydrogenations, characterization of the resulting macrocycles. That derived from **40** features a 114-membered ring.

9.8 GYROSCOPE-LIKE COMPLEXES DERIVED FROM *TRANS*-BIS(PHOSPHINE) COMPLEXES

An extensive series of metal complexes featuring *trans*-phosphine ligands of the formula $P((CH_2)_n(CH{=}CH_2))_3$ have been investigated in the authors' laboratories. As illustrated by F in Scheme 9.3, two modes of threefold ring-closing metatheses are possible (**XII**, **XIII**). Of these, **XII** results in a class of cagelike complexes that the authors have termed *molecular gyroscopes*. Interestingly, this cyclization mode dominates in all of the coordination geometries examined to date (trigonal bipyramidal, square planar, octahedral), as detailed below. When such metatheses are attempted in the absence of a templating metal, for example, using the phosphine borane $H_3B{\cdot}P((CH_2)_6(CH{=}CH_2))_3$, the yields of cagelike diphosphorus products are miniscule (23).

As shown in Scheme 9.16, the trigonal bipyramidal iron tricarbonyl complexes *trans*-$Fe(CO)_3(P((CH_2)_nCH{=}CH_2)_3)_2$ ($n = 4$, 5, 6, 8; **42d**,**e**,**f**,**h**) were treated with Grubbs' catalyst and then hydrogenated. Workups gave the target gyroscope-like complexes **43d**,**e**,**f**,**h** in 50–74% overall yields (24, Wang, L., unpublished results, Universität Erlangen-Nürnberg.). No products derived from alternative cyclization modes were detected. The smallest macrocycle features thirteen membered rings, and was obtained in somewhat higher yield with Grubbs' second-generation catalyst. This trend has also been found with related complexes with identical ring sizes, but is not observed with the larger cycles.



$n = 4$, **42d**
5, **42e**
6, **42f**
8, **42h**
(0.007–0.008 M)

43d, 50% (64%*)
43e, 63%
43f, 64%
43h, 74%
*Grubbs' second-generation catalyst

Scheme 9.16

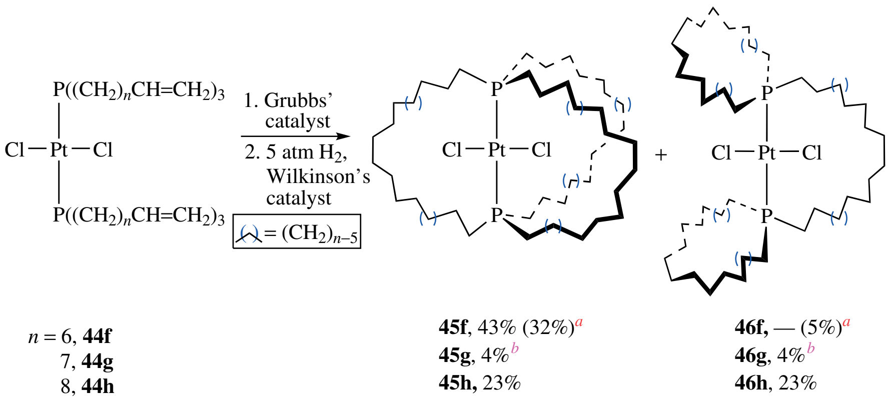
Parallel sequences have been effected with analogous iron bis(phosphite) complexes (25). However, the products could only be obtained as oils and yields were much lower.

Why do **42d**,**e**,**f**,**h** exhibit such high selectivities for threefold interligand metathesis? Since both the iron fragment $Fe(CO)_3$ and the phosphines possess threefold symmetry axes, the CO ligands and $(CH_2)_nCH{=}CH_2$ substituents can adopt staggered arrangements, as shown in **XVII** in Scheme 9.16 (bottom). As a result, the $(CH_2)_nCH{=}CH_2$ substituents on the *trans*-phosphine ligands become eclipsed, and are directed into the same OC–Fe–CO interstice. Consequently, **42d**,**e**,**f**,**h** can be viewed as preorganized for threefold interligand metatheses.

Analogous metathesis/hydrogenation sequences involving square planar $PdCl_2$, $PtBr_2$, and $PtCl_2$ adducts have been investigated (23,26). The last are representative and are depicted in Scheme 9.17. Square planar complexes are not preorganized for interligand metatheses as proposed for **42** in Scheme 9.16, and no monometallic complexes were detected for substrates with $n = 4$ or 5. However, with $n = 6$ (**44f**), threefold interligand metathesis dominated to give the gyroscope-like complex **45f**. On smaller scales, **45f** could be reproducibly isolated in 43% yield as the exclusive product. However, on scales larger than 1 g, the yield of **45f** appeared to drop and some of the alternative metathesis product **46f** was isolated. The latter is analogous to product **XIII** from F in Scheme 9.3.

When one more methylene group was added to the phosphine substituents ($n = 7$, **44g**), yields of monoplatinum complexes decreased dramatically. Furthermore, both modes of threefold ring-closing metathesis were observed (**XII**, **XIII**). When another methylene group was added ($n = 8$, **44h**), yields of monoplatinum complexes greatly increased. Threefold interligand metathesis to give **45h** dominated (28% after workup), but the yield of the alternative metathesis product **46h** was also significant (23%). Some related organic hexaolefins in which the P–M–P axis is replaced by a phenylene or *p*-CC≡C–C_6H_4–C≡CC moiety also undergo threefold intramolecular ring-closing metatheses (27). So far, only the second cyclization mode (**XIII**) has been observed.

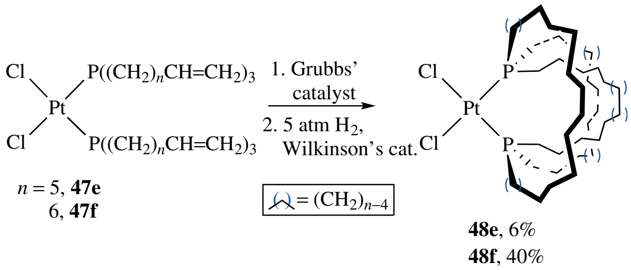
An obvious question is whether comparable olefin metatheses can be effected when such phosphine ligands bear cis relationships. As depicted in Scheme 9.18, the *cis*-dichloroplatinum complexes **47e**,**f** undergo threefold



[a] Larger scale reaction (see text).

[b] Yields from different experiments.

Scheme 9.17



Scheme 9.18

interligand metatheses to give the "parachute" systems **48e**,**f** (28). No products derived from intraligand metathesis were detected. Although **45f** (Scheme 9.17) and **48f** are isomeric, they exhibit no tendency to interconvert at temperatures of greater than 150 °C.

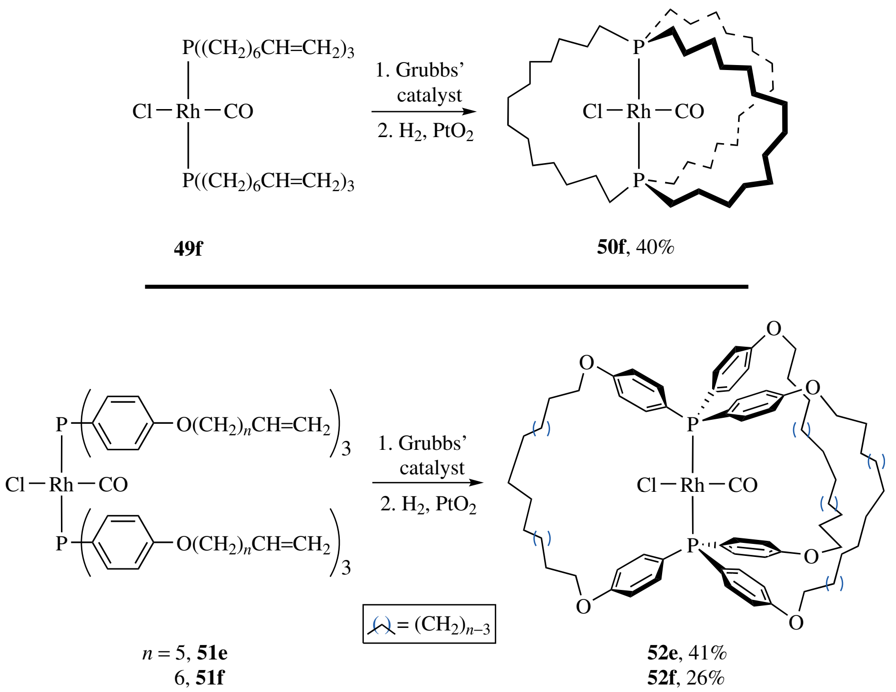
As shown in Scheme 9.19, square planar rhodium complexes with *trans*-phosphine ligands have also been investigated (29,30). In contrast to the palladium and platinum complexes, these feature two different ligands on the "rotator," chlorine and carbon monoxide. The analog of the platinum complex **44f**, **49f**, underwent a similar threefold interligand metathesis to give **50f** in 40% yield after workup (29). Interestingly, analogous cyclizations could be effected with the triarylphosphine complexes **51e**,**f** in which the para positions have been substituted with O(CH$_2$)$_n$CH=CH$_2$ groups (30). The products **52e**,**f** feature 25- and 27-membered macrocycles. In none of these reactions have alternative cyclization modes been detected.

As illustrated in Scheme 9.20, a related palladium tribenzylphosphine complex, in which an ortho position in each ring has been substituted by a O(CH$_2$)$_4$CH=CH$_2$ group, has been investigated (**53d**) (31). With this substrate, the only product isolated (**54d**, 86%) was derived by a combination of interligand and intraligand metathesis, analogous to **XIII**. Some related complexes with phosphine ligands with only two benzyl substituents were also investigated. These results, which are more relevant to the types of reactions in Section 3, are depicted in Scheme 9.21.

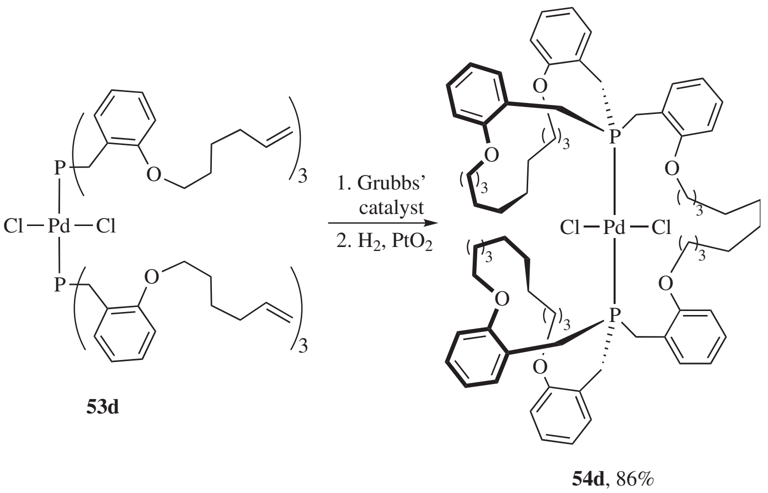
Analogous metathesis/hydrogenation sequences involving two series of octahedral metal complexes with *trans*-phosphine ligands P((CH$_2$)$_n$(CH=CH$_2$))$_3$ have been investigated. It was thought that such substrates, with their more congested equatorial planes consisting of four ligands, would be particularly prone to intermolecular metatheses and oligomerization. However, as shown in Scheme 9.22, the *mer* rhenium tricarbonyl chloride and bromide complexes **60f** and **63f** ($n = 6$) afforded the gyroscope-like complexes **61f** and **64f** in 61% and 37% yields (32). The lower yield of the latter has been ascribed to the increased size of the bromine ligand, a trend also seen with related square planar palladium complexes. With **60f**, a second product, derived from a combination of interligand and intraligand metatheses, was obtained in 6% yield (**62f**; see **XIII**).

As with palladium and platinum analogs, no monometallic products could be detected with substrates with shorter phosphine ligand methylene chains. When an additional methylene group was added to each chain ($n = 7$, **60g** and **63g**), little or no gyroscope-like products could be detected. Rather, complexes analogous to **62f**, namely, **62g** and **65g**, were isolated in 27% and 20% yields (Scheme 9.22). When yet another methylene group was added to each ($n = 8$, **60h** and **63h**), gyroscope-like products again dominated (**61h**, 25%; **64h**, 18%). However, some of the alternative interligand metathesis products were also obtained (**62h**, 11%; **65h**, traces).

As shown in Scheme 9.23, similar results have been obtained with related octahedral osmium dicarbonyl dihalide complexes (33). Although a more extensive data set would



Scheme 9.19

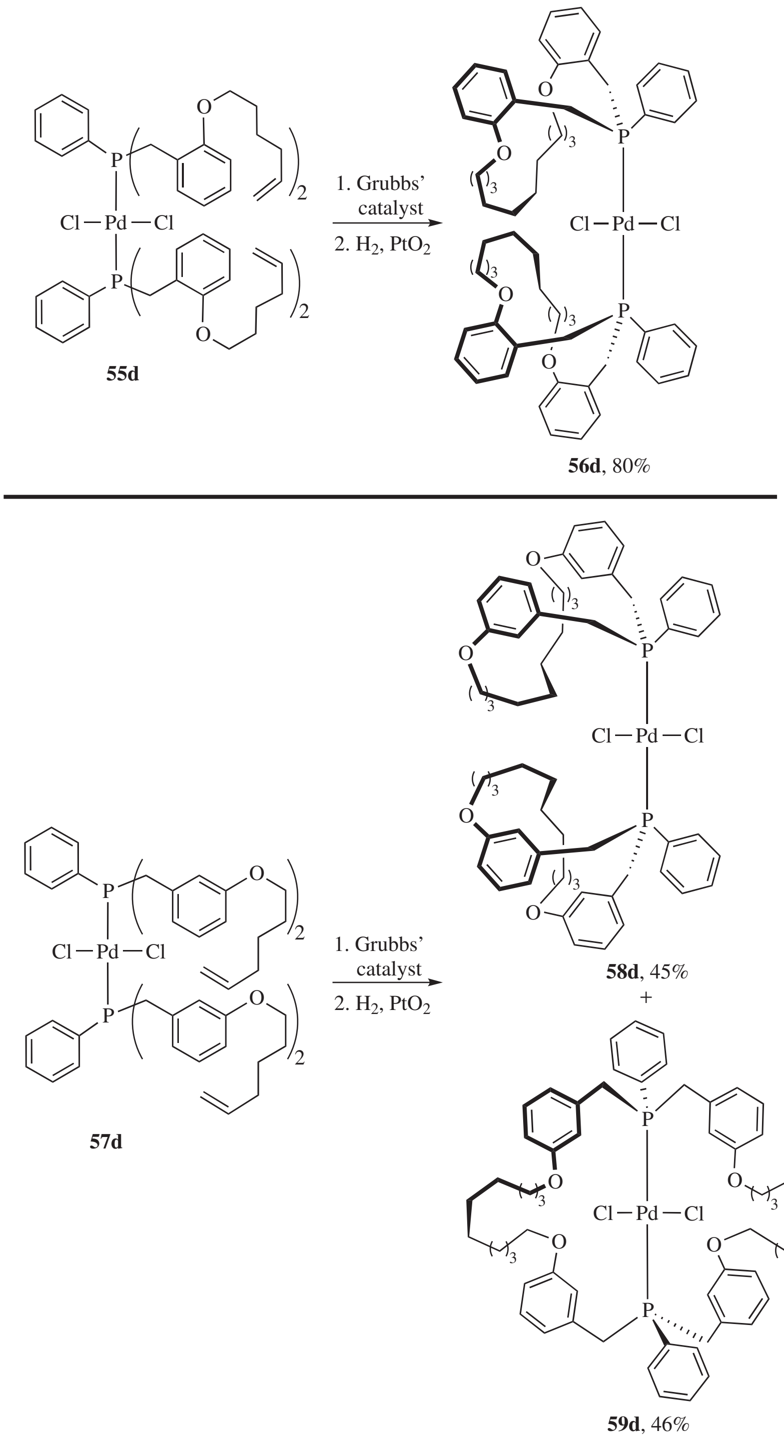


Scheme 9.20

be desirable, it does seem that when there are even numbers of methylene groups in every phosphine substituent, there is a marked preference for products of the type **XII** (see F, Scheme 9.3), and when there are odd numbers of methylene groups, there is a marked preference for products of the type **XIII**. Even/odd relationships have been found for a number of physical and chemical properties of polymethylene-containing compounds (34), but the factors underlying the yield trends in Schemes 9.22 and 9.23 remain to be elucidated.

9.9 OTHER RELEVANT MULTIFOLD RING-CLOSING METATHESES

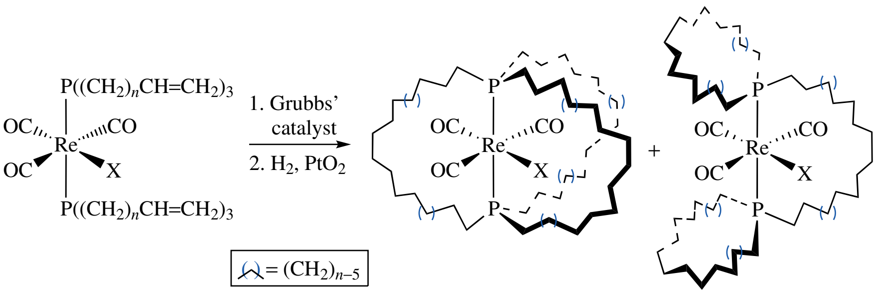
In collecting the literature for this chapter, the authors encountered additional examples of higher order intramolecular ring-closing metatheses in metal coordination spheres that, owing to their overall complexity, seemed beyond the scope of this treatment (35). However, just as the introduction featured a single example of a catenane precursor with interlocked rings, it was thought to conclude the descriptive



Scheme 9.21

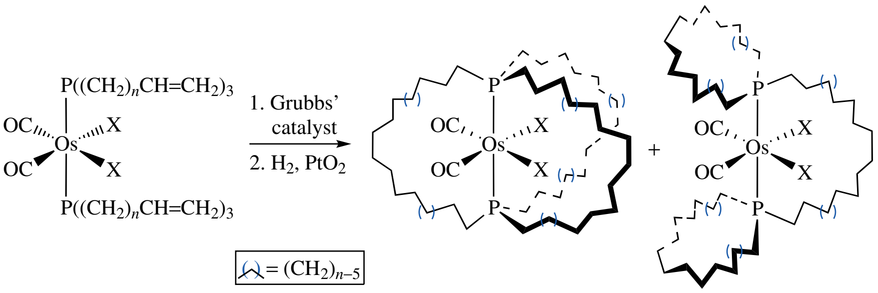
chemistry in this review with an example that illustrates both an emerging frontier for and the immense synthetic power of this methodology.

The octahedral hexapalladium capsule compounds **73** shown in Scheme 9.24 can be synthesized in high yields by self-assembly.[35c] On each trigonal face, three tethers of the formula $O(CH_2)_nCH{=}CH_2$ ($n = 2$–4) were installed. For the cases with $n = 3$ and 4, reactions with Grubbs' catalyst effected 12-fold olefin metatheses to give what might be viewed as "stapled" octahedra, **74**, with each trigonal face tied to all three neighbors. Reactions were complete within 1–2 days, as assayed by mass spectrometry, and



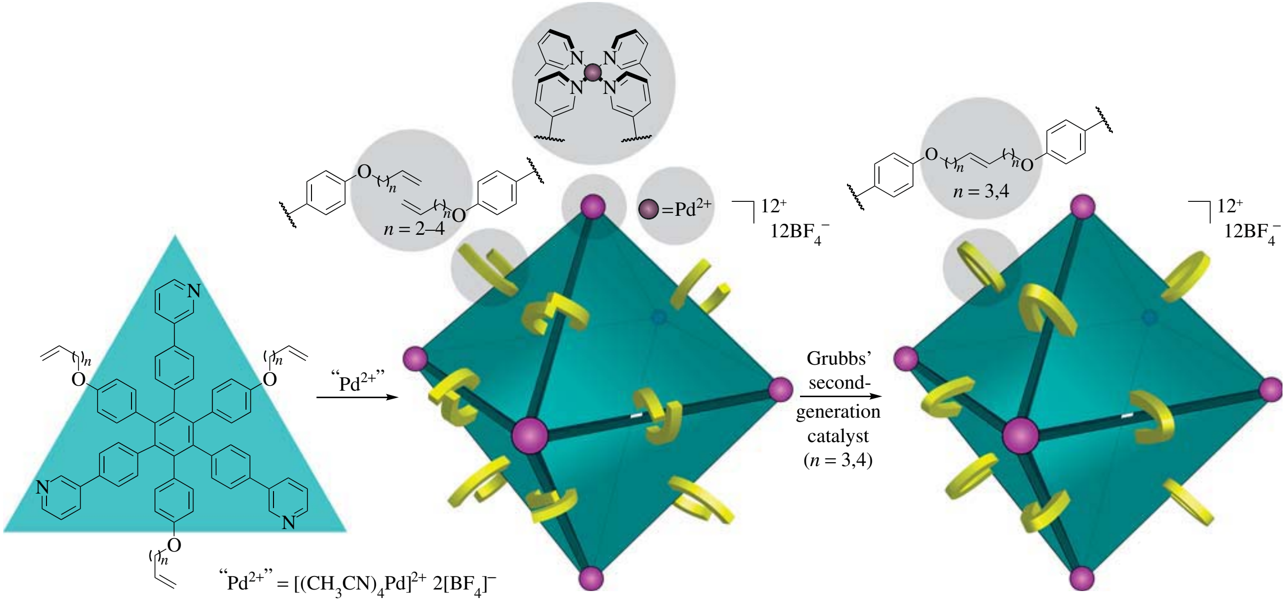
n/X = 6/Cl, **60f**	**61f**, 61%	**62f**, 6%
7/Cl, **60g**	**61g**, traces	**62g**, 27%
8/Cl, **60h**	**61h**, 25%	**62h**, 11%
6/Br, **63f**	**64f**, 37%	**65f**, —
7/Br, **63g**	**64g**, —	**65g**, 20%
8/Br, **63h**	**64h**, 18%	**65h**, traces

Scheme 9.22



n/X = 6/Cl, **66f**	**67f**, 28%	**68f**, 13%
7/Cl, **66g**	**67g**, 5%	**68g**, 51%
8/Cl, **66h**	**67h**, 23%	**68h**, 12%
6/Br, **69f**	**70f**, 31%	**71f**, 18%
7/Br, **69g**	**70g**, 5%	**71g**, 40%
8/Br, **69h**	**70h**, 27%	**71h**, 24%

Scheme 9.23



72

73
[Pd$_6$**72**$_8$]$^{12+}$ 12[BF$_4$]$^-$

74

Scheme 9.24 (*See plate section for color version.*)

mixtures of *Z*/*E* C=C isomers were obtained. Similarly to the chemistry in Section 9.7, the metals were removed and the C=C linkages hydrogenated, leaving purely organic capsules containing only covalent bonds. For the case with $n = 3$, the overall yield was an impressive 43%.

9.10 KINETIC AND THERMODYNAMIC CONTROL

Most researchers, including the authors, have made no special attempt to distinguish kinetic versus thermodynamic control in any of the preceding olefin metatheses. Most reactions are believed to be under kinetic control, although equilibrium has been unambiguously reached in certain cases (36). For example, Grubbs' second-generation catalyst is able to further transform the oligomeric or polyplatinum by-products initially generated from **3d** in Scheme 9.4, greatly enhancing the yield of monoplatinum complex **4d**. Prior to hydrogenation, the equilibrium can be reversibly shifted between precursors to **4d** and unsaturated oligomers by increasing or decreasing the concentration.

In any event, the deliberate application of kinetic or thermodynamic metathesis conditions represents an obvious approach to enhancing selectivities for the various cyclization motifs in Schemes 9.2 and 9.3. Furthermore, a variety of unsuccessful multifold ring-closing metatheses have been noted (37), which for obvious reasons were not treated in the preceding narrative. There are probably many more "failures" that have remained unreported. Perhaps some of these sequences would be feasible under carefully optimized conditions.

One approach to probing kinetic versus thermodynamic control in many of the above schemes would involve separation of the two types of metathesis products prior to the customary hydrogenation. Each species would then independently be subjected to further metathesis, ideally achieving the same equilibrium ratio. However, the necessary separations are rendered more challenging by the fact that mixtures of *Z*/*E* isomers are commonly obtained. Perhaps newly developed metathesis catalysts with high *Z*-selectivities (7) could be helpful here.

Importantly, Fogg has emphasized that oligomers can dominate kinetically in certain classes of ring-closing metatheses. However, she has shown how they can be converted to monocyclic products given sufficient time, catalyst, and ethylene coproduct (38). Thus, there remains much potential for optimization in the preceding chemistry; it is only a matter of effort.

9.11 PROSPECTIVE

The preceding sections have established the immense utility of multifold intramolecular ring-closing metatheses in the syntheses of a variety of unusual organometallic complexes. In retrospect, one lesson is that one should never let oneself be "talked out" of trying such speculative sequences. If it is possible for a target structure to be realized from a polyolefin precursor without engendering significant ring strain, the synthesis should by all means be attempted, even if numerous other products are possible.

It is likely that as more experience is gained, additional control over the various types of product distributions (e.g., Schemes 9.2 and 9.3) will be realized. One approach will involve exploiting kinetic and thermodynamic control, which as noted above has frequently been ignored in what are often admittedly "run and gun" studies. Other approaches may involve alkyne metatheses, which do not suffer from complicating *Z*/*E* product mixtures and for which increasing numbers of catalysts are becoming available (39). In any event, it is hoped that this review of a rather scattered literature will help stimulate thinking and activity in targeted syntheses of topologically novel organometallic molecules with unusual connectivities.

ACKNOWLEDGMENTS

The authors thank the US National Science Foundation for support (CHE-0719267) and Dr. Giovanni P. Rachiero for helpful comments.

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