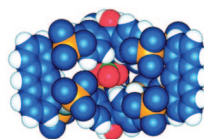# JOC*Perspective*

From Solvolysis to Self-Assembly[†]

Peter J. Stang

University of Utah, Department of Chemistry, 315 South 1400 East, Salt Lake City, Utah 84112

stang@chem.utah.edu

My sojourn from classical physical-organic chemistry and solvolysis to self-assembly and supramolecular chemistry, over the last forty years, is described. My contributions to unsaturated reactive intermediates, namely vinyl cations and unsaturated carbenes, along with my decade-long involvement with polyvalent iodine chemistry, especially alkynyliodonium salts, as well as my more recent research with metal−ligand, coordination driven, and directed self-assembly of finite supramolecular ensembles are discussed.

Introduction

During a forty-year career of active research, I have had the pleasure of being involved in and making contributions in three distinct research areas. In the first third of my career I was a classical physical-organic chemist in the area of unsaturated reactive intermediates. In the middle portion I was involved in polyvalent iodine as well as some organometallic chemistry. Since the early 1990s, my contributions have primarily been in supramolecular chemistry and self-assembly. In this Perspective, I shall discuss how and why I got involved in each area, what the critical prior discoveries were and literature results that provided the background and groundwork for our contributions, and what our own seminal contributions were to the field. During each period there were also key persons who had an impact and influence on the course of events that I shall mention as well. However, as will be seen, this is a personal narrative based on recollection of events, dependent upon the frailties of human memory, beclouded by the passage of time.

I first became interested in chemistry in high school in Hungary where I grew up. As a freshman in Gymnasium in 1955 I had a chemistry course that was the equivalent of what we now teach in general chemistry to first year students in college in this country. Moreover, in those days in Hungary there were no restrictions on the purchase, even by a teenager, of common chemicals such as inorganic salts, NaOH, common acids, etc., easily available in the corner drug store and

elsewhere, so that I was able to set up my own home laboratory and experiments. I clearly recall making "slow burning" black gunpowder from readily available potassium nitrate, sulfur, and charcoal powder. Phenolphthalein, used as a primitive laxative by the then pharmacist and as an indicator by the chemist, was available for acid−base titrations and the fascinating color changes that it underwent. When my family moved to the USA in 1956, I continued with chemistry in high school. I was also fortunate to have a dedicated, inspiring college chemistry teacher Robert C. Miller who invited me to do research with him in organophosphorous chemistry in my sophomore year at DePaul University. He also motivated his students to go to the best graduate schools anywhere in the country.

I was a graduate student at UC Berkeley from the fall of 1963 until the fall of 1966 in the group of Andrew Streitwieser, Jr. My Ph.D. Dissertation was on the "Kinetics and Mechanism of Boron Fluoride−Alcohol Alkylations", a classical physical-organic study of Friedel−Crafts alkylations[1] including an investigation of the stereochemistry of the alkylation of benzene with chiral 2-propanol-1-d_3.[2] During this period, the Streitwieser and Noyce groups held joint research group meetings. Among the interests of Professor D. Noyce and his group were electrophilic additions to alkynes and vinyl cations.[3] Early work on vinyl cations involved essentially only electrophilic additions to alkynes.[4] Unlike the rich chemistry on the solvolytic generation of carbonium ions,[5] little was known about the direct solvolytic generation of vinyl cations. Only systems substituted by an aromatic ring,[6] a vinyl group,[7] or a cyclopropyl ring[8] directly attached to the carbon bearing the leaving group

---

SCHEME 1. Solvolytic Generation of a Vinyl Cation[18]

1a: R=H
1b: R = CH$_3$

2a: R=R'=H
2b: R=CH$_3$; R'=H
2c: R=H, R'=CH$_3$

3c

58%   33%   9%
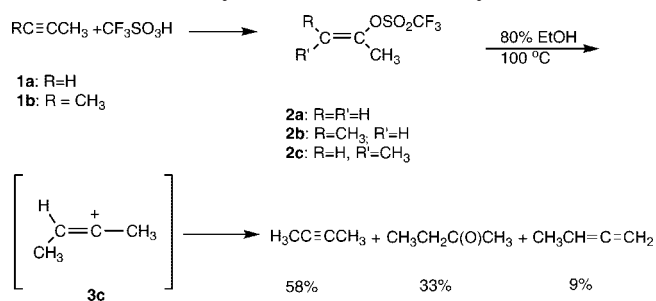
underwent solvolysis, resulting in "stabilized" vinyl cations. Even the normally highly reactive arenesulfonates, like the 1-cyclohexenyl tosylate and brosylate and the *cis*-2-buten-2-yl tosylate and brosylate, reacted via an addition–elimination mechanism rather than unimolecular ionization and vinyl cations.[9]

Sometime during this period, Streitwieser visited the DuPont Company, where he was a consultant, and became aware of trifluoromethanesulfonic acid, CF$_3$SO$_3$H, also known as triflic acid.[10] Triflic acid, first reported by Haszeldine and Kidd,[11] is known to be the strongest Brønsted acid, much stronger than such common acids as HNO$_3$, H$_2$SO$_4$, or even HClO$_4$.[10] I remember Streitwieser requesting a sample of Ba(OSO$_2$CF$_3$)$_2$ from the 3M Company in St. Paul, MN, from which the acid was obtained by reaction with fuming H$_2$SO$_4$ and distillation. He and co-workers[12] used CF$_3$SO$_3$H to prepare CH$_3$-CH$_2$OSO$_2$CF$_3$, as well as the deuterio analogues CD$_3$CH$_2$OTf, and CH$_3$CD$_2$OTf, and via solvolytic studies establish that the reaction occurs via "a transition state with comparatively little positive charge and substantial bonding to a nucleophilic solvent molecule." In other words, it was mostly an S$_N$2 process with little, if any S$_N$1 character,[12] despite the superior leaving ability of the triflate group.

By December 1966, I had obtained my Ph.D. and left for Princeton for postdoctoral studies with Paul v. R. Schleyer. The 1950s and 1960s were the golden age of physical-organic chemistry, and among the challenges was the so-called nonclassical ion[13] problem, typified by the 2-norbornyl system. Hence, I became involved in the study of "remote" methoxy groups as probes for delocalized cations and their substituent effects on 2-norbornyl solvolysis rates.[14] However, Schleyer also encouraged his co-workers and, in particular, postdoctoral fellows to develop independent projects.

It was at this point that I put two and two together to see if one could generate simple alkylvinyl cations via solvolysis. I told Schleyer about triflic acid and encouraged him to obtain some Ba(OSO$_2$CF$_3$)$_2$ from 3M, which he did. From literature data,[15] as well as work in progress in both the Streitwieser[12] and Schleyer[16] groups, it was known that a triflate was almost 10^4 times more reactive[17] than a comparable tosylate in solvolytic reactions. So the challenge was to prepare a simple alkylvinyl triflate and investigate its solvolytic behavior. Ultimately, we succeeded by the direct addition of CF$_3$SO$_3$H to alkynes, in a sealed tube, and established[18] that *cis*-2-buten-2-yl tiflate, **2c**, reacted in aqueous ethanol via an S$_N$1 process and the elusive simple alkylvinyl cation **3c** (Scheme 1).

This was the first example of the preparation of a vinyl trifluoromethanesulfonate (of immense importance in cross-coupling reactions, vide infra) and the observation of a simple alkylvinyl cation generated via solvolysis and bond heterolysis.

Throughout my graduate and postdoctoral period I was pretty sure I was interested in an academic career. I liked research, I liked the opportunity of working with young people, I enjoyed teaching (as a TA in Berkeley and as instructor for a year at Princeton), and above all I appreciated the challenge and independence that an academic career afforded. By the late 1960s, the academic market started to tighten (one of those periodic cycles that seem to occur every 12–15 years). In 1967/68, I interviewed at 6–9 places (I no longer recall the exact number) and received four offers. I was particularly attracted by Utah for a number of reasons: (1) it was a growing department on the move; (2) it had just received an NSF Centers of Excellence Grant; (3) it had just attracted Robert W. Parry from the University of Michigan, a distinguished inorganic chemist, founding editor of *Inorganic Chemistry* (later ACS President), and was negotiating with Cheves Walling from Columbia University, a distinguished physical-organic chemist and a pre-eminent free-radical expert (already a member of the U.S. National Academy of Sciences, later Editor of *JACS*); (4) it just completed in 1968 a brand new chemistry building with excellent facilities; (5) my wife to be, Christine, whom I met at Berkeley, although originally from Germany, grew up in San Francisco and was a westerner (as was I after having been in the midwest, B.S. in Chicago, the west at Berkeley, and the east at Princeton), and Salt Lake was as far "east" as she was willing to move; and (6) I found it to be a very collegial place. So in early 1969 I accepted the offer from the University of Utah, effective July 1, 1969. I have never regretted this decision, and after 40 years and a half-dozen outside offers (three as chair of major research institutions) I am still at Utah and will likely remain here for the rest of my career. Many colleagues and friends in the chemical profession thrive by moving, with the challenges and opportunities that a new position and place offer. However, just as many, or even more, thrive by staying at the same place, developing their career parallel with the growth and development of the department at their "home" institution.

Independent Career: First Period. Like all young assistant professors, I was now faced with starting my own research. I decided to investigate the generation, nature, and chemistry of vinyl cations. It was an area that was different from my Ph.D. work and different from the main thrust of my postdoctoral work but still in the realm of physical-organic chemistry that I was trained in, knew something about, and enjoyed. Moreover, and most important, it was my own idea, developed all on my own from careful observations at Berkeley, from reading the literature, and with encouragement from my mentors. Furthermore, I had excellent preliminary results as described above,[18] which served as a platform for starting an independent career in, at that time, a very active and highly visible area.

The challenge was to generalize the formation of vinyl triflates so that any and all types of alkenyl triflates could be made and investigated, not just the limited number and type accessible by addition of CF$_3$SO$_3$H to alkynes. We were fortunate to discover (independently, but simultaneously with Schleyer and Hanack) that this could be accomplished by reacting enolizable carbonyl compounds, such as aldehydes and ketones with triflic anhydride, (CF$_3$SO$_2$)$_2$O, in the presence of a weak base.[17,19] To date, this is the way most vinyl(enol) triflates are prepared and currently widely used in cross-coupling reactions.[20] For us, this opened up the entire spectrum of solvolytic generation of a variety of vinyl cations[4a,21] and allowed us to examine cyclic vinyl cations,[22] rearrangements of vinyl cations,[19b,23] deuterium

SCHEME 2. Mechanism of Reaction of (*E*)- and (*Z*)-3-aryl-2-buten-2-yl Triflates[29]
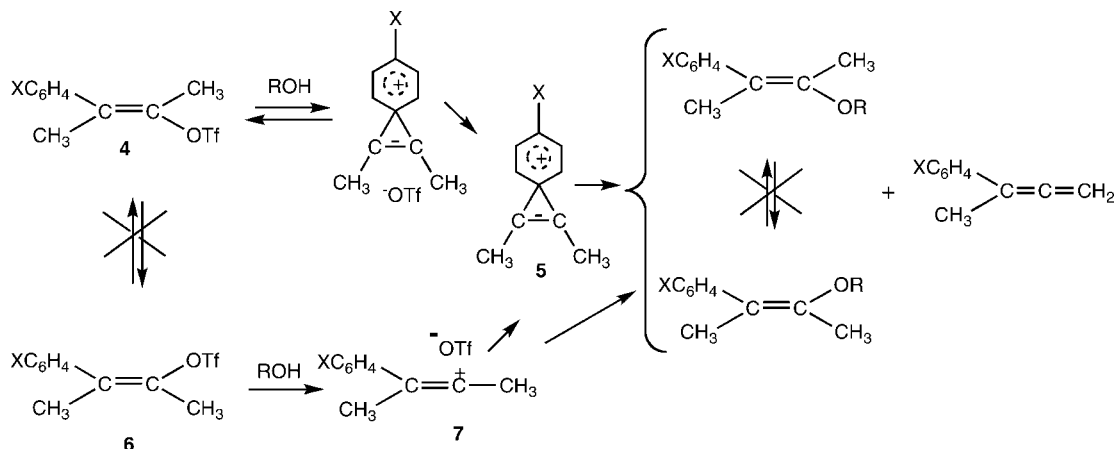

isotope effects in the generation of vinyl cations,[24] and the effect different substituents, various solvents, and nucleophiles[25] have on their generation. We also examined Friedel−Crafts-type alkylation of aromatic substrates using enol triflates.[26]

A typical example of our investigations of vinyl cations was the detailed study of the solvolysis of *cis*- and *trans*-3-phenyl-2-buten-2-yl triflates. Using kinetic deuterium isotope effects, Hammett $\sigma-\rho$ effects, stereochemistry, and product studies, we established that the *E*-isomer **4** reacted via a vinylidene phenonium ion **5**, analogous to the well-known σ-bridged phenonium ion,[27] first prepared by Cram,[28] whereas the *Z*-isomer **6** reacted via the open vinyl cation **7** as shown in Scheme 2.[24a,29]

Of course, we were not alone in our study of vinyl cations; as in any active area there were many investigators, key among them, C. Grob (Basel), M. Hanack (Tübingen), G. Modena (Padova), R. G. Bergman (then Caltech), P. v. R. Schleyer (then Princeton), and Z. Rappoport (Jerusalem), as described and summarized in our two monographs on this topic.[21b,c] Hence, by the late 1970s and early 1980s vinyl cations were fully accepted members of the family of reactive intermediates and in fact observed[30] by NMR, analogous to the NMR observation of carbocations in the seminal work of Olah.[5] Therefore, it was time to move on to a different area. Moreover, one needed to be active and productive in more than one area to be successful in academia.

While investigating vinyl cations, taking advantage of the superior[17] leaving group ability (nucleofugality) of triflates, it occurred to us that this superior nucleofugality of triflates could also be applied to the generation of unsaturated carbenes from primary vinyl triflates and cognates.

A large amount of work had been done in carbene chemistry since the pioneering studies of H. Meerwein, J. Hine, W. v. E. Doering, P. Skell, and G. Closs.[31] Besides simple carbenes **8**, vinylidene carbenes **9a** and allenidene carbenes **9b** were already known. Vinylidene carbenes **9a** were generated via the elimination of HX from primary vinyl halides by bases,[32] deamination of vinyl amines,[33] photofragmentation,[34] and base decomposition of 5,5-disubstituted *N*-nitrosooxazolidones,[35] none of which were ideal, whereas allenidene carbenes **9b** were mostly generated from popargyl halides and/or haloallenes in the presence of bases.[36]
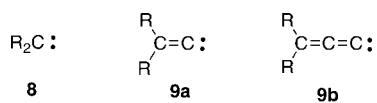

In the 1970s and early 1980s, we established[37] that primary vinyl triflates,[38] $(R)_2C=CHOSO_2CF_3$, and silylvinyl triflates,[39] $(R)_2C=C(SiMe_3)OSO_2CF_3$, serve as progenitors par excellence for vinylidene carbenes **9a**. We showed that triflate-generated carbenes are singlets,[40] electrophilic[41] and behave as free carbenes[42] rather than carbenoids.[31,43] We demonstrated via stereochemical and computational investigations that $R_2C=C$: addition to alkenes is stereoselective and proceeds via a "C2-inward" transition state.[44] Via isotopic labeling we determined[45] that the rearrangements of β-aryl or β-alkyl vinylidene carbenes to afford alkynes occur via the free carbene rather than by the Fritsch−Buttenberg−Wiechell type of organometallic intermediate[46] and a carbenoid.

Addition of $R_2C=C$: to π-systems provided a simple and general means of entry to interesting small and strained ring compounds,[47] including alkyledenecyclopropenes[48] **10** and *m*-xylylene[49] **11a**. The parent *m*-xylylene **11b** was just recently spectroscopically fully characterized and investigated via matrix isolation.[50] Likewise, reaction with azoarenes afforded 2(*H*)-indazoles **12** via an ylide-type process.[51] Furthermore, reaction with isonitriles gave heterocumulenes[52] **13**, and interaction with isocyanates resulted in vinyl carbamates[53] **14**.
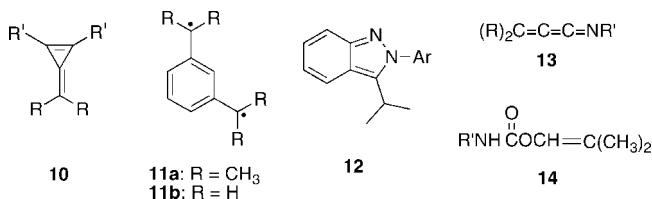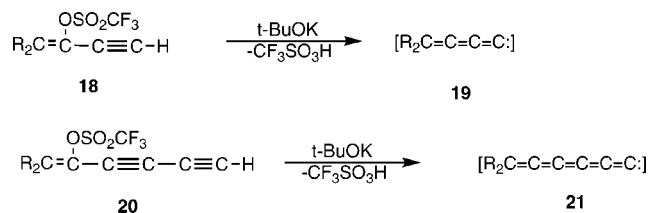

Insertion of $R_2C=C$: into diphenyl diselenide and diphenyl ditelluride yielded little known phenylseleno, **15**, and phenyl-telluro, **16**, ketals, respectively.[54]
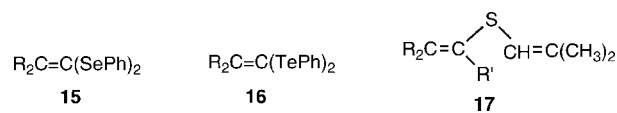

We also established that insertion of unsaturated carbenes into Si−H bonds occurs stereospecifically via a concerted three-centered transition state[55] analogous to the insertion of Br_2C: and Cl_2C: into chiral NpPhMeSiH.[56] Insertion of $R_2C=C$: into enethiols gave divinyl sulfides **17**.[57]

We were also able to extend our unsaturated carbene studies to previously unknown, longer, congeners, alkadienylidenecar-

SCHEME 3. Generation of Extended Unsaturated Carbenes

$$R_2C\overset{OSO_2CF_3}{=}C-C\equiv C-H \xrightarrow[-CF_3SO_3H]{t\text{-BuOK}} [R_2C=C=C=C:]$$

18   **19**

$$R_2C\overset{OSO_2CF_3}{=}C-C\equiv C-C\equiv C-H \xrightarrow[-CF_3SO_3H]{t\text{-BuOK}} [R_2C=C=C=C=C=C:]$$

20   **21**

benes **19**, and alkatetraenylidenecarbenes **21** as shown in Scheme 3.[37] Carbene **19** was readily available from 1-(ethynyl)vinyl triflates[58] **18** and **21** from 1-(butadiynyl)vinyl triflates[59] **20**. As previously, we established[60,61] that both **19** and **21** are singlets, electrophilic, and free carbenes. Insertion of **19** into group 4 hydrides resulted in the formation of novel Si-, Ge-, and Sn-functionalized cumulenes **22**.[62]

$$R_2C=C=C=CHMR'_3$$

22: M = Si, Ge, Sn
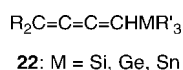
The impact and legacy of this work in unsaturated reactive intermediates is interesting. Vinyl (enol) triflates, that are the precursors to the solvolytic generation of vinyl cations and that we were the first to prepare and report,[18,19] are now widely used in metal-catalyzed cross-coupling protocols.[20] Enol triflates serve as the premier electrophilic coupling partners in a variety of cross-coupling reactions that are of importance in natural product synthesis[63] as well as materials science.

Unsaturated carbenes have recently been found and are among the most abundant carbon-containing species in interstellar space.[64,65] Moreover, metal vinylidenes and allenylidenes and metallacumulenes are extensively employed in alkene metathesis[66,67] and various catalytic reactions,[68] including pericyclic reactions[69] and substitution reactions.[70]

Middle Period. By the mid-1980s, it became obvious to me that we had exhausted the chemistry of unsaturated reactive intermediates. Moreover, in the late 1970s and early 1980s, a senior colleague at Utah wisely counseled me to broaden my horizons and look beyond the generation, nature, and chemistry of reactive intermediates as, by this time, the bloom was off classical physical-organic chemistry and, in particular, carbocations and carbenes. At the time, I thought that there may still be interest in the solvolytic generation of the elusive alkynyl cations $RC\equiv C^+$, and I describe below how our quest for this high energy species led us to polyvalent iodine chemistry. However, I also took this advice to heart and began looking for new areas. Furthermore, I enjoyed the challenge of venturing into new territory and learning and mastering new chemistry. Initially, we explored two areas that were tangential to and an outgrowth of our previous work. First, our interest in selenium, tellurium, germanium, and tin compounds **15**, **16**, and **22** led us to organometallic chemistry. Hence, we explored the interaction of various organometallic nucleophiles with our vinyl **2**, ethynylvinyl **18**, and butadiynylvinyl **20** triflates. We discovered that these precursors readily undergo reactions with cobalt species to give vinylcobaloxime complexes[71] **23** and σ-butatrienyl cobaloxime complexes[72] **24**. Likewise, vinyl triflates as well

$$R_2C=CR'[Co(dmgH)_2py] \qquad R_2C=C=C=CR'[Co(dmgH)_2py]$$

23   **24**

as **18** readily react with (Ph₃P)₄Pt to yield four-coordinate cationic σ-vinyl Pt(II) complexes[73] and σ-butatrienyl cationic

Pt(II) complexes.[74] Similarly, we explored the reaction of Vaska's compound, (Ph₃P)₂Ir(CO)Cl, with various triflates.[75] We examined the mechanism of formation and the chemistry of vinylic acyl Pt(II) complexes.[76] We investigated the formation of heterobimetallic Ir−Pt complexes.[77] We prepared and studied Rh and Pt π-cumulene complexes[78,79] **25**, **26** and **27**, **28** below. We also investigated the mechanism, oxidative addition,[80] and reductive elimination[81] of metal-mediated vinylic cross-coupling reactions, using our previously prepared, readily available vinyl(enol) triflates.

25   **26**

**27**   **28**
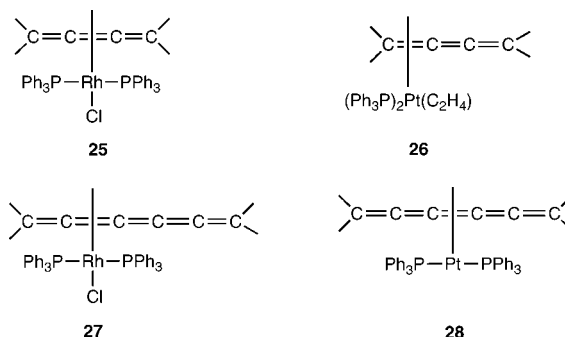
This brief excursion into organometallics at this stage of my career, and what I learned about various metals and their complexes, in particular platinum chemistry, served me well later when we employed metal−ligand interactions in abiological self-assembly (vide infra).

Second, a combination of my interest in small and strained ring chemistry via alkylidene carbene additions to π-bonds, briefly described above, and a fortuitous event in 1982 got us involved in alkylidenecyclopropapenes. That year, Professor Brian Halton, from Victoria University in Wellington, New Zealand, spent a year with me at Utah as a senior Fulbright Scholar. Brian's interest and expertise was in strained organic molecules and, in particular, cyclopropapenes.[82] Because of their strain and consequent high energy, such molecules have novel physical, spectral, and chemical properties that are of both theoretical as well as synthetic interest and challenge.[83] Among the intriguing and more strained hydrocarbons are the ortho-bridged aromatics. The parent member of the family, benzyne **29**, is easily generated and well-known as a transient intermediate[84] but observed spectroscopically only in an Ar matrix at 8 K.[85] Cyclopropabenzene **30**, the next homologue, is an isolable compound, despite its nearly 70 kcal/mol strain energy.[82] The cross-conjugated fulvenes[86] **31** and radialenes **32** represent another class of alluring strained hydrocarbons.[83]

**29**   **30**   **31**   **32**
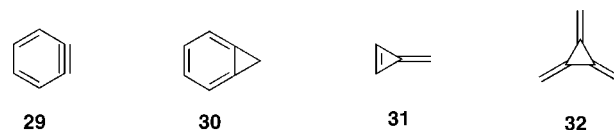
Hence, Brian and I decided to combine our expertise to investigate the preparation, characterization, properties, and chemistry of the then unknown alkylidenecyclopropapenes, e.g., **33**, a unique class of strained hydrocarbons that combine into a single molecular framework the features of the ortho-bridged benzene **30** and the cross-conjugated triafulvenes **31** and **32**:

33   **33a**   **33b**   **33c**
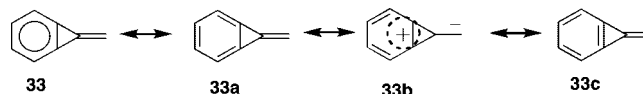
SCHEME 4. Preparation of Alkylidenecycloproparene 38
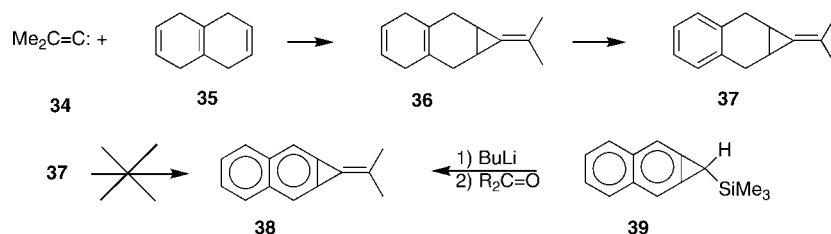
Due to the then unknown nature of **33** and its anticipated high strain of about 80 kcal/mol, and hence possible instability at room temperature, we decided to focus our initial efforts on **38** for two reasons. First, strained derivatives of naphthalene are known[84] to be more stable than those of benzene, and furthermore, alkyl substituents stabilize double bonds. Second, we anticipated that **37** would be easily accessible via an alkylidecarbene, **34**, addition to tetrahydronaphthalene, **35**, a reaction known[87] to give adduct **36**, followed by oxidation to the desired **38** as shown in Scheme 4. However, all attempts to oxidize **36** to **38**, with numerous reagents under a wide variety of conditions, failed. Only unreacted starting material and/or partially oxidized hydrocarbon **37** was observed.[88]

Brian's year at Utah, from a chemical perspective, was a year of frustration, with no progress and publication. However, after Brian's return to Wellington, the alternative Peterson olefination[89] of **39** worked well;[88] that started a decade-plus long trans-oceanic collaboration[90] with Brian, which resulted not only in nearly 20 joint publications but also a lifelong friendship. In a collaborative fashion, we investigated the electrochemical properties,[91] photoelectron spectra,[92] polarity,[93] ^{13}C NMR[94] and ambiphilicity[95] of these novel strained hydrocarbons. We explored their reactions with both electrophiles[96] and nucleophiles.[97] We used them as unique ligands in the formation of interesting Pt, Pd, and Rh complexes.[98] We prepared and characterized related benzocalicenes and benzotriaheptaful-valenes.[99]
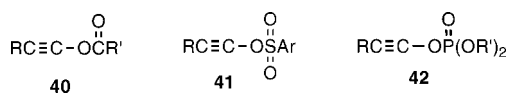

During this period, we were still intrigued by the possible solvolytic generation of alkynyl cations, $RC{\equiv}C^+$, the only remaining member of the family of ubiquitous carbocations that were not known in solution. Although they were detected in interstellar space,[100] and in the gas phase by mass spectrometry,[101] there was no evidence of their formation in the condensed phase. In fact, both experimental data and theoretical calculations indicated that the parent ethynyl cation, $HC{\equiv}C^+$ has a heat of formation of about 400 kcal/mol.[102] However, given the superior leaving ability of triflate, I reasoned that alkynyl triflates, like $ArC{\equiv}COSO_2CF_3$ *might* afford this elusive species in solution. Unfortunately, alkynyl esters of any kind, carboxylate **40**, sulfonate **41**, or phosphate **42**, were unknown compounds prior to the 1980s. At this point, two serendipitous events occurred that resulted in a major change and new direction in my research. I had a phone conversation with a former Ph.D. student of mine, Albert G. Anderson (Ph.D. 1977, University of Utah), who was at Central Research at DuPont, and I mentioned the fact that alkynyl esters were unknown. He suggested that I consider using iodonium species as possible progenitors and called my attention to the seminal work of

Koser[103] on alkynyl iodonium salts that appeared in 1981. This was the beginning of my interest in polyvalent iodine chemistry that occupied my interest for over a decade, from the mid 1980s onward and ultimately also led to my involvement in abiological self-assembly (vide infra). My interest and involvement in polyvalent iodine species was further facilitated by the arrival of a very talented postdoctoral fellow, Dr. Viktor Zhdankin from N. Zefirov's group at Moscow State University in Russia, during this time. He was not only very talented, dedicated, hardworking, and creative but was already familiar with polyvalent iodine species as well as the extensive Russian literature in this area.

Iodine was discovered in 1811 and most commonly occurs in the monovalent form with an oxidation state of −1 in organoiodine compounds. However, because it is the largest, most polarizable, and least electronegative of the halogens, iodine also readily forms stable, polycoordinate, high-valent compounds, generally as I(III) and I(V) species. Over 120 years ago, the German chemist C. Willgerodt reported[104] the preparaton of $PhICl_2$, followed by the preparation[105] of $PhI(OAc)_2$ and numerous[106] diaryliodonium salts, $Ar_2I^+X^-$. Since then, interest and activity in multicoordinate iodine species waxed and waned until the early 1980s when the chemistry of hypervalent, multicoordinate iodine experienced a renaissance.[107]

SCHEME 5. Formation and Decomposition of 43
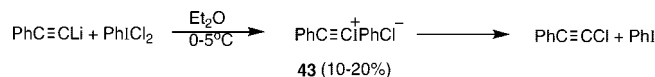
Our primary interest in this area was focused on alkynyliodonium species[108] $RC{\equiv}CI^+Ph$ as potential progenitors of alkynyl sulfonate esters **41** and, in particular, alkynyl triflates as possible solvolytic precursors of $RC{\equiv}C^+$. Beringer and Galton[109] were the first to report an alkynyliodonium species **43**, but only in 10−20% yield (Scheme 5). Moreover, **43** decomposed at room temperature in a few hours, as shown in Scheme 5. The first stable, crystalline iodonium salt, **44**, was
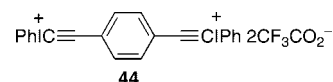

reported by Merkushev and co-workers,[110] but it was characterized only by IR and its hydrolysis product. A major advance was made by Koser and co-workers[103] in the formation of alkynyl(phenyl)iodonium tosylates, **46**, via addition of what has become known as "Koser's reagent," **45**,[111] to terminal alkynes. Although this early work had serious limitations,[108] it galvanized the field. Improvements rapidly followed so that by the mid-1980s a variety of alkynyl(phenyl)iodonium salts were readily available as stable microcrystalline compounds.[112,113]

Arguably, the most general and widely used methods[114] of preparing alkynyliodonium species involve alkynylsilanes and

SCHEME 6. Formation of Alkynyl(phenyl)iodonium Tosylates
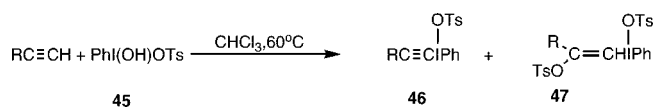
in situ Zefirov's reagent[115] **48** or the use of stannylalkynes[116] **49** and iodonium triflate **50**[117] as shown in Scheme 7. This later methodology affords a wide variety of β-functionalized alkynyliodonium salts **51**. This procedure is also applicable to the preparation of the parent system[118] HC≡CI[+]Ph [−]OTf, as well as PhI[+]C≡CI[+]Ph 2[−]OTf,[119] and other bis-alkynyliodonium compounds.[120] Similar procedures have been developed for the ready preparation of alkenyliodonium species[121−123] as well as heteroaryliodonium salts.[124]

All pure alkynyliodonium species are microcrystalline solids sparingly soluble in most organic solvents, the best solvent being acetonitrile. Their stability depends both on the counteranion and the β-substituent on the alkyne. The more nucleophilic the counterion, the less stable the alkynyliodonium compound, the most stable and hence most widely employed being the triflates, tetrafluoroborates, and tosylates. They have highly characteristic signals in both the IR and NMR; in particular ^{13}C NMR.[125] X-ray analysis indicates a pseudobipyramidal or T-shaped structure **52** with the alkyne and counterion in an axial arrangement, and the phenyl group and two lone pairs on the iodine in the equatorial position,[118a,126] in accord with the hypervalent (10-I-3) nature of these salts.[127]
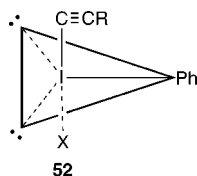

The reactions of alkynyliodonium salts may be described in three broad classes: (1) interaction with nucleophiles, (2) cycloadditions, and (3) cross-coupling reactions. In a formal sense, alkynyliodonium salts can serve as electrophilic acetylene equivalents or as "alkynylating" agents "RC≡C[+]". Indeed, they undergo reactions with a wide variety of nucleophiles, including C, N, O, S, P, As, Se, Te, and organometallic nucleophiles as described below. The actual mechanism of reaction of course does not involve the high-energy alkynyl cation but goes through ylids and carbenes as summarized in Scheme 8.

The preponderance of evidence[107c,d] indicates that the mechanism of these reactions involves a conjugate addition of the nucleophile to the electron-deficient β-carbon to form an iodonium ylide **53**,(Scheme 8). Loss of iodobenzene forms the alkylidenecarbene **54**, which rearranges via migration of either R or the nucleophile to provide the final product **56**. Among the evidence for this mechanism is that in the presence of acid, ylide **53** can be trapped to give stable alkenyliodonium salts **55**. Moreover, if either the alkyl group or the Nu on the β-carbon of **54** has a 1,5-C−H bond, the carbene can insert and provide a cyclopentene or five-membered heterocycle **57** (vide infra). Both the ylide **53** and carbene **54** have been trapped.[128] The addition of the nucleophile to the β-alkynyl carbon (Michael type addition) is facilitated by the strong inductive electron-withdrawing nature of the PhI[+] moiety ($\sigma_I = 1.24$ for PhI[+] vs $\sigma_I = 0.39$ for I itself).[129]

Only "soft" carbon nucleophiles, such as β-dicarbonyl compounds, react with alkynyliodonium salts; enolates of simple aldehydes or ketones analogous to hard nucleophiles, like RO[−], result in decomposition products. This reaction represents a convenient way of directly introducing the RC≡C− group into a variety of β-dicarbonyl compounds.[130]

Reaction with R_1R_2NLi affords aminoalkynes RC≡CNR$_1$R$_2$.[131] Sulfur nucleophiles provide ready access to RC≡CSCN,[132] RC≡CS(O)$_2$Ar,[133] RC≡CSS(O)$_2$Ar,[134] and RC≡CP(S)(OR$_1$)$_2$.[135] Phosphorus nucleophiles provide alkynyl phosphonium salts RC≡CP[+]Ph$_3$X[−][136] and RC≡CP(O)(OR$_1$)$_2$.[137] Acetylenic arsonium salts RC≡CAs[+]Ph$_3$BF$_4$[−],[138] selenides RC≡CSeAr,[139] and tellurides RC≡CTeAr[139] are obtained from reactions with Ph$_3$As, NaSeAr, and NaTeAr, respectively. Organometallic nucleophiles, such as (Ph$_3$P)$_2$M(CO)(Cl), M = Ir, Rh, and others, provide interesting organometallic complexes.[120c,140,141]
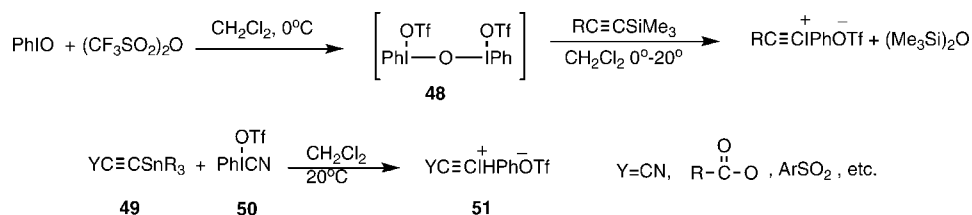
However, the most interesting reaction is the formation of the previously unknown alkynyl esters **40−42**, which combine two of the most common and important functional groups in organic chemistry, namely the carbon−carbon triple bond and esters into a single moiety.[142] Simple carboxylate, phosphate, and sulfonate esters are important in synthetic, mechanistic, and biochemistry and are so ubiquitous that they are often taken for granted by most chemists. As described in all introductory textbooks of organic chemistry, esters are most readily made by the reaction of acid halides RC(O)X, (RO)$_2$P(O)X, and RS(O)$_2$X with an alcohol. Likewise, vinyl(enol) esters are made by the reaction of enolates with acid halides. Therein was the problem. The preparation of alkynyl esters by an analogous process requires hydroxyalkynes **58a** or ynols that are the triple-bond analogs of enols **59a**. Whereas enols are readily accessible,[143] in the case of ynols the tautomeric equilibrium is completely on the side of ketenes **58b** and hence, ynols **58a** are not available. Theoretical calculations[144] indicate that the ketene−ynol CH$_2$=C=O/HC≡COH energy difference is 37 kcal/mol in favor of the ketene, while the energy difference between CH$_3$CHO and CH$_2$=CHOH is only 14 kcal/mol.
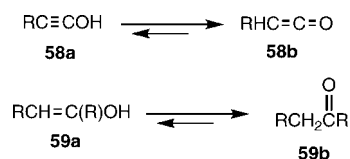
We prepared these unique esters by interaction of alkynyl(phenyl)iodonium triflates with ArCO$_2$Na for the carboxylate esters[145] **40** CuOTf or AgOTf for the sulfonate esters[112a,b] **41** and (R'O)$_2$P(O)ONa for the phosphate esters[146] **42** as shown in Scheme 9. X-ray structure determination of the carboxylate ester[147] **40** and the sulfonate ester[148] **41** established, as anticipated, that the C$_{sp}$−O bond is considerably shorter than the C$_{sp^2}$−O bond of ordinary esters with a value of 1.366 Å vs 1.445 Å for carboxylate esters and 1.331 Å vs 1.465 Å for the sulfonate esters, respectively.[147,148]

Acid-catalyzed hydrolysis of these esters proceeds via an Ad$_E$2 process involving a rate-limiting proton transfer to the β-carbon and formation of a vinyl cation that rapidly reacts with H$_2$O to give the respective acids as final products.[149] Whereas the base-catalyzed reaction involves [−]OH attack on the acyl moiety, C=O, P=O, SO$_2$, and the usual standard mechanistic steps.[149] Since alkynyl esters are electron-rich acetylenes, they do not undergo Diels−Alder-type cycloadditions but do react with an azete to give interesting Dewar pyridines.[150]

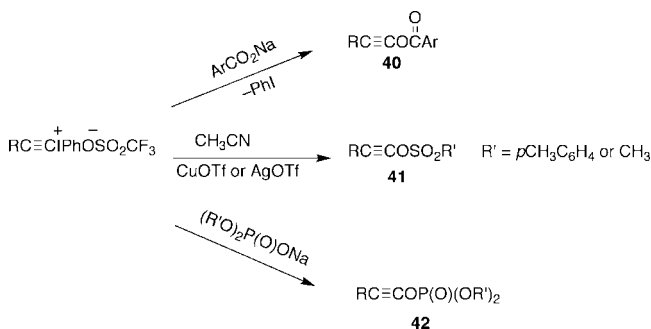**SCHEME 7. Formation of Alkynyl(phenyl)iodonium Triflates**

PhIO + (CF$_3$SO$_2$)$_2$O $\xrightarrow{\text{CH}_2\text{Cl}_2, 0°\text{C}}$ $\left[\begin{array}{cc} \text{OTf} & \text{OTf} \\ \text{PhI} - \text{O} - \text{IPh} \end{array} \right]$ $\xrightarrow[\text{CH}_2\text{Cl}_2\ 0°\text{-}20°]{\text{RC≡CSiMe}_3}$ RC≡CIPhOTf + (Me$_3$Si)$_2$O

48

YC≡CSnR$_3$ + PhI$\overset{\text{OTf}}{\text{CN}}$ $\xrightarrow[\text{20°C}]{\text{CH}_2\text{Cl}_2}$ YC≡CIHPhOTf   Y=CN, R–$\overset{\text{O}}{\text{C}}$–O , ArSO$_2$, etc.

49   **50**   **51**

SCHEME 8. Mechanism of Reaction of Alkynyliodonium Salts via Ylids and Carbenes
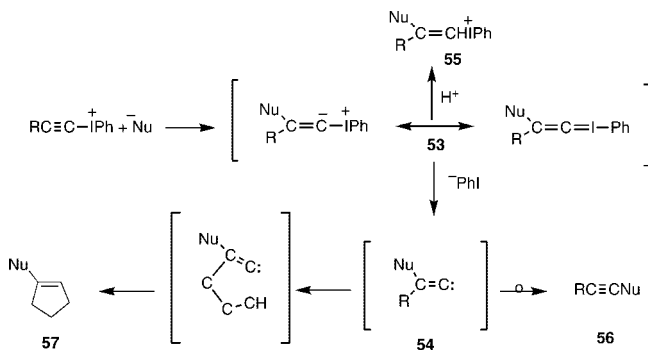
**SCHEME 9. Preparation of Alkynyl Esters 40−42**

These alkynyl esters **40−42** also have interesting biological activity. Both alkynyl carboxylates **40** and alkynyl phosphates **42** are potent serine protease inhibitors.[151] Moreover, the alkynylphosphate esters **42** are potent inhibitors of bacterial phosphotriesterase.[152] For example, 1-hexynyl diethyl phosphate, *n*-BuC≡COP(O)(OEt)$_2$, effectively inhibits the phosphotriesterase from *Pseudomonas diminuta* in less than 1 min with <1% residual activity.[152b,c] As I had no background in biochemistry, these studies were carried out in collaboration with Y. Shalitin at the Technion in Isreal and F. Raushel at Texas A & M.

However, as shown in Scheme 8, the reaction of a nucleophile with alkynyl iodonium salts, besides resulting in a wide variety of functionalized acetylenes **56** as just described, can take an alternative route. If there is a 1,5-C−H bond available the intermediate carbene **54**, instead of rearranging to **56**, will undergo intramolecular C−H insertion, resulting in a cyclopentene, **57**. This tandem Michael addition/carbene-insertion process provides an efficient means to some interesting cyclopentene derivatives.[153] We have taken advantage of this process to prepare[154] a variety of interesting cyclopentenones with yields of 44−75% at room temperature in CH$_2$Cl$_2$. This provides a nice alternative to the Nazarov[155] and Pauson−Khand[156,157] reactions for the synthesis of cyclopentenones. Feldman and co-workers have also used this tandem Michael-addition/carbene-insertion procedure to prepare highly substituted dihy-

SCHEME 10. Diels−Alder Reactions Involving Alkynyliodonium Salts
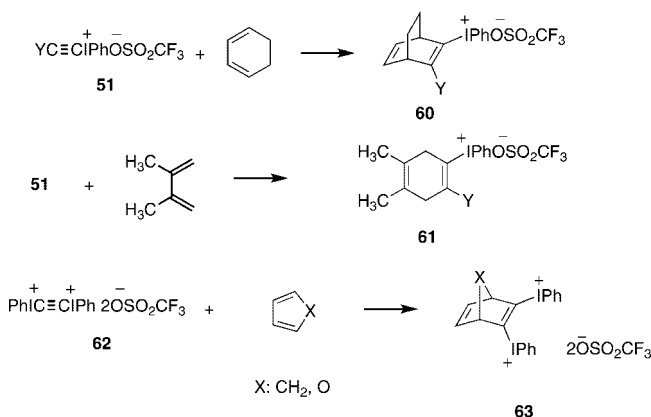
**SCHEME 11. [3 + 2]-Cycloadditions Involving Alkynyliodonium Salts as 1,3-Dipolarophiles**
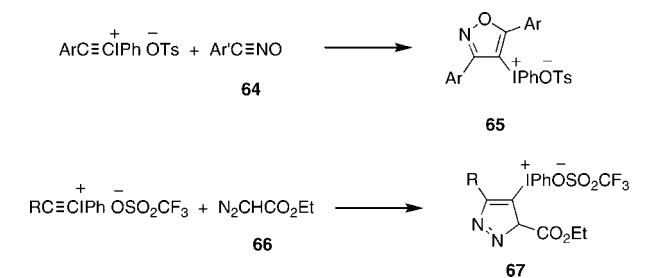
dropyrrole derivatives[158] as well as polycyclic alkaloids.[159] This method has also been used to prepare thiazoles[160] as well as benzofurans,[161] furopyridines,[162] and 2-mercaptothiazoles.[163]

The second type of reaction that alkynyl(phenyl)iodonium species undergo is cycloadditions. β-Functionalized alkynyliodonium salts **51** undergo Diels−Alder cycloadditions with symmetrical dienes[114c] under mild conditions to give cycloadducts **60** and **61** in good yields as shown in Scheme 10, whereas unsymmetrical dienes[164] result in mixtures of products with little, if any, regioselectivity. Similarly, bisiodonium triflate **62** reacts with furan or cyclopentadiene at room temperature to give **63** (Scheme 10).[119b,165]

Since alkynyliodonium salts are also excellent 1,3-dipolarophiles, various [3 + 2]-cycloadditions have been studied. Nitrile oxides **64** give cycloadducts[166] **65** as sole products, whereas ethyl diazoacetate **66** yields regioisomeric pyrazoles **67** in only moderate yields as shown in Scheme 11. Organic azides, PhN$_3$ and CH$_3$N$_3$, give triazolyliodonium salts, and diazocarbonyl compounds afford pyrazolyliodonium salts, but only in low yields.[168]

Because of the superior leaving ability of the PhI$^+$ moiety, various iodonium species are excellent electrophilic partners in a range of metal-catalyzed cross-coupling reactions.[169,170] Perhaps the most interesting of these is the preferential and

SCHEME 12. Coupling of Alkenyliodonium Salt 68 with Alkynes
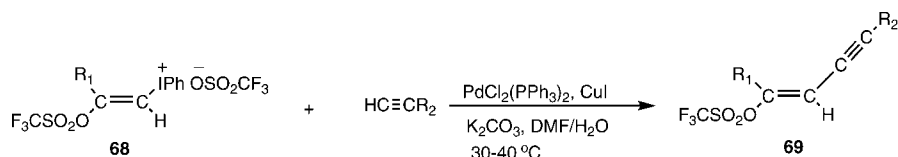
selective coupling of alkenyliodonium salt **68** with alkynes, in the presence of a triflate in the same molecule, to give conjugated enynes **69** stereospecifically,[171] as shown in Scheme 12.

Finally, alkynyliodonium and other iodonium salts have significant biological activity;[107b,c] specifically, alkynyl and aryl mono- and diiodonium salts are effective inhibitors of PQQ **70**, an organic cofactor in certain biological redox processes,[172] and have very potent in vitro activity against oral and dental anaerobes.[173]

70: PQQ
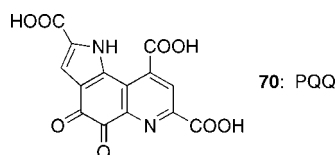
Although we did not succeed in our original goal of the generation of alkynyl cations, RC≡C+, that has only been accomplished[174] via nuclear decay processes involving tritium and ³He, we have uncovered some very interesting chemistry. The legacy and significance of this work is the increasing use and involvement of polyvalent iodine species in contemporary organic chemistry.[175] Examples include the Feldman and Cutarrellis[116] elegant synthesis of pareitropone,[176] a potent anticancer alkaloid, and the synthesis of discorhabdin[177] and morphinandienone and neospirinedienone[178] among many others. Most recently, the unique reactivity of polyvalent iodine reagents in conjunction with Pd(O) and Pd(II) complexes has been exploited for a wide range of synthetically useful organic transformations.[179]

Third Period. At this juncture, another serendipitous and fortunate event occurred that started and influenced my current interest and involvement in abiological self-assembly. In 1991, I visited the University of Nevada at Reno and gave a seminar on the above-described polyvalent iodine chemistry. During the question and answer period, Professor Lawrence Scott (then at Reno, now at Boston College) asked whether, given the pseudotrigonal pyramidal nature and concomitant 90° angle of alkynyliodonium species **52**, I had thought of making macrocyclic systems. I had not, but immediately grasped the significance of his suggestion and, upon returning to Utah, discussed it with my theoretical colleague Jack Simons and with V. Zhdankin, my postdoctoral fellow already mentioned. In collaboration with Jack, we examined the structures, stabilities, and vibrational frequencies of square planar tetraalkynyl and tetraaryl tetraiodonium salts[180] **71–73** and with Dr. Zhdankin started the synthesis of the triflate salt of **73** as shown in Scheme 13. Although we succeeded in the preparation of **78** from commercially available **74** in just three steps, the overall yield was only 7–10%.[181] Moreover, getting satisfactory structure proof (mass spec, NMR, etc.) proved to be a challenge and frustration due to

the insolubility of **78**, and hence, this even delayed publication.[181] Although more recently we succeeded[182] in improving the overall yield for the formation of **78** to 70%, at the time, this made me think of how one could make such macrocycles in a simpler, better way in much higher yields. My aforementioned experience in organometallic chemistry, and in particular Pt(II) chemistry and the square planar nature and concomitant 90° angle of Pt(II) complexes, provided the insight that transition-metal chemistry, metal–ligand dative interactions,[183] and likely self-assembly were an answer.

71   **72**   **73**
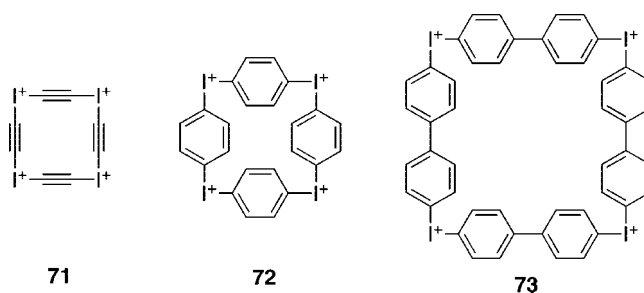
Self-assembly is a process whereby appropriate complementary molecular subunits spontaneously assemble according to the specific information encoded within their structures. Nature is the supreme and consummate master of self-assembly and supramolecular chemistry. It embraces the principles of, and adroitly exploits, noncovalent interactions of all types in a multitude of ways to enable and facilitate

SCHEME 13. Synthesis of Macrocyclic Tetraaryltetraiodonium Compound 78

78a: X = TfO⁻ ; **78b**: X = BPh₄⁻
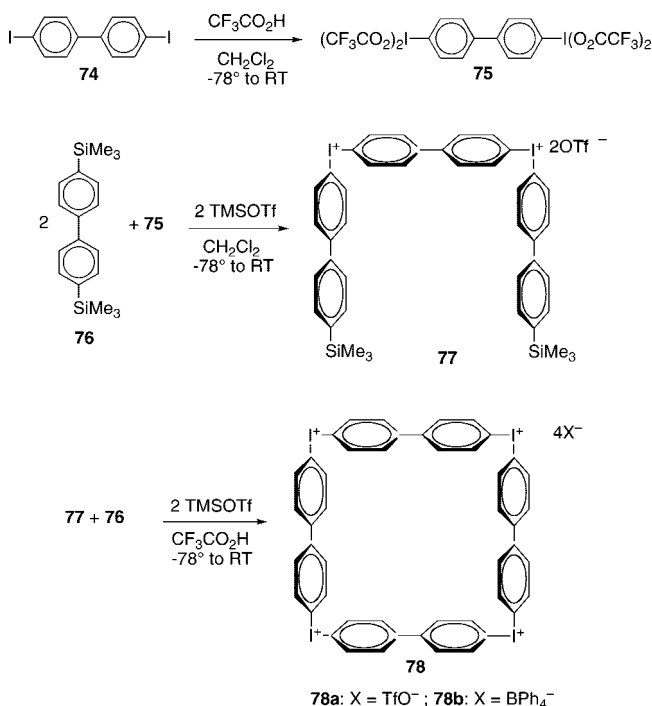
SCHEME 14. Self-Assembly of dppp-Chelated Pt and Pd Macrocyclic Molecular Squares 80

79a: M=Pt
79b: M=Pd

80a: M=Pt (87%)
80b: M=Pd(96%)
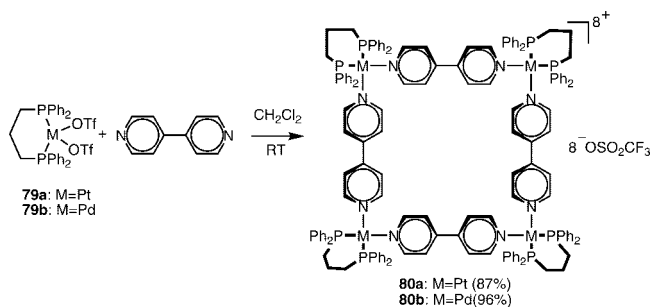
countless biological processes. All living organisms, from the simplest to humans, depend upon some form of molecular self-assembly. Nature performs the most amazing feats of self-assembly with an artistry and facility we can only admire and all too often take for granted. Protein folding,[184] nucleic acid assembly, and tertiary structures,[185] phospholipid membranes,[186] ribosomes, microtubules, etc. are but some representative examples of self-assembly in nature that are of critical importance in living organisms.[187] The protein coat of all viruses around their nucleic acid consists of a self-assembled spherical capsid, in the shape of either a dodecahedron or an icosahedron.[188]

The power and beauty of spontaneous self-assembly derives from its ability to rapidly, and deceptively simply, generate large, complex, and sophisticated "supramolecules" from easily available building blocks with maximum efficiency, generally under mild conditions (at or near room temperature, at 1 atm) in water or other common solvents. Self-assembly depends upon appropriate direction and control being exerted at all stages of the process via preprogramming of the subunits or building blocks such that the requisite recognition elements for self-assembly are contained in the subunits. Nature's repertoire of information to guide self-assembly includes hydrogen bonding, $\pi-\pi$ stacking,

hydrophobic−hydrophilic interactions, electrostatic and van der Waals interactions, conformations, etc., all commonly referred to as "weak interactions." Among the difficulties encountered in our attempts to mimic nature's elegant self-assembly processes, particularly in the formation of ensembles with well-defined shapes and sizes such as polyhedra like dodecahedra, is our inability to use the directionality of the "weaker interactions" nature employs. In contrast, because of d-orbital involvement, dative, metal−ligand bonds are highly directional. Moreover, third-row metal ligand bonds have bond energies of ca. 15−25 kcal/mol, much less than covalent bonds (ca. 60−120 kcal/mol) but stronger than the weak interactions of biology (ca. 0.5−10 kcal/mol). Hence, coordination kinetics can be modulated to engage in self-repair to achieve thermodynamic control of superstructure. Furthermore, by being stronger than weak interactions one dative metal−ligand bond can replace several hydrogen bonds in the self-assembly process.

An important and critical feature of coordination driven, and indeed all self-assembly processes, is that they must occur under thermodynamic control with kinetically rapid reversible equilibria between starting materials, intermediates, and products. As the equilibrium is reversible, the process is self-correcting: an "incorrectly" formed bond can dissociate and reassociate "correctly." However, to be practically useful, any thermodynamic self-assembly process must generate one product, which is substantially more stable than any starting material, intermediate or competitors, thus ensuring a near-quantitative yield. This is generally, albeit not always, the case in coordination driven self-assembly. In such a thermodynamically controlled, kinetically rapid, self-assembly process, all components are continuously being formed and are in thermodynamic equilibrium.[189,190]

Elegant, pioneering work by J.-M. Lehn and J.-P. Sauvage (Strasbourg) demonstrated[191] the feasibility and usefulness of coordination-driven self-assembly in the formation of infinite helicates, grids, ladders, and racks.[192] Inspired by this work, my interest in molecular squares such as **71−73**,
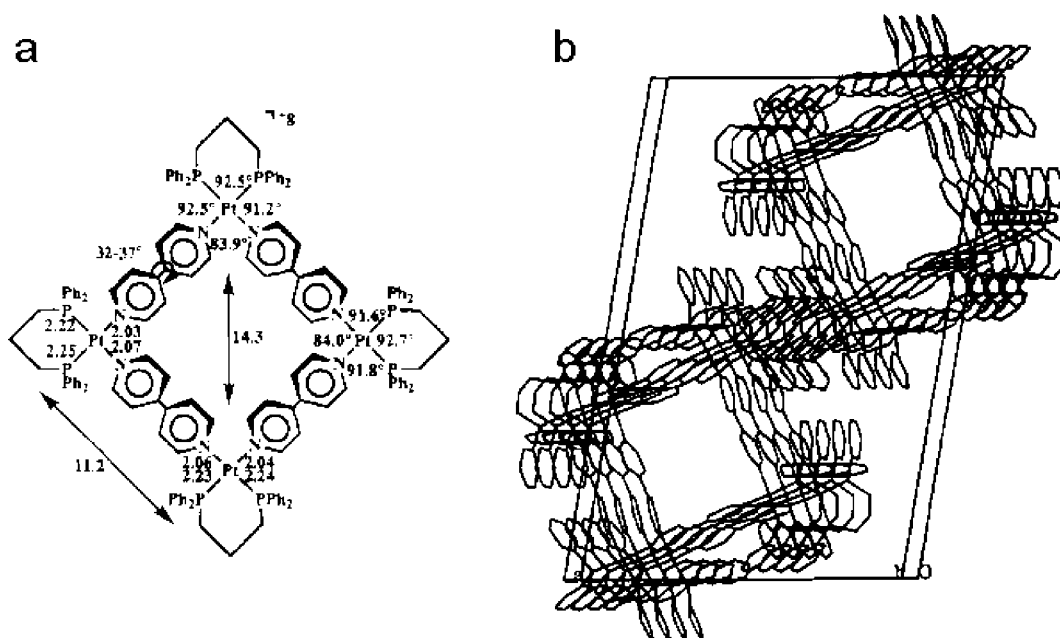

FIGURE 1. (a) Geometry of Pt-square **80a** based upon X-ray data; (b) solid-state stacking diagram of the cationic part of **80a**.
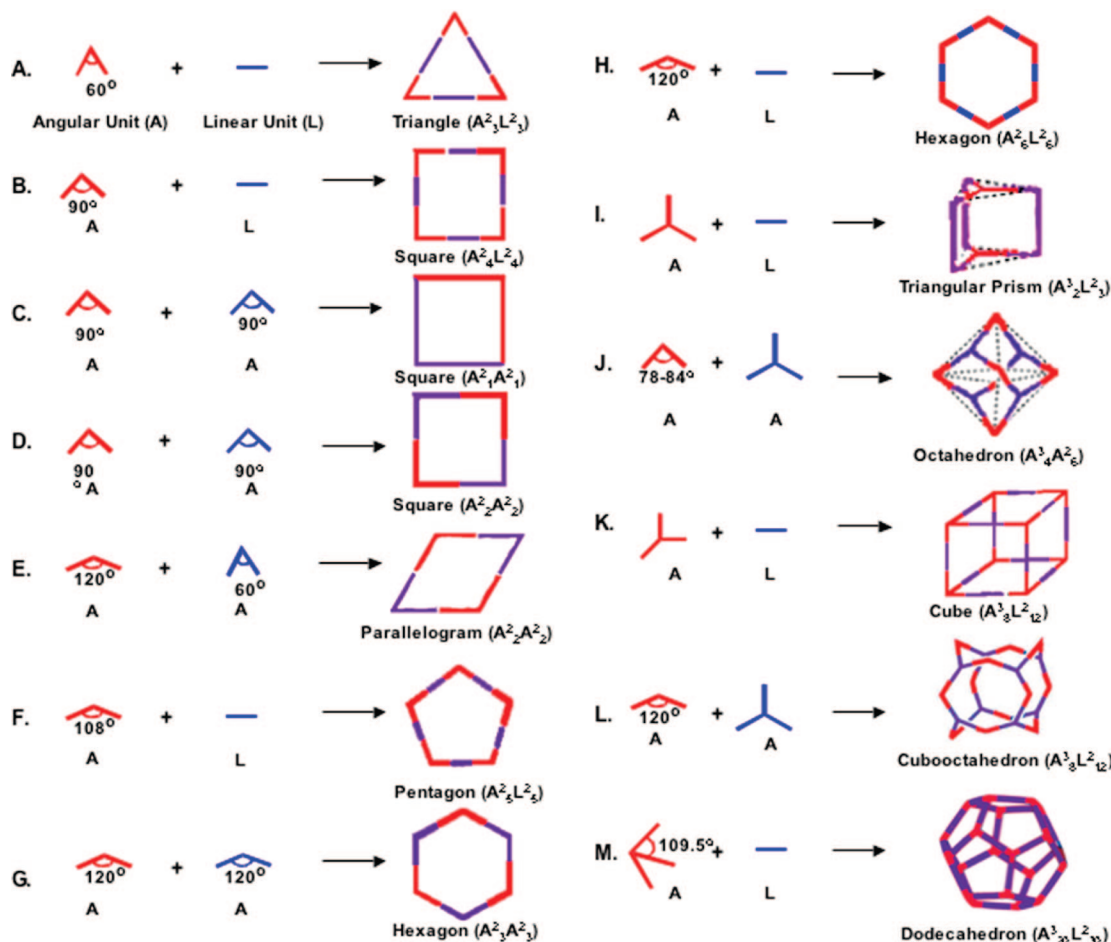
FIGURE 2. Directional bonding approach to the formation of 2D polygons and 3D cages via the combination of various angular (A) and linear (L) tectons.

and my experience with square planar Pt(II), the logical place to start was the formation of supramolecular squares via coordination driven self-assembly. Indeed, reaction of dppp-chelated Pt and Pd bis-triflates **79** with dipyridine afforded[193] the desired squares **80** in essentially quantitative yields as determined by NMR and high isolated yields, as shown in Scheme 14. Furthermore, X-ray data unambiguously established the structure and exact geometry (Figure 1a) as well as the novel solid-state packing of the cationic portion of molecular square **80a** (Figure 1b).

This initial success was rapidly followed by the formation of a wide variety of squares of different sizes and composition[194] such as mixed,[195] neutral-charged Pt−Pt and Pt−Pd, as well as hybrid[196] Pt−iodonium, early late[197] transition metal, large nanoscale,[198] and prophyrin[199]-based squares, all in essentially quantitative yields.

These achievements in turn made me think of the broader implications and advantages of metal-directed and driven abiological self-assembly and in particular of different types of finite, closed, rigid 2D and 3D architectures with predesigned shapes and sizes. As a consequence, together with Bogdan Olenyuk (then a graduate student at Utah, now an Assistant Professor of Chemistry at the University of Arizona), we developed[200] the so-called "directional bonding" approach for the ready, modular assembly of a wide range of 2D polygons and 3D cages as illustrated in Figure 2. This methodology combines rigid electron-poor metal centers and
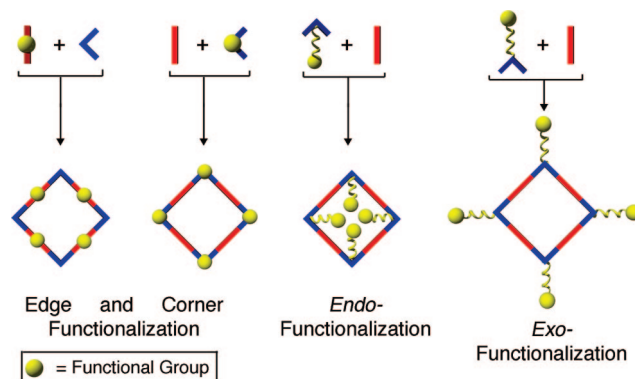

FIGURE 3. Different ways of incorporating functionality into self-assembled supramolecular metallacycles.
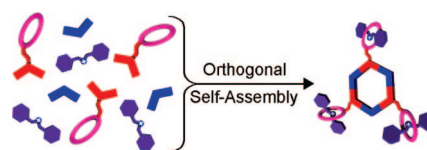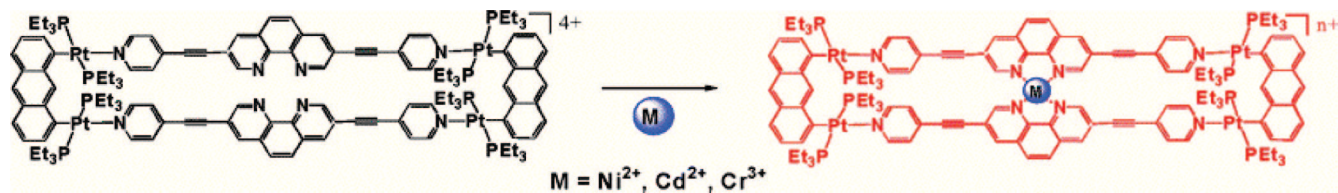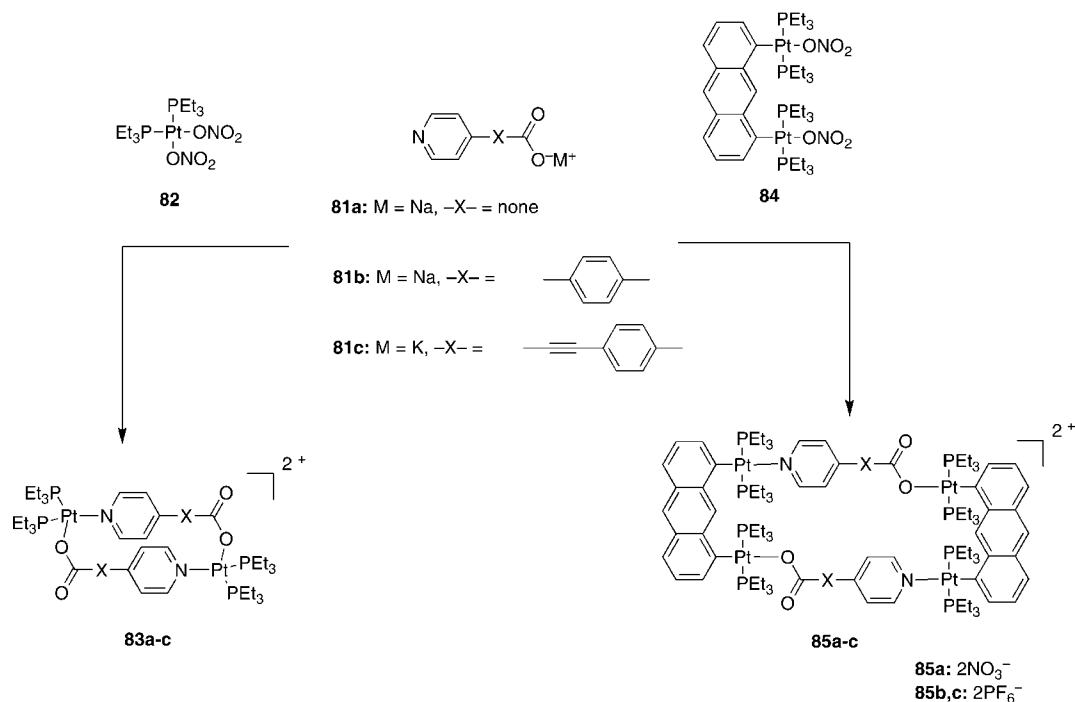

FIGURE 4. Orthogonal, one-pot self-assembly of poly[2]pseudo-rotaxanes.

complementary rigid electron-rich organic donors. The two most significant factors that largely determine the supramolecular structure so obtained are the shape and size of the

SCHEME 15.   **Supramolecular Chromogenic Sensor for Ni, Cd, and Cr**

SCHEME 16.   **Self-Selection in Self-Assembly**

individual component-building units (tectons). The shape of the donor/acceptor units is dominated by the turning angle, defined as the angle formed between the open valencies of a ditopic or tritopic donor or acceptor. For example, as seen in Figure 2, four 90° square planar Pt-units in combination with four linear donor units, such as bipyridine, afford a $A^2_4L^2_4$ molecular square or eight mutually perpendicular, tritopic angular, units in combination with 12 ditopic, linear units, can form a $A^3_8L^2_{12}$ molecular cube. Furthermore, the size of the individual building units determines the overall size of the self-assembled supramolecular species. As previously described,[200b] symmetry considerations also play an important role in this abiological self-assembly protocol.

Our "directional bonding" approach, which has been widely used and adopted,[201] allowed us to prepare other polygons such as triangles,[202] various rhomboids,[203] diverse rectangles,[204] and hexagons,[205] all in near-quantitative yields as expected for a self-correcting, self-healing process.

Of course, as in all active, cutting-edge research such as coordination driven self-assembly, we were and are not alone in the field. M. Fujita (University of Tokyo) and co-workers were pioneers in this area and reported the self-assembly of the first molecular square[206] as well as many other interesting metallacycles and metallacages.[207] K. Raymond (UC-Berkeley) and co-workers[208] have developed and applied a protocol based upon incommensurate *n*-fold symmetry axes, and C. Mirkin (Northwestern) and co-workers pioneered a

methodology based upon the weak-link approach[209] and, more recently, a new protocol using a halide induced ligand rearrangement reaction.[210] The late Professor Albert Cotton and co-workers employed dimetal building blocks in their approach.[211]

We proceeded to investigate both 2D[212] and 3D[213] chiral self-assembled supramolecular species. Chiral supramolecular systems[214] are particularly interesting because of their applications in asymmetric catalysis, chiral-host−guest events, and chiral sensing and their potential to mimic complex biological processes.

Likewise, functionalized supramolecular metal−organic assemblies are of considerable interest because of their potential uses in a variety of electronic, magnetic, catalytic, photonic, mechanic, and sensor applications.[215] There are at least three ways of incorporating functionalities into metal−organic supramolecular architectures: (1) edge or corner functionalization; (2) "inside" or endo functionalization via covalent attachment; and (3) "outside" or exo functionalization via covalent linking as shown in Figure 3.

Initially, we prepared corner-functionalized ferrocene[216] and crown ether and calixrene[217] systems; more recently, we self-assembled various edge-functionalized metal−organic architectures.[218] Most recently, we self-assembled a series of dendrimer,[219] ferrocene,[220] and crown ether[221] exofunctionalized architectures. A novel aspect of this work is the direct "one-

SCHEME 17. Self-Recognition in Self-Assembly
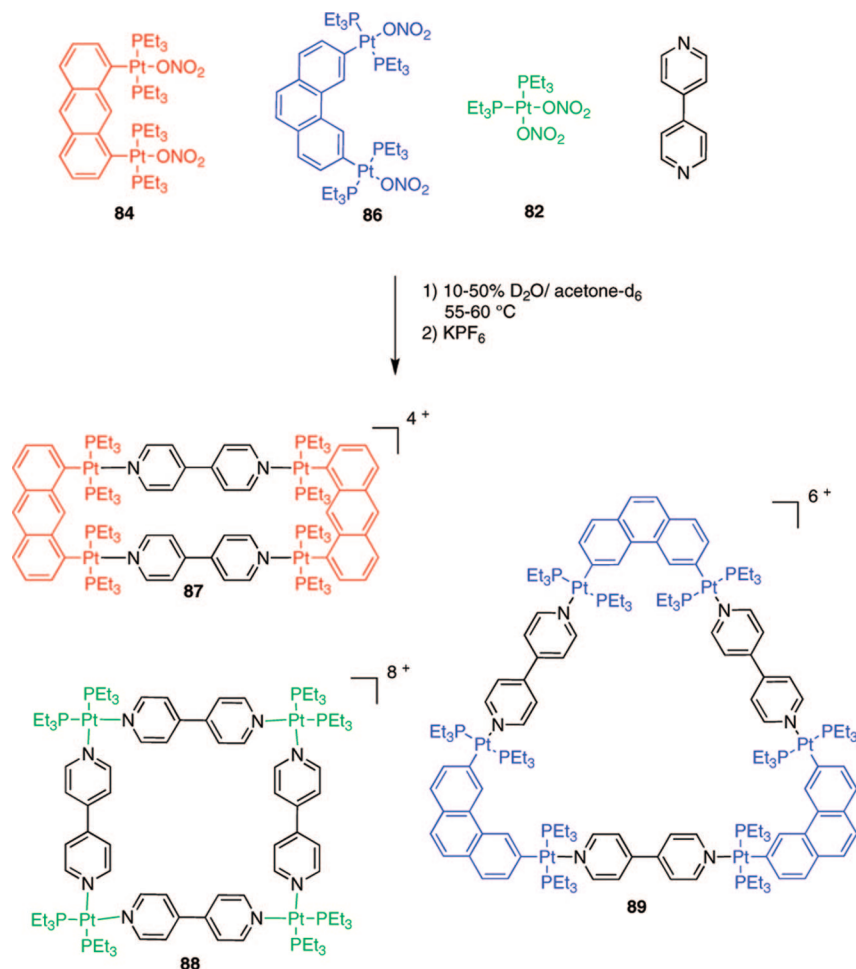
pot" self-assembly, via orthogonal noncovalent interactions of hexagonal cavity-cored poly[2]pseudorotaxanes[221] as shown in Figure 4.

Similarly, we have developed a functionalized rectangle as a chromogenic supramolecular optical sensor for Ni(II), Cd(II), and Cr(III) as illustrated in Scheme 15.

The vast majority of self-assembled supramolecular metallacycles are charged.[223] However, recently we[224] and others[225] have also prepared a range of neutral supramolecular ensembles via self-assembly. Similarly, ambidentate ligands, usually a pyridyl carboxylate, have also been employed[226,227] in the formation of self-assembled metallacycles.

In some cases, instead of a single product, there is an equilibrium between two species such as a triangle and square[202b] or a rhomboid and hexagon.[228] In some instances, there is also restricted rotation around the Pt−N bond[199b,229] resulting in AB multiplets due to the inequivalent α- and β-protons of the pyridyl moiety. This has been investigated using variable temperature NMR by us[230] and others[231] and a free energy of activation, $\Delta G^{\ddagger}$, for the rotation of the bipyridine unit was determined to be about 74 kJ/mol.

The mutual recognition of complementary components within a complex mixture, that is self-sorting, is a critical phenomenon in biological systems. Self-sorting allows for the formation of multiple higher order supramolecular structures from complex multicomponent mixtures when specific recognition information is encoded within the structure of molecular subunits.[232]

Therefore, we,[233] and many other groups,[234] investigated self-sorting in metal−ligand coordination-driven abiological self-assembly. As shown in Scheme 16, only head-to-tail ensembles **83** and **85** were observed,[233c] with no trace of head-to-head analogues in the reaction of the ambidentate pyridylcarboxylate unit **81** with acceptors **82** and **84**, respectively. Likewise, over 90% self-recognition, with but minor amounts of oligomers, and formation of the respective rectangle **87**, square **88**, and triangle **89** were observed[233d] after equilibration for about 120 h in the reaction of mixtures of tectons **82**, **84**, and **86** with 4,4′-bipyridine, as shown in Scheme 17. Hence, these coordination driven abiological self-assembly processes undergo self-selection via self-recognition analogous to biological systems and provide further evidence for the thermodynamic control, via fairly rapid kinetic pathways, in the self-assembly of these nanoscale supramolecular ensembles.

Molecular-based devices,[235] e.g., molecules that possess the ability to act as sensors, switches, motors, machines, memory components, etc., represent perhaps the ultimate in minaturization of functional machinery. Such devices, when properly designed and controlled, constitute the backbone of the nascent nanotechnology that has the potential to revolutionize manufacturing and consumer goods in the 21st century. Nano*technology*, however, will only develop to its full potential if preceded by nano*science*: a solid foundation and understanding of the fundamental properties of molecules at the nanoscale and of "bottom up" nanofabrication.[236]
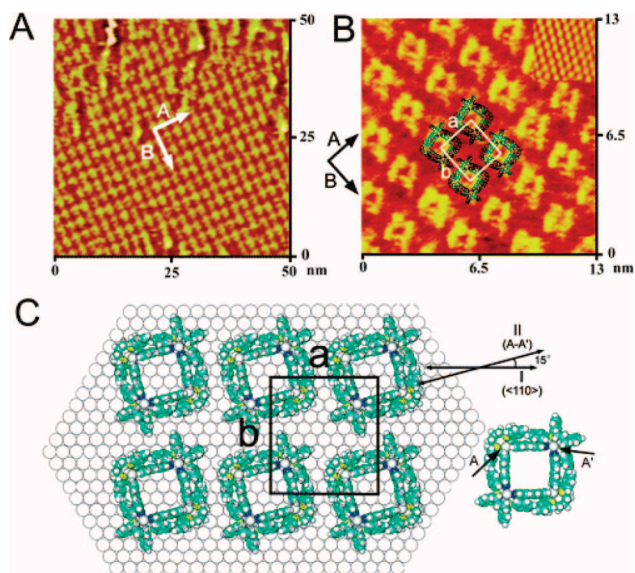
FIGURE 5. (A) Large-scale STM image of self-assembled squares adsorbed on a Au(111) surface. (B) High-resolution STM image of the adlayer also showing the underlying Au(111)-(1 × 1) lattice in the upper right corner. (C) Proposed structural model for the adlayer.

As already described above, the synthesis and characterization of self-assembled 2D and 3D coordination based supramolecular architectures is well established, as are their solution- and solid-state properties.[229] Very little is known, however, about their behavior on surfaces. While solution-phase studies are essential for the establishment and understanding of many of the configurational, physical, optical, and dynamic properties of molecules, and solid-state studies provide unequivocal structural information, neither phase is ideal for the design and fabrication of molecular devices.[237] Where the solution state lacks coherence and orientational control, and the solid state often imparts too much rigidity and confinement, the deposition of molecules and supramolecules on surfaces provides[238] a means of control-

ling and integrating them with other known materials in typical device settings, provided that they can be aligned, distributed, and addressed appropriately. For these reasons, investigating the behavior and properties of these species on surfaces will provide the necessary nanoscience foundation that is critical for the design, development, and fabrication of nanomolecular devices.

The advantages of incorporating functional organic and organometallic molecules into device settings by integrating them onto/into surfaces have been known for some time. Surface-confined molecular films that contain functional electronic materials include photovoltaic devices, optical and nonlinear optical materials, light emitting diodes, and field-effect transistors.[239] The reduced symmetry of surface-confined, molecular film-based components and devices offers the opportunity to systematically manipulate and tune their collective optical, electronic, and other properties through molecular design in a manner that is often more effective than may be achieved by the same components in the less coherent solution phase. Even with the great many successes[239] of molecular film-based devices, the use of self-assembled supramolecular metallacycles provides additional advantages owing to the ease with which large, symmetric, structurally complex polygons and polyhedra can be prepared. It is in this regard that the incorporation of metallacycles onto surfaces can be considered multitiered self-assembly: the supramolecules are first themselves self-assembled and then they are collectively self-assembled onto the desired surface. Taking advantage of thermodynamically driven self-assembly processes at each step avoids many of the time-consuming and costly elements of device fabrication, such as multistep covalent synthetic procedures, high-vacuum sublimation—deposition of monolayers, harsh surface treatments necessary for etching, and the like.

The primary method of characterizing and understanding surface confined nanoscale molecules is scanning probe microscopy[237] and, in particular, the primary instruments are
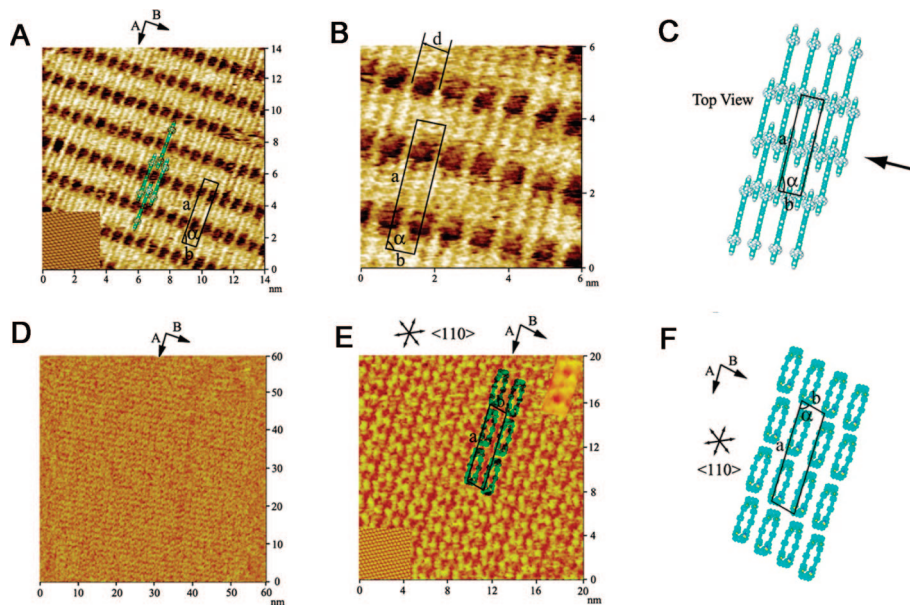
FIGURE 6. (A) Low-resolution image of a supramolecular rectangle on HOPG, showing the underlying HOPG surface in the lower left corner. (B) High-resolution STM image of the supramolecular rectangle on HOPG. (C) A proposed structural model for the adlayer of the rectangle on HOPG. (D) A large-scale (60 × 60 nm) image of the same supramolecular rectangle on Au(111). (E) High-resolution image of the rectangle adlayer, showing the underlying Au(111) lattice in the lower left corner. (F) A proposed structural model for the adlayer of the rectangle on the Au(111) surface.

SCHEME 18.   Face-Directed Self-Assembly of a Cuboctahedron from Triangle-Tectons and 12 Connectors
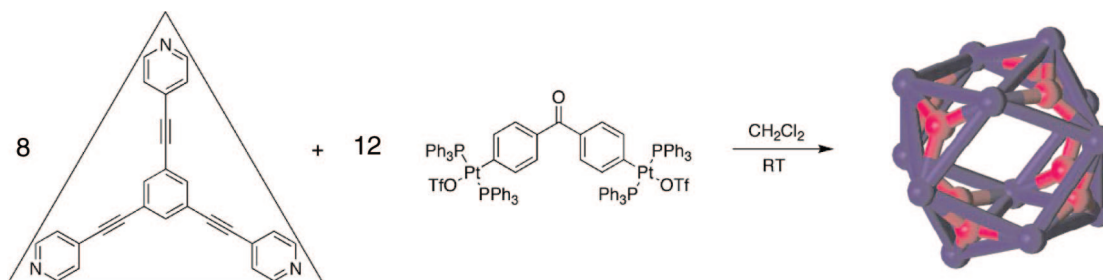
SCHEME 19.   Self-Assembly of a Nanoscale Dodecahedra
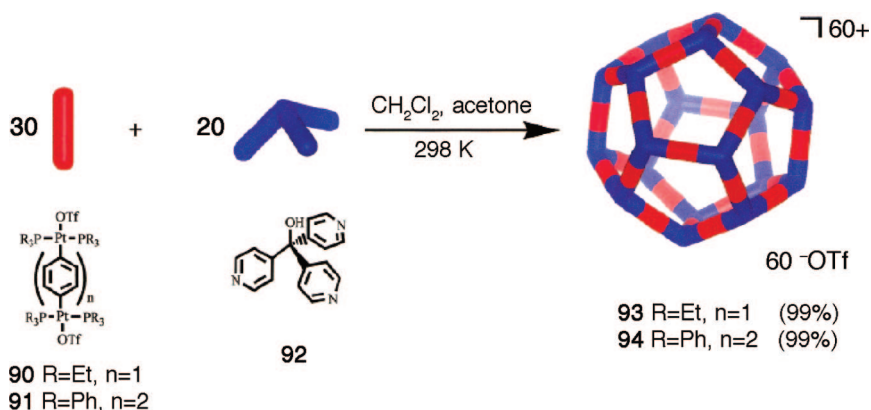
scanning tunneling microscopes (STM) and electrochemical STM (ECSTM).[240] STM has unparalleled spacial resolution and is thereby able to provide real-time, real-space, 3D surface structural information up to atomic resolution in the exploration of single molecules and their aggregates on surfaces.[240]

To date, a large number of surface-confined complex organic, inorganic, and biological molecules have been studied.[241] There have been, however, very few investigations of the structure and properties of nanosized 2D metallacycles or 3D metalla-supramolecular cages on surfaces.[242] Therefore we,[243] in collaboration with Professor L. J. Wan at the Institute of Chemistry in Beijing, China, and others[244] investigated surface-confined metallacycles and metallacages. Figure 5 demonstrates that molecular square **80a** physisorbs on a Au(111) surface and, as seen in Figure 6, supramolecular rectangles physisorb on both HOPG and on Au(111) surfaces and self-organize to form highly ordered adlayers. Interestingly, as seen in Figure 6, the rectangles uniformly adopt an edge on orientation on HOPG but a flat orientation on Au(111). The reason for this difference of orientation on the two different surfaces, graphite and gold, is not fully understood, but likely has to do with the stronger π−Au interactions on gold vs the weaker substrate−surface interaction on graphite. These results nicely demonstrate that nanoscale supramolecular metallacycles do indeed form well-ordered adlayers on surfaces, and hence, it will be possible to integrate these molecules into devices such as molecular sensors, switches, etc.

A fascinating and important aspect of abiological coordination driven self-assembly is the formation of three-dimensional supramolecular polyhedra and cages.[223,245] Such systems may be self-assembled via either a face-directed or edge/corner directed approach. We have used the face directed approach to self-assemble a truncated tetrahedron[246] and cuboctahedra[247] (Scheme 18) as well as various molecular prisms.[230c,248]
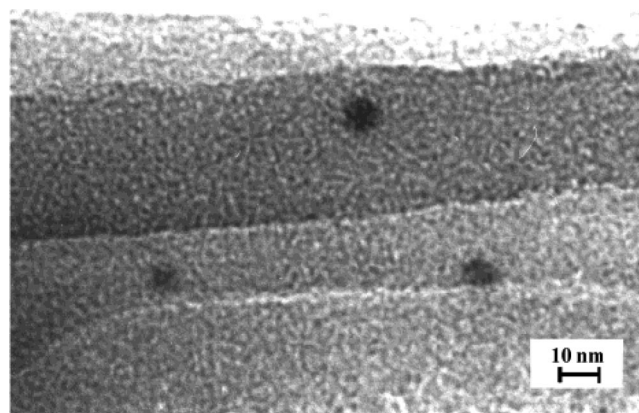
FIGURE 7.   TEM micrograph of individual dodecahedra deposited on a carbon film at low concentrations and dried at −130 °C.[250a]

The edge/corner directed approach was used in the self-assembly of a variety of 3D cages[249] as well as dodecahedra[250] (Scheme 19).

This last reaction is truly remarkable as 50 individual building units have to combine in just the right way to form the desired dodecahedron in quantitative yield as observed.[250] Although we do not have an X-ray structure of the dodecahedra, various spectral techniques, including spin−echo NMR and TEM (Figure 7) establish their structure with a high level of confidence.

Similarly, Fujita[251] and Raymond[252] have self-assembled a remarkable array of interesting metallacages and investigated their host−guest properties and used them as nano reaction vessels.

These rationally designed self-assembled coordination based metallacages are also related to metal-organic frameworks (MOF) that are currently very topical because of their potential use in gas (H_2, CO_2, etc.) uptake and storage.[253]

Our own contributions to this burgeoning field of abiological self-assembly via coordination has been the introduction of the "directional bonding" approach for the rational design of metallacycles and metallacages; the self-assembly of the first chiral architectures and the demonstration that they form highly ordered adlayers on HOPG and gold surfaces. The significance of this work lies in providing insights, by analogy, into biological self-assembly processes and, more importantly, in the nascent nanotechnology area by providing a means of rationally designing new materials, methods for "bottom-up" fabrication and new platforms for devices such as biomedical sensors, molecular machines, and switches, etc.

Summary and Conclusions

I have been fortunate to make contributions in three distinct areas in three different phases of my career. Early on I was involved in physical-organic chemistry and unsaturated reactive intermediates, in particular, vinyl cations and unsaturated carbenes that has enriched the family of reactive carbon intermediates. Perhaps the most important legacy of this work is the discovery and first preparation of vinyl(enol) trifluoromethanesulfonates (triflates) that have become important and widely used in contemporary metal catalyzed cross coupling reactions. In the middle of my career I was involved in polyvalent iodine chemistry and some organometallic chemistry as well as strained, unusual aromatic hydrocarbons. The significance of this work is our discovery of several new iodonium reagents, in particular PhICNOTf, and a general method for the ready formation of alkynyliodonium species that are increasingly being employed in synthetic organic chemistry. For the last 15−18 years I have been involved in supramolecular chemistry and self-assembly where we have developed an entire new paradigm for the rational design of complex, nanoscale, finite metallacycles, and metallacages that has an impact upon nanoscience and nanotechnology and inspired numerous young scientists to enter the field.[254] A common thread in all three areas has been my "mechanistic" thinking and approach acquired during my training as a physical-organic chemist. I continue to see a bright future for physical-organic chemistry and the rigorous thinking and approach that it demands and affords. My own involvement for the remainder of my active career will undoubtedly be in the area of supramolecular chemistry and self-assembly where there is a wealth of exciting and new things to be discovered and exploited.

References

(1) *Friedel−Crafts and Related Reactions*; Olah, G. A., Ed.; Wiley-Interscience: New York, London, 1963; Vols. *1−4*.

(2) Streitwieser, A., Jr.; Stang, P. J. *J. Am. Chem. Soc.* **1965**, *87*, 4953.

(3) Inter alia: (a) Noyce, D. S.; Matesich, M. A.; Peterson, P. E. *J. Am. Chem. Soc.* **1967**, *89*, 6225. (b) Noyce, D. S.; Schiavelli, M. D. *J. Am. Chem. Soc.* **1968**, *90*, 1020. (c) Noyce, D. S.; DeBruin, K. E. *J. Am. Chem. Soc.* **1968**, *90*, 372.

(4) Reviews: (a) Stang, P. J. *Prog. Phys. Org. Chem.* **1973**, *10*, 205. (b) Modena, G.; Tonellato, U. *Adv. Phys. Org. Chem.* **1971**, *9*, 185.

(5) (a) *Carbonium Ions*; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley-Interscience: New York, London, 1968; Vols. *1−5*. (b) *Carbocation Chemistry*; Olah, G. A., Prakash, G. K. S., Eds.; Wiley: Hoboken, NJ, 2004.

(6) (a) Grob, C. A.; Cseh, G. *Helv. Chim. Acta* **1964**, *47*, 194. (b) Capozzi, G.; Melloni, G.; Modena, G.; Piscitelli, M. *Tetrahedron Lett.* **1968**, 4039. (c) Miller, L. L.; Kaufman, D. A. *J. Am. Chem. Soc.* **1968**, *90*, 7282. (d) Jones, W. M.; Maness, D. D. *J. Am. Chem. Soc.* **1969**, *91*, 4314.

(7) Grob, C. A.; Spaar, R. *Tetrahedron Lett.* **1969**, 1439.

(8) Sherrod, S. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1969**, *91*, 2115. (b) Hanack, M.; Bässler, T. *J. Am. Chem. Soc.* **1969**, *91*, 2117.

(9) Peterson, P. E.; Indelicato, J. M. *J. Am. Chem. Soc.* **1968**, *90*, 6515.

(10) Review: Howells, R. D.; McCown, J. D. *Chem. Rev.* **1977**, *77*, 69, and references therein.

(11) Haszeldine, R. N.; Kidd, J. M. *J. Chem. Soc.* **1954**, 4228.

(12) Streitwieser, A., Jr.; Wilkins, C. L.; Kiehlmann, E. *J. Am. Chem. Soc.* **1968**, *90*, 1598.

(13) *Nonclassical Ions*; Bartlett, P. D., Ed.; Benjamin, Inc.: New York, 1965.

(14) Schleyer, P. v. R.; Stang, P. J.; Raber, D. J *J. Am. Chem. Soc.* **1970**, *92*, 4725.

(15) Hansen, R. L. *J. Org. Chem.* **1965**, *30*, 4322.

(16) Su, T. M.; Sliwinski, W. F.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1969**, *91*, 5386.

(17) Review: Stang, P. J.; Hanack, M.; Subramanian, L. R. *Synthesis* **1982**, 85.

(18) Stang, P. J.; Summerville, R. *J. Am. Chem. Soc.* **1969**, *91*, 4600.

(19) (a) Dueber, T. E.; Stang, P. J.; Pfeifer, W. D.; Summerville, R. H.; Imhoff, M. A.; Schleyer, P. v. R.; Hummel, K.; Bocher, S.; Harding, C. E.; Hanack, M. *Angew. Chem., Int. Ed. Engl.* **1970**, *9*, 521. (b) Imhoff, M. A.; Summerville, R. H.; Schleyer, P. v. R.; Martinez, A. G.; Hanack, M.; Dueber, T. E.; Stang, P. J. *J. Am. Chem. Soc.* **1970**, *92*, 3802. (c) Stang, P. J.; Dueber, T. E. *Organic Syntheses* **1974**, *54*, 79. (d) Stang, P. J.; Treptow, W. *Synthesis* **1980**, 283. (e) Stang, P. J.; Dueber, T. E. *Organic Synthesis*; Wiley: New York, 1988; Collect. Vol. VI, p 757.

(20) Reviews: (a) *Metal-catalyzed Cross-Coupling Reactions*, Diederich, F.; Stang, P. J. , Eds.; Wiley-VCH: Weinheim, 1998. (b) *Metal-Catalyzed Cross-Coupling Reactions*, 2nd ed., de Meijere, A., Diederich, F., Eds.; Wiley-VCH: Weinheim, 2004.

(21) Reviews: (a) Stang, P. J. *Acc. Chem. Res.* **1978**, *11*, 107. (b) *Vinyl Cations*; Stang, P. J., Rappoport, Z., Hanack, M., Subramanian, L. R., Eds.; Academic Press: New York, 1979. (c) *Dicoordinated Carbocations*; Rappoport, Z., Stang, P. J., Eds.; J. Wiley and Sons: Chichester, 1997.

(22) (a) Pfeifer, W. D.; Bahn, C. A.; Schleyer, P. v. R.; Bocher, S.; Harding, C. E.; Hummel, K.; Hanack, M.; Stang, P. J. *J. Am. Chem. Soc.* **1971**, *93*, 1513. (b) Hargrove, R. J.; Stang, P. J. *Tetrahedron* **1976**, *32*, 37. (c) Ladika, M.; Stang, P. J.; Schiavelli, M. D.; Kowalski, M. H. *J. Am. Chem. Soc.* **1984**, *106*, 6372.

(23) (a) Martinez, A. G.; Hanack, M.; Summerville, R. H.; Schleyer, P. v. R.; Stang, P. J *Angew. Chem., Int. Ed. Engl.* **1970**, *9*, 302. (b) Stang, P. J.; Dueber, T. E. *Tetrahedron Lett.* **1977**, *18*, 563.

(24) (a) Hargrove, R. J.; Dueber, T. E.; Stang, P. J. *Chem. Commun.* **1970**, 1614. (b) Stang, P. J.; Dueber, T. E. *J. Am. Chem. Soc.* **1973**, *95*, 2686. (c) Stang, P. J.; Hargrove, R. J.; Dueber, T. E. *J. Chem. Soc., Perkin Trans. 2* **1974**, 843. (d) Stang, P. J.; Hargrove, R. J.; Dueber, T. E. *J. Chem. Soc., Perkin Trans. 2* **1977**, 1486. (e) Ladika, M.; Schiavelli, M. D.; Kowalski, M. H.; Stang, P. J. *J. Org. Chem.* **1985**, *50*, 4397.

(25) (a) Summerville, R. H.; Senkler, C. A.; Schleyer, P. v. R.; Dueber, T. E.; Stang, P. J. *J. Am. Chem. Soc.* **1974**, *96*, 1100. (b) Ladika, M.; Stang, P. J.; Schiavelli, M. D.; Hughey, M. R. *J. Org. Chem.* **1982**, *47*, 4563. (c) Schiavelli, M. D.; Jung, D. M.; Vaden, A. K.; Stang, P. J.; Fisk, T. E.; Morrison, D. S. *J. Org. Chem.* **1981**, *46*, 92.

(26) (a) Stang, P. J.; Anderson, A. G. *Tetrahedron Lett.* **1977**, *17*, 1485. (b) Stang, P. J.; Anderson, A. G. *J. Am. Chem. Soc.* **1978**, *100*, 1520.

(27) Reviews: (a) Lancelot, C. J.; Cram, D. J.; Schleyer, P. V. R. In *Carbonium Ions*; Olah, G. A., Schleyer, P. V. R., Eds.; Wiley-Interscience: New York, 1972; Vol. III. (b) Reference 13 and references therein. (c) Capon, C. *Q. Rev. Chem. Soc.* **1964**, *18*, 45.

(28) (a) Cram, D. J. *J. Am. Chem. Soc.* **1948**, *70*, 4244. (b) Cram, D. J. *J. Am. Chem. Soc.* **1949**, *71*, 3863. (c) Cram, D. J. *J. Am. Chem. Soc.* **1949**, *71*, 3875. (d) Cram, D. J. *J. Am. Chem. Soc.* **1952**, *74*, 2129, 2137, 2159.

(29) (a) Stang, P. J.; Dueber, T. E. *J. Am. Chem. Soc.* **1973**, *95*, 2683. (b) Stang, P. J.; Dueber, T. E. *J. Am. Chem. Soc.* **1977**, *99*, 2602.

(30) Inter alia: (a) Review: Siehl H.-U. In *Stable Carbocation Chemistry*; Prakash, G. K. S., Schleyer, P. V. R., Eds.; Wiley: New York, 1997; pp 165−196. (b) Müller, T.; Meyer, R.; Lennartz, D.; Siehl, H.-U. *Angew. Chem., Int. Ed.* **2000**, *39*, 3074. (c) Kaufmann, F.-P.; Siehl, H.-U. *J. Am. Chem. Soc.* **1992**, *114*, 4937. (d) Siehl, H.-U.; Mayr, H. *J. Am. Chem. Soc.* **1982**, *104*, 909.

(31) Reviews: (a) Hine, J. *Divalent Carbon*; Ronald Press: New York, 1964. (b) Gilcrist, T. L.; Rees, C. W. *Carbenes, Nitrenes and Arynes*; Appleton-

Century-Crofts: New York, 1969. (c) Kirmse, W. *Carbene Chemistry*, 2nd ed.; Academic Press: New York, 1971. (d) Jones, M., Jr.; Moss, R. A. *Carbenes*; Wiley: New York, 1973; Vol. I.

(32) Review: Köbrich, G. *Angew. Chem., Int. Ed.* **1967**, *6*, 41.

(33) Curtin, D. Y.; Kampeier, J. A.; O'Connor, B. R. *J. Am. Chem. Soc.* **1965**, *87*, 863.

(34) Gilbert, J. C.; Butler, J. R. *J. Am. Chem. Soc.* **1970**, *92*, 7493.

(35) (a) Newman, M. S.; Okorodudu, O. M. *J. Am. Chem. Soc.* **1968**, *90*, 4189. (b) Newman, M. S.; Patrick, T. B. *J. Am. Chem. Soc.* **1969**, *97*, 5677.

(36) (a) Hartzler, H. D. *J. Am. Chem. Soc.* **1971**, *93*, 4527, and references therein. (b) LeNoble, W. J.; Tatsukani, Y.; Morris, H. F. *J. Am. Chem. Soc.* **1970**, *92*, 5681.

(37) Reviews: (a) Stang, P. J. *Chem. Rev.* **1978**, *78*, 383. (b) Stang, P. J. *Acc. Chem. Res.* **1982**, *15*, 348. (c) Stang, P. J. *Pure Appl. Chem.* **1983**, *55*, 369.

(38) Stang, P. J.; Mangum, M. G.; Fox, D. P.; Haak, P. *J. Am. Chem. Soc.* **1974**, *96*, 4562.

(39) (a) Stang, P. J.; Fox, D. P. *J. Org. Chem.* **1977**, *42*, 1667. (b) Fox, D. P.; Bjork, J. A.; Stang, P. J *J. Org. Chem.* **1983**, *48*, 3994.

(40) Stang, P. J.; Mangum, M. G. *J. Am. Chem. Soc.* **1975**, *97*, 1459.

(41) (a) Stang, P. J.; Madsen, J. R.; Mangum, M. G.; Fox, D. P. *J. Org. Chem.* **1977**, *42*, 1802. (b) Apeloig, Y.; Karni, M.; Christensen, S. B.; Stang, P. J. *Tetrahedron Lett.* **1986**, *27*, 6115.

(42) Stang, P. J.; Mangum, M. G. *J. Am. Chem. Soc.* **1975**, *97*, 6478.

(43) Closs, G. L.; Moss, R. A. *J. Am. Chem. Soc.* **1964**, *86*, 4042.

(44) (a) Apeloig, Y.; Karni, M.; Stang, P. J.; Fox, D. P. *J. Am. Chem. Soc.* **1983**, *105*, 4781. (b) Fox, D. P.; Stang, P. J.; Apeloig, Y.; Karni, M. *J. Am. Chem. Soc.* **1986**, *108*, 750. (c) Apeloig, Y; Schrieber, R.; Stang, P. J. *Tetrahedron Lett.* **1980**, *21*, 411.

(45) (a) Stang, P. J.; Davis, J.; Fox, D. P. *J. Chem. Soc., Chem. Commun.* **1975**, 17. (b) Stang, P. J.; Fox, D. P.; Collins, C. J.; Watson, C. R., Jr *J. Org. Chem.* **1978**, *43*, 364.

(46) (a) Bothner-By, A. A. *J. Am. Chem. Soc.* **1955**, *77*, 3293. (b) Curtin, D. Y.; Flynn, E. W.; Nystrom, R. F. *J. Am. Chem. Soc.* **1958**, *80*, 4599.

(47) (a) Stang, P. J. *Israel J. Chem.* **1981**, *21*, 119. (b) Kaftory, M. I.; Agmon, Ladika, M.; Stang, P. J. *J. Am. Chem. Soc.* **1987**, *109*, 782. (c) Learned, A. E.; Arif, A. M.; Stang, P. J. *J. Org. Chem.* **1988**, *53*, 3122.

(48) Stang, P. J.; Mangum, M. G. *J. Am. Chem. Soc.* **1975**, *97*, 3854.

(49) Gajewski, J. J.; Chang, M. J.; Stang, P. J.; Fisk, T. E. *J. Am. Chem. Soc.* **1980**, *102*, 2096.

(50) Neuhaus, P.; Grote, D.; Sander, W. *J. Am. Chem. Soc.* **2008**, *130*, 2993.

(51) (a) Stang, P. J.; Mangum, M. G. *J. Am. Chem. Soc.* **1977**, *99*, 2597. (b) Krageloh, K.; Anderson, G. H.; Stang, P. J. *J. Am. Chem. Soc.* **1984**, *106*, 6015.

(52) Stang, P. J.; Bjork, J. A. *J. Chem. Soc., Chem. Commun.* **1978**, 1057.

(53) Stang, P. J.; Anderson, G. H. *J. Org. Chem.* **1981**, *46*, 4585.

(54) Stang, P. J.; Roberts, K. A.; Lynch, L. E. *J. Org. Chem.* **1984**, *49*, 1653.

(55) Stang, P. J.; Learned, A. E. *J. Am. Chem. Soc.* **1987**, *109*, 5019.

(56) Sommer, L. H.; Ulland, L. A.; Parker, G. A. *J. Am. Chem. Soc.* **1972**, *94*, 3469.

(57) Stang, P. J.; Christensen, S. B. *J. Org. Chem.* **1981**, *46*, 823.

(58) Stang, P. J.; Fisk, T. E. *Synthesis* **1979**, 438.

(59) Stang, P. J.; Ladika, M. *Synthesis* **1981**, 29.

(60) (a) Stang, P. J.; Fisk, T. E. *J. Am. Chem. Soc.* **1979**, *101*, 4772. (b) Stang, P. J.; Fisk, T. E. *J. Am. Chem. Soc.* **1980**, *102*, 6813.

(61) (a) Stang, P. J.; Learned, A. E. *J. Chem. Soc., Chem. Commun.* **1988**, 301. (b) Stang, P. J.; Ladika, M. *J. Am. Chem. Soc.* **1980**, *102*, 5406. (c) Stang, P. J.; Ladika, M. *J. Am. Chem. Soc.* **1981**, *103*, 6437.

(62) Stang, P. J.; White, M. R. *J. Am. Chem. Soc.* **1981**, *103*, 5429.

(63) Reviews: (a) Nicolaou, K. C.; Bulger, P. G.; Sarlah, D. *Angew. Chem., Int. Ed.* **2005**, *44*, 4442. (b) Dounay, D. B.; Overman, L. E. *Chem. Rev.* **2003**, *103*, 2945.

(64) McCarthy, M. C.; Thaddeus, P. *Chem. Soc. Rev.* **2001**, *30*, 177.

(65) Thaddeus, P.; Gottlieb, C. A.; Mollaaghababa, R.; Vrtilek, J. M. *J. Chem. Soc., Faraday Trans.* **1993**, *89*, 2125.

(66) Reviews: (a) Grubbs, R. H. *Angew. Chem., Int. Ed.* **2006**, *45*, 3760. (b) Bruneau, C.; Dixneuf, P. H. *Angew. Chem., Int. Ed.* **2006**, *45*, 2176. (c) Touchard, D.; Dixneuf, P. H. *Coord. Chem. Rev.* **1998**, *178*, 409.

(67) Trnka, T. M.; Morgan, J. P.; Sandford, M. S. *J. Am. Chem. Soc.* **2003**, *125*, 2546.

(68) Reviews: (a) Seleque, J. P. *Coord. Chem. Rev.* **2004**, *248*, 1543. (b) Cadierna, V.; Gamasa, M. P.; Gimeno, J. *Coord. Chem. Rev.* **2004**, *248*, 1627. (c) Ilg, J.; Werner, H. *Chem.—Eur. J.* **2002**, *8*, 2812.

(69) Varela, J. A.; Saá, C. *Chem.—Eur. J.* **2006**, *12*, 6450.

(70) Yamauchi, Y.; Yuki, M.; Tanabe, T.; Miyake, Y.; Inada, Y.; Uemura, S.; Nishibayashi, Y. *J. Am. Chem. Soc.* **2008**, *130*, 2908.

(71) Stang, P. J.; Datta, A. K. *J. Am. Chem. Soc.* **1989**, *111*, 1358.

(72) (a) Stang, P. J.; Wistrand, L. G. *J. Organomet. Chem.* **1981**, *204*, 405. (b) Stang, P. J.; Datta, A. K.; Dixit, V.; Wistrand, L. G. *Organometallics* **1989**, *8*, 1020. (c) Stang, P. J.; Dixit, V. *Tetrahedron Lett.* **1985**, *26*, 2301.

(73) (a) Kowalski, M. H.; Stang, P. J. *Organometallics* **1986**, *5*, 2392. (b) Stang, P. J.; Kowalski, M. H.; Zhong, Z. *Organometallics* **1990**, *9*, 833. (c) Kowalski, M. H.; Arif, A. M.; Stang, P. J. *Organometallics* **1988**, *7*, 1227. (d) Zhong, Z.; Stang, P. J.; Arif, A. M. *Organometallics* **1990**, *9*, 1703. (e) Zhong, Z.; Hinkle, R. J.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **1991**, *113*, 6196.

(74) (a) Stang, P. J.; Cao, D. H.; Poulter, G. T.; Arif, A. M. *Organometallics* **1995**, *14*, 1110. (b) Stang, P. J.; Datta, A. K. *Organometallics* **1989**, *8*, 1024.

(75) (a) Stang, P. J.; Schiavelli, M. D.; Chenault, H. K.; Breidegam, J. L. *Organometallics* **1984**, *3*, 1133. (b) Stang, P. J.; Dixit, V.; Schiavelli, M. D.; Drees, P. *J. Am. Chem. Soc.* **1987**, *109*, 1150.

(76) (a) Stang, P. J.; Zhong, Z.; Arif, A. M. *Organometallics* **1992**, *11*, 1017. (b) Stang, P. J.; Zhong, Z. *Organometallics* **1992**, *11*, 1026.

(77) (a) Stang, P. J.; Song, L.; Halton, B. *J. Organomet. Chem.* **1990**, *388*, 215. (b) Huang, Y.-H.; Stang, P. J.; Arif, A. M. *J. Am. Chem. Soc.* **1990**, *112*, 5648. (c) Stang, P. J.; Huang, Y. H.; Arif, A. M. *Organometallics* **1992**, *11*, 231.

(78) (a) Stang, P. J.; White, M. R.; Maas, G. *Organometallics* **1983**, *2*, 720. (b) White, M. R.; Stang, P. J. *Organometallics* **1983**, *2*, 1382. (c) White, M. R.; Stang, P. J. *Organometallics* **1983**, *2*, 1654.

(79) Song, L.; Arif, A. M.; Stang, P. J. *J. Organomet. Chem.* **1990**, *395*, 219.

(80) Stang, P. J.; Kowalski, M. H.; Schiavelli, M. D.; Longford, D. *J. Am. Chem. Soc.* **1989**, *111*, 3347.

(81) Stang, P. J.; Kowalski, M. H. *J. Am. Chem. Soc.* **1989**, *111*, 3356.

(82) Review: (a) Halton, B. *Chem. Rev.* **1973**, *73*, 113. (b) Billups, W. E. *Acc. Chem. Res.* **1978**, *11*, 245. (c) Halton, B. *Chem. Rev.* **2003**, *103*, 1327.

(83) Greenberg, A.; Liebman, J. F. *Strained Organic Molecules*; Academic Press: New York, 1978.

(84) Review: *Dehydrobenzene and Cycloalkynes*; Hoffman, R. W., Ed.; Academic Press: New York, 1967.

(85) Chapman, O. L; Mattes, K.; McIntosh, C. L.; Pacansky, J.; Calder, G. V.; Orr, G. J. *J. Am. Chem. Soc.* **1973**, *95*, 6134.

(86) Review: Halton, B *Eur. J. Org. Chem.* **2005**, 3391.

(87) Newman, M. S.; Patrick, T. B. *J. Am. Chem. Soc.* **1969**, *91*, 6461.

(88) (a) Halton, B.; Randall, C. J; Stang, P. J. *J. Am. Chem. Soc.* **1984**, *106*, 6108. (b) Halton, B.; Randall, C. J.; Gainsford, G. J.; Stang, P. J. *J. Am. Chem. Soc.* **1986**, *108*, 5949. (c) Halton, B.; Lu, Q.; Stang, P. J. *Aust. J. Chem.* **1990**, *43*, 1277.

(89) Weber, W. P. *Silica—Reagents for Organic Synthesis*; Springer-Verlag: New York, 1983.

(90) Reviews: (a) Halton, B.; Stang, P. J. *Acc. Chem. Res.* **1987**, *20*, 443. (b) Halton, B.; Stang, P. J. *Synlett* **1997**, 145.

(91) (a) Ashley, K.; Foley, J. K.; Mei, Q.; Ghoroghchian, J.; Sarfarazi, F.; Cassidy, J.; Halton, B.; Stang, P. J.; Pons, S. *J. Org. Chem.* **1986**, *51*, 2089. (b) Ashley, K.; Sarfarazi, F.; Buckland, S. J.; Foley, J. K.; Mei, Q.; Halton, B.; Stang, P. J.; Pons, S. *Can. J. Chem.* **1987**, *65*, 2062. (c) McNichols, A. T.; Stang, P. J.; Halton, B.; Kay, A. J. *Tetrahedron Lett.* **1993**, *34*, 3131.

(92) Koenig, V.; Curtiss, T.; Winter, R.; Ashley, K.; Mei, Q.; Stang, P. J.; Pons, S.; Buckland, S. J.; Halton, B.; Rolison, D. *J. Org. Chem.* **1988**, *53*, 3735.

(93) Halton, B.; Buckland, S. J.; Lu, Q.; Mei, Q.; Stang, P. J. *J. Org. Chem.* **1988**, *53*, 2418.

(94) Halton, B.; Lu, Q.; Stang, P. J. *J. Org. Chem.* **1990**, *55*, 3056.

(95) Halton, B.; Lu, Q.; Stang, P. J. *J. Chem. Soc., Chem. Commun.* **1988**, 879.

(96) Buckland, S. J.; Halton, B.; Mei, Q; Stang, P. J. *Aust. J. Chem.* **1987**, *40*, 1375.

(97) Buckland, S. J.; Halton, B.; Stang, P. J. *Aust. J. Chem.* **1988**, *41*, 845.

(98) (a) Stang, P. J.; Song, L.; Halton, B. *J. Organomet. Chem.* **1990**, *388*, 215. (b) Stang, P. J.; Song, L.; Lu, Q.; Halton, B. *Organometallics* **1990**, *9*, 2149. (c) Song, L.; Arif, A. M.; Stang, P. J. *Organometallics* **1990**, *9*, 2792.

(99) (a) Halton, B.; Buckland, S. J.; Mei, Q.; Stang, P. J. *Tetrahedron Lett.* **1986**, *27*, 5159. (b) McNichols, A. T.; Stang, P. J.; Addington, D. M.; Halton, B. *Tetrahedron Lett.* **1994**, *35*, 437.

(100) (a) Mul, P. M.; McGowan, J. W. *Astrophys. J.* **1980**, *237*, 749. (b) Herbst, E *Astrophys. J. Suppl. Ser* **1983**, *53*, 41. (c) Krolik, J. H.; Kallman, T. R. *Astrophys. J.* **1983**, *267*, 610.

(101) Burgers, P. C.; Holmes, J. L.; Mommers, A. A.; Szulejko, J. E. *J. Am. Chem. Soc.* **1984**, *106*, 521.

(102) Apeloig, Y. *Theory and Calculations in Dicoordinated Carbocations*; Rappoport, Z., Stang, P. J., Eds.; Wiley: Chichester, 1997; Chapter 2, pp 9−104.

(103) (a) Koser, G. F.; Rebrovic, L.; Wettach, R. H. *J. Org. Chem.* **1981**, *46*, 4324. (b) Rebrovic, L.; Koser, G. F. *J. Org. Chem.* **1984**, *49*, 4700.

(104) Willgerodt, C. *J. Prakt. Chem.* **1886**, *33*, 155.

(105) Willgerodt, C. *Chem. Ber.* **1892**, *25*, 3494.

(106) Willgerodt C. *Die Organischen Verbindugen mit Mehrwertigen Iod*; Enke: Stuttgart, 1914.

(107) (a) Varvoglis, A. *Hypervalent Iodine in Organic Synthesis*; Academic Press: London, 1997. (b) Varvoglis, A. *The Organic Chemistry of Polycoordinate Iodine*; VCH Publishers: New York, 1992. (c) Stang, P. J.; Zhdankin, V. V. *Chem. Rev.* **1996**, *96*, 1123. (d) Zhdankin, V. V.; Stang, P. J. *Chem. Rev.* **2002**, *102*, 2523. (e) Wirth, T. Hypervalent Iodine Chemistry: Modern Developments in Organic Synthesis. *Top. Curr. Chem.* 2003, 224.

(108) Review: Stang, P. J. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 274.

(109) Beringer, F. M.; Galton, S. A. *J. Org. Chem.* **1965**, *30*, 1930.

(110) Merkushev, E. B.; Karpitskaya, L. G.; Novosel'tseva, G. I. *Dokl. Akad. Nauk. SSSR* **1979**, *245*, 607.

(111) (a) Neiland, O.; Karele, B. *J. Org. Chem. USSR (Eng. Transl.)* **1970**, *6*, 889. (b) Moriarty, R. M.; Vaid, R. K.; Koser, G. F. *Synlett* **1990**, 365.

(112) (a) Stang, P. J.; Surber, B. W. *J. Am. Chem. Soc.* **1985**, *107*, 1452. (b) Stang, P. J.; Surber, B. W.; Chen, Z. C.; Roberts, K. A.; Anderson, A. G. *J. Am. Chem. Soc.* **1987**, *109*, 228. (c) Stang, P. J.; Kitamura, T. *Org. Synth.* **1991**, *70*, 215. (d) Kitamura, T.; Stang, P. J. *J. Org. Chem.* **1988**, *53*, 4105. (e) Stang, P. J.; Roberts, K. A. *J. Am. Chem. Soc.* **1986**, *108*, 7832.

(113) Ochiai, M.; Kunishima, M.; Sumi, K.; Nagao, K.; Fujita, E.; Ariomoto, M.; Yamaguchi, H. *Tetrahedron Lett.* **1985**, *26*, 4501.

(114) (a) Bachi, M. D.; Bar-Ner, N.; Crittell, C. M.; Stang, P. J.; Williamson, B. L. *J. Org. Chem.* **1991**, *56*, 3912. (b) Stang, P. J.; Zhdankin, V. V.; Williamson, B. L. *J. Am. Chem. Soc.* **1991**, *113*, 5870. (c) Williamson, B. L.; Stang, P. J.; Arif, A. M. *J. Am. Chem. Soc.* **1993**, *115*, 2590.

(115) Zefirov, N. S.; Zhdankin, V. V.; Dan'kov, Y. Y.; Kozmin, A. S. *Zh. Org. Khim.* **1984**, *20*, 446.

(116) Williamson, B. L.; Stang, P. J. *Synlett* **1992**, 199.

(117) (a) Zhdankin, V. V.; Crittell, C. M.; Stang, P. J.; Zefirov, N. S. *Tetrahedron Lett.* **1990**, *31*, 4821. (b) Zhdankin, V. V.; Scheuller, M. C.; Stang, P. J. *Tetrahedron Lett.* **1993**, 6853. (c) Stang, P. J.; Zhdankin, V. V.; Tykwinski, R.; Zefirov, N. S. *Tetrahedron Lett.* **1992**, *33*, 1419.

(118) (a) Stang, P. J.; Arif, A. M.; Crittell, C. M. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 287. (b) Ochiai, M.; Ho, T.; Takaoka, Y.; Masaki, Y.; Kunishima, M.; Tani, S.; Nagao, Y. *J. Chem. Soc., Chem. Commun.* **1990**, 118.

(119) Stang, P. J.; Zhdankin, V. V. *J. Am. Chem. Soc.* **1990**, *112*, 6437. (b) Stang, P. J.; Zhdankin, V. V. *J. Am. Chem. Soc.* **1991**, *113*, 4571.

(120) (a) Stang, P. J.; Zhdankin, V. V.; Arif, A. M. *J. Am. Chem. Soc.* **1991**, *113*, 8997. (b) Stang, P. J.; Ullmann, J. *Synthesis* **1991**, 1073. (c) Stang, P. J.; Tykwinski, R.; Zhdankin, V. V. *J. Org. Chem.* **1992**, *57*, 1861. (d) Tykwinski, R.; Stang, P. J. *Organometallics* **1994**, *13*, 3203. (e) Kitamura, T.; Furuki, R.; Taniguchi, H.; Stang, P. J. *Mendeleev Commun.* **1991**, 148. (f) Stang, P. J.; Zhdankin, V. V.; Arif, A. M. *Mendeleev Commun.* **1992**, 158.

(121) (a) Stang, P. J.; Ullmann, J. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1469. (b) Hinkle, R. J.; Stang, P. J. *Synthesis* **1994**, 313. (c) Kasumov, T. M.; Pirguliyev, N. S.; Brel, V. K.; Grishin, Y. K.; Zefirov, N. S.; Stang, P. J. *Tetrahedron* **1997**, *53*, 13139.

(122) Ochiai, M.; Suni, K.; Takuoka, Y.; Kunishima, Y.; Nagao, Y.; Shiro, M.; Fujita, E. *Tetrahedron* **1998**, *54*, 4095.

(123) (a) Kitamura, T.; Furuki, R.; Taniguchi, H.; Stang, P. J. *Tetrahedron Lett.* **1990**, *31*, 703. (b) Kitamura, T.; Furuki, R.; Nagata, K.; Taniguchi, H.; Stang, P. J. *J. Org. Chem.* **1992**, *57*, 6810. (c) Kitamura, T.; Furuki, R.; Taniguchi, H.; Stang, P. J. *Tetrahedron* **1992**, *48*, 7149.

(124) (a) Stang, P. J.; Tykwinski, R.; Zhdankin, V. V. *J. Heterocycl. Chem.* **1992**, *29*, 815. (b) Stang, P. J.; Olenyuk, B.; Chen, K. *Synthesis* **1995**, 937.

(125) Stang P. J. In *Modern Acetylene Chemistry*; Stang, P. J., Diederich, F., Eds.; VCH Publishers: Weinheim, 1995.

(126) Stang, P. J.; Wingert, H.; Arif, A. M. *J. Am. Chem. Soc.* **1987**, *109*, 7235.

(127) Martin, J. C. *Science* **1983**, *221*, 509.

(128) (a) Kitamura, T.; Stang, P. J. *Tetrahedron Lett.* **1988**, *29*, 1887. (b) Ochiai, M.; Kunishima, M.; Fuj, K.; Nagao, Y. *J. Org. Chem.* **1988**, *53*, 6144.

(129) Mironova, A. A.; Maletina, I. I.; Iksanova, S. V.; Yagapulski, L. M. *Zh. Org. Khim.* **1989**, *25*, 306.

(130) (a) Ochiai, M.; Ito, T.; Takaoka, Y.; Masuki, Y.; Kunishima, M.; Tani, S.; Nagao, Y. *J. Chem. Soc., Chem. Commun.* **1990**, 118. (b) Susuki, T.; Uozumi, T.; Shibasaki, M. *J. Chem. Soc., Chem. Commun.* **1991**, 1593. (c) Bachi, M. D.; Bar-Ner, N.; Stang, P. J.; Williamson, B. L. *J. Org. Chem.* **1993**, *58*, 7923. (d) Kitamura, T.; Nagata, K.; Taniguchi, H. *Tetrahedron Lett.* **1995**, 1081. (e) Kitamura, T.; Fukuoka, T.; Zheng, L.; Fujimoto, T.; Taniguchi, H.; Fujiwara, Y. *Bull. Soc. Chem. Jpn.* **1996**, *69*, 2649.

(131) (a) Witulski, B.; Stengel, T. *Angew. Chem., Int. Ed.* **1998**, *37*, 489. (b) Witulski, B.; Stengel, T. *Angew. Chem., Int. Ed.* **1999**, *38*, 2426. (c) Witulski, T.; Gossman, M. *J. Chem. Soc., Chem. Commun.* **1999**, 1897. (d) Murch, P.; Williamson, B. L.; Stang, P. J. *Synthesis* **1994**, 1255.

(132) Fischer, D. R.; Williamson, B. L.; Stang, P. J. *Synlett* **1992**, 535.

(133) Tykwinski, R. R.; Williamson, B. L.; Fischer, D. R.; Stang, P. J.; Arif, A. M. *J. Org. Chem.* **1993**, *58*, 5235.

(134) Williamson, B. L.; Murch, P.; Fischer, D. R.; Stang, P. J. *Synlett* **1993**, 858.

(135) Liu, Z. D.; Chen, Z. C. *J. Org. Chem.* **1993**, *58*, 1924.

(136) (a) Stang, P. J.; Crittell, C. M. *J. Org. Chem.* **1992**, *57*, 4305. (b) Schmidpeter, A.; Mayer, P.; Stocker, J.; Roberts, K. A.; Stang, P. J. *Heteroatom Chem.* **1991**, *2*, 569. (c) Laali, K. K.; Regitz, M.; Birkel, M.; Stang, P. J.; Crittell, C. M. *J. Org. Chem.* **1993**, *58*, 4105.

(137) Lodoya, J. S.; Koser, G. F. *J. Org. Chem.* **1993**, *58*, 1924.

(138) Nagaoka, T.; Sueda, T.; Ochiai, M. *Tetrahedron Lett.* **1995**, 261.

(139) Stang, P. J.; Murch, P. *Synthesis* **1997**, 1378.

(140) (a) Stang, P. J.; Crittell, C. M. *Organometallics* **1990**, *9*, 3191. (b) Stang, P. J.; Tykwinski, R. *J. Am. Chem. Soc.* **1992**, *114*, 4411. (c) Stang, P. J.; Crittell, C. M.; Arif, A. M. *Organometallics* **1993**, *12*, 4799.

(141) (a) Kunz, R.; Fehlhanmer, W. P. *Angew. Chem., Int. Ed.* **1994**, *33*, 330. (b) Dembinski, R.; Lis, T.; Szafert, S; Mayne, C. L.; Bartik, T.; Gladysz, J. A. *J. Organomet. Chem.* **1999**, *578*, 229.

(142) Review: Stang, P. J. *Acc. Chem. Res.* **1991**, *24*, 304.

(143) Review: *The Chemistry of Enols*; Rappoport, Z., Ed.; Wiley-Interscience: London, 1990.

(144) (a) Smith, B. J.; Radom, L.; Kresge, A. J. *J. Am. Chem. Soc.* **1989**, *111*, 8297. (b) Bouma, W. J.; Nobes, R. H.; Radom, L.; Woodward, C. E. *J. Org. Chem.* **1982**, *47*, 1869. (c) Holmes, J. L.; Lossing, F. P. *J. Am. Chem. Soc.* **1982**, *104*, 2648.

(145) (a) Stang, P. J.; Boehshar, M.; Lin, J. *J. Am. Chem. Soc.* **1986**, *108*, 7832. (b) Stang, P. J.; Boehshar, M.; Wingert, H.; Kitamura, T. *J. Am. Chem. Soc.* **1988**, *110*, 3272.

(146) (a) Stang, P. J.; Kitamura, T.; Boehshar, M.; Wingert, H. *J. Am. Chem. Soc.* **1989**, *111*, 2225. (b) Zhdankin, V. V.; Stang, P. J. *Tetrahedron Lett.* **1993**, *34*, 1461. (c) Tykwinski, R. R.; Stang, P. J. *Tetrahedron* **1993**, *49*, 3043.

(147) Stang, P. J.; Kitamura, T.; Arif, A. M.; Karni, M.; Apeloig, Y. *J. Am. Chem. Soc.* **1990**, *112*, 374.

(148) Stang, P. J.; Crittell, C. M.; Arif, A. M.; Karni, M.; Apeloig, Y. *J. Am. Chem. Soc.* **1991**, *113*, 7461.

(149) (a) Allen, A. D.; Roberts, K. A.; Kitamura, T.; Stang, P. J.; Tidwell, T. T. *J. Am. Chem. Soc.* **1988**, *110*, 622. (b) Allen, A. D.; Kitamura, T.; McClelland, R. A.; Stang, P. J.; Tidwell, T. T. *J. Am. Chem. Soc.* **1990**, *112*, 8873.

(150) (a) Maas, G.; Regitz, M.; Rahm, R.; Schneider, J.; Stang, P. J.; Crittell, C. M. *J. Chem. Soc., Chem. Commun.* **1990**, 1456. (b) Maas, G.; Rahm, R.; Krebs, F.; Regitz, M.; Stang, P. J.; Crittell, C. M. *Chem. Ber.* **1991**, *124*, 1661.

(151) (a) Segal, D.; Shalitin, Y.; Wingert, H.; Kitamura, T.; Stang, P. J *FEBS Lett.* **1989**, *247*, 217. (b) Segal, D.; Shalitin, C.; Shalitin, Y.; Fischer, D. R.; Stang, P. J. *FEBS Lett.* **1996**, *392*, 117.

(152) (a) Blenkenship, J. N.; Abu-Soud, H.; Francisco, W. A.; Raushel, F. M.; Fischer, D. R.; Stang, P. J. *J. Am. Chem. Soc.* **1991**, *113*, 8560. (b) Banzon, J. A.; Kuo, J. M.; Miles, B.; Fischer, D. R.; Stang, P. J.; Raushel, F. M. *Biochemistry* **1995**, *34*, 743. (c) Banzon, J. A.; Kuo, J.-M.; Fischer, D. R.; Stang, P. J.; Raushel, F. M. *Biochemistry* **1995**, *34*, 750.

(153) (a) Ochiai, M.; Kunishima, M.; Tani, S.; Nagao, Y. *J. Am. Chem. Soc.* **1991**, *113*, 3135. (b) Ochiai, M.; Kunishima, M.; Nagao, Y.; Fuji, M.; Shiro, M.; Fujita, E. *J. Am. Chem. Soc.* **1986**, *108*, 8221. (c) Tykwinski, R. R.; Stang, P. J.; Persky, N. E. *Tetrahedron Lett.* **1994**, *35*, 23.

(154) Williamson, B. L.; Tykwinski, R. R.; Stang, P. J. *J. Am. Chem. Soc.* **1994**, *116*, 93.

(155) Reviews: (a) Pellissier, H. *Tetrahedron* **2005**, *61*, 6479. (b) Denmark, S. E. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: New York, 1991; Vol. 5, pp 751−784.

(156) Reviews: (a) Gibson, S. E.; Stevenazzi, A. *Angew. Chem., Int. Ed.* **2003**, *42*, 1800. (b) Brummond, K. M.; Kent, J. L. *Tetrahedron* **2000**, *56*, 3263.

(157) Pauson, P. L. *Tetrahedron* **1985**, *41*, 5855.

(158) (a) Feldman, K. S.; Mareska, D. A. *J. Org. Chem.* **1999**, *64*, 5650. (b) Feldman, K. S.; Mareska, D. A. *Tetrahedron Lett.* **1998**, 4781. (c) Feldman, K. S.; Mareska, D. A. *J. Am. Chem. Soc.* **1998**, *120*, 4027.

(159) (a) Schildknegt, K.; Bohnstedt, A. C.; Feldman, K. S.; Sambandam, A. *J. Am. Chem. Soc.* **1995**, *117*, 7544. (b) Feldman, K. S.; Bruendl, M. M.; Schildknegt, K. *J. Org. Chem.* **1995**, *60*, 7722.

(160) Wipf, P.; Venkatraman, S. *J. Org. Chem.* **1996**, *61*, 8004.

(161) (a) Kitamura, T.; Zheng, L.; Fukuoka, T.; Fujiwara, Y.; Taniguchi, H.; Sakurai, M.; Tanaka, R. *J. Chem. Soc., Perkin Trans. 2* **1997**, 1511. (b) Nikas, S.; Rodios, N.; Varvoglis, A. *Molecules* **2000**, *5*, 1182.

(162) Kitamura, T.; Tsuda, K.; Fujiwara, Y. *Tetrahedron Lett.* **1998**, 5375.

(163) Zhang, P. F.; Chen, Z. C. *Synthesis* **2001**, 238.

(164) Murch, P.; Arif, A. M.; Stang, P. J. *J. Org. Chem.* **1997**, *62*, 5959.

(165) (a) Stang, P. J.; Schwarz, A.; Blume, T.; Zhdankin, V. V. *Tetrahedron Lett.* **1992**, *33*, 6759. (b) Stang, P. J.; Blume, T.; Zhdankin, V. V. *Synthesis* **1993**, *1*, 35.

(166) Kotali, E.; Varvoglis, A.; Bozopoulos, A. *J. Chem. Soc., Perkin Trans. 1* **1989**, 827.

(167) Stang, P. J.; Murch, P. *Tetrahedron Lett.* **1997**, 8793.

(168) Maas, G.; Regitz, M.; Moll, U.; Rahm, R.; Krebs, F.; Hector, R.; Stang, P. J.; Crittell, C. M.; Williamson, B. L *Tetrahedron* **1992**, *48*, 3527.

(169) (a) Moriarty, R. M.; Epa, W. R.; Awasthi, A. K. *J. Am. Chem. Soc.* **1991**, *113*, 6315. (b) Kang, S. K.; Lee, H. W.; Jang, S. B.; Kim, T. J.; Pyun, S. J. *J. Org. Chem.* **1996**, *61*, 260. (c) Ho, P. S. *J. Org. Chem.* **1996**, *61*, 9082. (d) Kang, S. K.; Ryu, H. C.; Lee, S. W. *J. Chem. Soc., Perkin Trans. 1* **1999**, 2661. (e) Huang, X.; Xu, X. *J. Chem. Soc., Perkin Trans. 1* **1998**, 3321. (f) Roh, K. R.; Kim, J. Y; Kim, Y. H. *Tetrahedron Lett.* **1999**, 1903. (g) Hinkle, R. J.; Levi, A.; David, G. A.; Erwin, W. M. *Org. Lett.* **2002**, *4*, 1521.

(170) (a) Hinkle, R. J.; Poulter, G. T.; Stang, P. J. *J. J. A. Chem. Soc.* **1993**, *115*, 11626. (b) Ryan, J. H.; Stang, P. J. *J. Org. Chem.* **1996**, *61*, 6162. (c) Ryan, J. H.; Stang, P. J. *Tetrahedron Lett.* **1997**, *38*, 5061. (d) Radhakrishnan, U.; Stang, P. J. *Org. Lett.* **2001**, *3*, 859. (e) Kitamura, T.; Tanaka, T.; Taniguchi, H.; Stang, P. J *J. Chem. Soc., Perkin Trans. 1* **1991**, 2892. (f) Stang, P. J.; Kitamura, T. *J. Am. Chem. Soc.* **1987**, *109*, 7561. (g) Kitamura, T.; Mihara, I.; Tamisuchi, H.; Stang, P. J. *J. Chem. Soc., Chem. Commun.* **1990**, 614.

(171) Pirguliyev, N. Sh.; Brel, V. K.; Zefirov, N. S.; Stang, P. J. *Tetrahedron* **1999**, *55*, 12377.

(172) Gallop, P. M.; Paz, M. A.; Flückiger, R.; Stang, P. J.; Zhdankin, V. V.; Tykwinski, R. R. *J. Am. Chem. Soc.* **1993**, *115*, 11702.

(173) Goldstein, E. J. C.; Citron, D. M.; Warren, Y.; Merriam, C. V.; Tyrrell, K.; Fernandez, H.; Radhakrishnan, U.; Stang, P. J.; Conrads, G. *Antimicrob. Agents Chemother.* **2004**, *48*, 2766.

(174) (a) Angelini, G.; Hanack, M.; Vermehren, J.; Speranza, M. *J. Am. Chem. Soc.* **1988**, *110*, 1298. (b) see also Zhdankin, V. V.; Stang, P. J.; Zefirov, N. S. *Chem. Commun.* **1992**, 578.

(175) Reviews: (a) Moriarty, R. M. *J. Org. Chem.* **2005**, *70*, 2893. (b) Stang, P. J. *J. Org. Chem.* **2003**, *68*, 2997. (c) Zhdankin, V. V.; Stang, P. J. *Tetrahedron* **1998**, *54*, 10927. (d) Wirth, T. *Angew. Chem., Int. Ed.* **2005**, *44*, 3656. (e) Chaudhari, S. S. *Synlett* **2000**, 278.

(176) Feldman, K. S.; Cutarelli, T. D. *J. Am. Chem. Soc.* **2002**, *124*, 11600.

(177) Tohma, H.; Harayama, Y.; Hashizume, M.; Iwata, M.; Kiyono, Y.; Egi, M.; Kita, Y. *J. Am. Chem. Soc.* **2003**, *125*, 11235.

(178) Hamamoto, H.; Shiozaki, Y.; Nambu, H.; Hata, K.; Tohma, H.; Kita, Y, *Chem.—Eur. J.* **2004**, *10*, 4977.

(179) Reviews: (a) Deprez, N. R.; Sanford, M. S. *Inorg. Chem.* **2007**, *46*, 1924. (b) Zhdankin, V. V.; Stang, P. J. *Chem. Rev* **2009**, *109*, in press.

(180) Boldyrev, A. I.; Zhdankin, V. V.; Simons, J.; Stang, P. J. *J. Am. Chem. Soc.* **1992**, *114*, 10569.

(181) Stang, P. J.; Zhdankin, V. V. *J. Am. Chem. Soc.* **1993**, *115*, 9808.

(182) Radhakrishnan, U.; Stang, P. J. *J. Org. Chem.* **2003**, *68*, 9209.

(183) (a) *Principles and Applications of Organotransition Metal Chemistry*; Collman, J. P., Hegedus, L. S., Norton, J. R., Finke, R. G., Eds.; University Science Books: Mill Valley, CA, 1987. (b) *Advanced Inorganic Chemistry*, 5th ed.; Cotton, F. A., Wilkinson, G., Eds.; Wiley-Interscience: New York, 1988.

(184) Reviews: Gellman, S. H., Guest Ed. *Chem. Rev.* **1997**, *97*, 1231.

(185) *Oxford Handbook of Nucleic Acid Structure*; Neidle, S., Ed.; Oxford University Press: Oxford, 1999.

(186) *Micelles, Monolayers, and Biomembranes*; Jones, M. N., Chapman, D., Eds.; Wiley-Liss: New York, 1995.

(187) *At Home in the Universe: the Search for Laws of Self-Organization and Complexity*; Kauffman, S., Eds.; OUP: New York, 1995.

(188) *Principles of Molecular Virology*, 2nd ed.; Cann, A. J., Ed.; Academic Press: New York, 1997.

(189) Ercolani, G. *J. Am. Chem. Soc.* **2003**, *123*, 16097.

(190) (a) Lehn, J. M. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4763. (b) Lehn, J. M *Chem.—Eur. J.* **2097**, *200*, 6. (c) Lehn, J.-M. *Proc. Natl. Acad. Sci. U.S.A.* **1997**, *94*, 2106.

(191) Reviews: (a) Chambron, J. C.; Dietrich-Buchecker, C.; Sauvage, J. P. In *Comprehensive Supramolecular Chemistry*; Lehn, J.-M., Atwood, J. L., Davis, J. E. D., MacNicol, D. D., Vögtle, Eds.; Pergamon Press: Oxford, 1996; Vol. 9, Chapter 2, p 43. (b) Baxter, P. N. W. See ref 191a, Chapter 5, p 165. (c) Constable, E. C. See ref 191a, Chapter 6, p 213.

(192) Reviews: (a) Steel, P. J. *Acc. Chem. Res.* **2005**, *38*, 243. (b) Swieger, G. F.; Malefetse, T. J. *Chem. Rev.* **2000**, *1000*, 3483.

(193) (a) Stang, P. J.; Cao, D. H. *J. Am. Chem. Soc.* **1994**, *116*, 4981. (b) Stang, P. J.; Cao, D. H.; Saito, S.; Arif, A. M. *J. Am. Chem. Soc.* **1995**, *117*, 6273.

(194) Cao, D. H.; Chen, K.; Fan, J.; Manna, J.; Olenyuk, B.; Whiteford, J. A.; Stang, P. J. *Pure Appl. Chem.* **1997**, *69*, 1979.

(195) Stang, P. J.; Whiteford, J. A. *Organometallics* **1994**, *13*, 3776.

(196) (a) Stang, P. J.; Chen, K. *J. Am. Chem. Soc.* **1995**, *117*, 1667. (b) Stang, P. J.; Chen, K.; Arif, A. M. *J. Am. Chem. Soc.* **1995**, *117*, 8793. (c) Whiteford, J. A.; Lu, C. V.; Stang, P. J. *J. Am. Chem. Soc.* **1997**, *119*, 2524. (d) Whiteford, J. A.; Stang, P. J.; Huang, S. D. *Inorg. Chem.* **1998**, *37*, 5595.

(197) Stang, P. J.; Persky, N. E. *J. Chem. Soc., Chem. Commun.* **1997**, 77.

(198) (a) Manna, J.; Whiteford, J. A.; Stang, P. J.; Muddiman, D. C.; Smith, R. D *J. Am. Chem. Soc.* **1996**, *118*, 8731. (b) Manna, J.; Kuehl, C. J.; Whiteford, J. A.; Stang, P. J.; Muddiman, D. C.; Hofstadler, S. A.; Smith, R. D. *J. Am. Chem. Soc.* **1997**, *119*, 11611.

(199) (a) Stang, P. J.; Fan, J.; Olenyuk, B. *J. Chem. Soc., Chem. Commun.* **1997**, 1453. (b) Fan, J.; Whiteford, J. A.; Olenyuk, B.; Levin, M. D.; Stang, P. J.; Fleischer, E. B. *J. Am. Chem. Soc.* **1999**, *121*, 2741.

(200) (a) Stang, P. J.; Olenyuk, B. *Acc. Chem. Res.* **1997**, *30*, 502. (b) Stang, P. J. *Chem.—Eur. J.* **1998**, *4*, 19. (c) Olenyuk, B.; Fechtenkötter, A.; Stang, P. J. *Dalton Trans.* **1998**, 1707.

(201) Reviews: (a) Leininger, S.; Olenyuk, B.; Stang, P. J. *Chem. Rev.* **2000**, *100*, 853. (b) Sweigers, G. F.; Malefetse, T. J. *Chem. Rev.* **2000**, *100*, 3483.

(202) (a) Schweiger, M.; Seidel, S. R.; Arif, A. M *Angew. Chem., Int. Ed.* **2001**, *40*, 3467. (b) Schweiger, M.; Seidel, S. R.; Arif, A. M.; Stang, P. J. *Inorg. Chem.* **2002**, *41*, 2556. (c) Kryschenko, Y. K.; Seidel, S. R.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **2003**, *125*, 5193.

(203) (a) Schmitz, M.; Leininger, S.; Fan, J.; Arif, A. M.; Stang, P. J *Organometallics* **1999**, *18*, 4817. (b) Tabellion, F. M.; Seidel, S. R.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **2001**, *123*, 7740. (c) Campbell, K.; Kuehl, C. J.; Ferguson, M. J.; Stang, P. J.; Tykwinski, R. R. *J. Am. Chem. Soc.* **2002**, *124*, 7266. (d) Chatterjee, B.; Noveron, J. C.; Resendiz, M. J. E.; Lui, J.; Yamamoto, T.; Parker, D.; Cinke, M.; Nguyen, C. V.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **2004**, *126*, 10645.

(204) (a) Kuehl, C. J.; Mayne, C. L.; Arif, A. M.; Stang, P. J. *Org. Lett.* **2000**, *2*, 3727. (b) Kuehl, C. J.; Huang, S. D.; Stang, P. J. *J. Am. Chem. Soc.*

(205) **2001**, *123*, 9634. (c) Addicott, C.; Oesterling, I.; Yamamoto, T.; Mullen, K.; Stang, P. J. *J. Org. Chem.* **2005**, *70*, 797. (d) Kaim, W.; Schwederski, B; Dogan, A.; Fiedler, J.; Kuehl, C. J.; Stang, P. J. *Inorg. Chem.* **2002**, *41*, 4025.

(205) (a) Stang, P. J.; Persky, N. E.; Manna, J. *J. Am. Chem. Soc.* **1997**, *119*, 4777. (b) Leininger, S.; Schmitz, M.; Stang, P. J. *Org. Lett.* **1999**, *1*, 1921. (c) Chi, K. W.; Addicott, A.; Arif, A. M.; Das, N.; Stang, P. J. *J. Org. Chem.* **2003**, *68*, 9798.

(206) (a) Fujita, M.; Yazaki, J.; Ogura, K. *J. Am. Chem. Soc.* **1990**, *112*, 5645. (b) Fujita, M.; Kwon, Y. J.; Washizu, S.; Ogura, K. *J. Am. Chem. Soc.* **1994**, *116*, 1151. See, however, (c) Stricklen, P. M.; Vocko, E. J.; Verkade, J. G *J. Am. Chem. Soc.* **1983**, *105*, 2494. for an early example of a neutral, tetranuclear, organometallic macrocycle.

(207) (a) Reviews: Kawano, M.; Fujita, M. *Coord. Chem. Rev.* **2007**, *251*, 2592. (b) Maurizot, V.; Yoshizawa, M.; Kawano, M.; Fujita, M. *Dalton. Trans.* **2006**, 2750. (c) Fujita, M.; Tominaga, M.; Hori, A.; Therien, B. *Acc. Chem. Res.* **2005**, *38*, 369. (d) Fujita, M.; Umemoto, K.; Yoshizawa, M.; Fujita, N.; Kusukawa, T.; Biradha, K. *Chem. Commun.* **2001**, 509. (e) Fujita, M. *Chem. Soc. Rev.* **1998**, *6*, 417.

(208) (a) Reviews: Caulder, D. L.; Raymond, K. N. *Acc. Chem. Res.* **1999**, *32*, 975. (b) Caulder, D. L.; Raymond, K. N. *J. Chem. Soc., Dalton Trans.* **1999**, 1185. (c) Fiedler, D.; Leung, D. H.; Bergman, R. G.; Raymond, K. N. *Acc. Chem. Res.* **2005**, *38*, 351.

(209) Reviews: (a) Holliday, B.; Mirkin, C. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 2022. (b) Gianneschi, N. C.; Maser, M. S.; Mirkin, C. A. *Acc. Chem. Res.* **2005**, *38*, 825.

(210) Oliveri, C. G.; Ulmann, P. A.; Wiester, M. J.; Mirkin, C. A. *Acc. Chem. Res.*, in press.

(211) Reviews: (a) Cotton, F. A.; Lin, C.; Murillo, C. A. *Acc. Chem. Res.* **2001**, *34*, 759. (b) Cotton, F. A.; Lin, C.; Murillo, C. A. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4810.

(212) (a) Stang, P. J.; Olenyuk, B.; Arif, A. M. *Organometallics* **1995**, *14*, 5281. (b) Stang, P. J.; Olenyuk, B. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 732. (c) Stang, P. J.; Whiteford, J. A.; Olenyuk, B. *J. Am. Chem. Soc.* **1996**, *118*, 8221. (d) Müller, C.; Whiteford, J. A.; Stang, P. J. *J. Am. Chem. Soc.* **1998**, *120*, 9827. (e) Das, N.; Ghosh, A.; Singh, O. M.; Stang, P. J. *Org. Lett.* **2006**, *8*, 1701.

(213) (a) Stang, P. J.; Olenyuk, B.; Muddiman, D. C.; Smith, R. D. *Organometallics* **1997**, *16*, 3094. (b) Schweiger, M.; Seidel, S.; Schmitz, M.; Stang, P. J. *Org. Lett.* **2000**, *2*, 1255. (c) Caskey, D. C.; Yamamoto, T.; Addicott, C.; Shoemaker, R. K.; Vacek, J.; Hawkridge, A. M.; Muddiman, D. C.; Kottas, G. S.; Michl, J.; Stang, P. J. *J. Am. Chem. Soc.* **2008**, *130*, 7620.

(214) Reviews: (a) Lee, S. J.; Lin, W. *Acc. Chem. Res.* **2008**, *41*, 521. (b) Seeber, G.; Tiedmann, B. E. F.; Raymond, K. N. *Top. Curr. Chem.* **2006**, *265*, 147.

(215) Reviews: (a) Northrop, B. H.; Yang, H.-B.; Stang, P. J. *Chem. Commun.* **2008**, 5896. (b) Lee, S. J.; Hupp, J. T. *Coord. Chem. Rev.* **2006**, *250*, 1710. (c) Thanasekaran, P.; Liao, R. T.; Liu, Y.-H.; Rajendran, T.; Rajagopal, S.; Lu, K. L. *Coord. Chem. Rev.* **2005**, *249*, 1085. (d) Würthner, F.; You, C. C.; Saha-Möller, C. R. *Chem. Soc. Rev.* **2004**, *33*, 133. (e) Dunbar, K. R. *Found. Nanosci. Proc.* **2004**, 171. (f) Keefe, M. H.; Benkstein, K. D.; Hupp, J. T. *Coord. Chem. Rev.* **2000**, *205*, 201.

(216) Stang, P. J.; Olenyuk, B.; Fan, J.; Arif, A. M. *Organometallics* **1996**, *15*, 904.

(217) Stang, P. J.; Cao, D. H.; Chen, K.; Gray, G. M.; Muddiman, D. C.; Smith, R. D. *J. Am. Chem. Soc.* **1997**, *119*, 5163.

(218) (a) Chi, K. W.; Addicott, C.; Stang, P. J. *J. Org. Chem.* **2004**, *69*, 2910. (b) Jude, H.; Disteldörf, H.; Fischer, S.; Wedge, T.; Hawkridge, A. H.; Arif, A. M.; Hawthorne, M. F.; Muddiman, D. C.; Stang, P. J. *J. Am. Chem. Soc.* **2005**, *127*, 12131. (c) Yang, H.; Das, N.; Huang, F.; Hawkridge, A. M.; Diaz, D. D.; Arif, A. M.; Finn, M. G.; Muddiman, D. C.; Stang, P. J. *J. Org. Chem.* **2006**, *71*, 6644. (d) Jude, H.; Sinclair, D. J.; Das, N.; Sherburn, M. S.; Stang, P. J. *J. Org. Chem.* **2006**, *71*, 4155. (e) Northrop, B. H.; Glöckner, A.; Stang, P. J. *J. Org. Chem.* **2008**, *73*, 1787.

(219) (a) Yang, H.-B.; Das, N.; Huang, F.; Hawkridge, A. M.; Muddiman, D. C.; Stang, P. J. *J. Am. Chem. Soc.* **2006**, *128*, 10014. (b) Yang, H. B.; Hawkridge, A. M.; Huang, S. D.; Das, N.; Bunge, S. D.; Muddiman, D. C.; Stang, P. J. *J. Am. Chem. Soc.* **2007**, *129*, 2120.

(220) (a) Yang, H.-B.; Ghosh, K.; Zhao, Y.; Northrop, B. H.; Lyndon, M. M.; Muddiman, D. C.; White, H. S.; Stang, P. J. *J. Am. Chem. Soc.* **2008**, *130*, 839. (b) Ghosh, K.; Zhao, Y.; Yang, H.-B.; Northrop, B. H.; White, H. S.; Stang, P. J. *J. Org. Chem.* **2008**, *73*, 8553.

(221) (a) Yang, H.-B.; Ghosh, K.; Northrop, B. H.; Zheng, Y. R.; Lyndon, M. M.; Muddiman, D. C.; Stang, P. J. *J. Am. Chem. Soc.* **2007**, *129*, 14187. (b) Ghosh, K.; Yang, H.-B.; Northrop, B. H.; Lyndon, M. M.; Zheng, Y. R.; Muddiman, D. C.; Stang, P. J. *J. Am. Chem. Soc.* **2008**, *130*, 5320.

(222) Resendiz, M. J. E.; Noveron, J. C.; Disteldorf, H.; Fischer, S.; Stang, P. J. *Org. Lett.* **2004**, *6*, 651.

(223) Review: Leininger, S.; Olenyuk, B.; Stang, P. J. *Chem. Rev.* **2000**, *100*, 853.

(224) (a) Das, N.; Mukherjee, P. S.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **2003**, *125*, 13950. (b) Mukherjee, P. S.; Das, N.; Kryschenko, Y.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **2004**, *126*, 2464. (c) Mukherjee, P. S.; Min, K. S.; Arif, A. M.; Stang, P. J. *Inorg. Chem.* **2004**, *43*, 6345. (d) Das, N.; Arif, A. M.; Stang, P. J.; Sieger, M.; Sarkar, B.; Kaim, W.;

Fiedler, J. *Inorg. Chem.* **2005**, *44*, 5798. (e) Das, N.; Ghosh, A.; Arif, A. M.; Stang, P. J. *Inorg. Chem.* **2005**, *44*, 7130. (f) Das, N.; Stang, P. J.; Arif, A. M.; Compana, C. F. *J. Org. Chem.* **2005**, *70*, 10440. (g) Huang, F.; Yang, H.; Maran, U.; Arif, A. M.; Gibson, H. W.; Stang, P. J. *J. Org. Chem.* **2006**, *71*, 6623.

(225) Inter alia: (a) Cotton, F. A.; Donahue, J. P.; Murillo, C. A *J. Am. Chem. Soc.* **2003**, *125*, 5436. (b) Cotton, F. A.; Lin, C.; Murillo, C. A. *Inorg. Chem.* **2001**, *40*, 478. (c) Cotton, F. A.; Lin, C.; Murillo, C. A. *Inorg. Chem.* **2001**, *40*, 6413. (d) Cheng, H.; Chung-Ying, D.; Chen-jie, F.; Yong-jiang, L.; Qing-jin, M *J. Chem. Soc., Dalton. Trans.* **2000**, 1207. (e) Cotton, F. A.; Daniels, L. M.; Lin, C.; Murillo, C. A. *J. Am. Chem. Soc.* **1999**, *121*, 4538. (f) Cotton, F. A.; Lin, C.; Daniels, M. L.; Murillo, C. A.; Yu, S.-Y. *J. Chem. Soc., Dalton Trans.* **2001**, 502. (g) Bala, M.; Thanasekaran, P.; Rajendran, T.; Liao, R. T.; Liu, Y. H.; Lee, G. H.; Peng, S. M.; Rajagopal, S.; Lu, K. L. *Inorg. Chem.* **2003**, *42*, 4795. (h) Manimaran, B.; Rajendran, T.; Lu, Y. L.; Lee, G. H.; Peng, S. M.; Lu, K. L. *Eur. J. Inorg. Chem.* **2001**, *3*, 633. (i) Slone, R. V.; Hupp, J. T.; Albrecht-Schmitt, T. E. *Inorg. Chem.* **1996**, *35*, 4096. (j) Saalfrank, R. W.; Reimann, U.; Goritz, M.; Hampel, E.; Scheurer, A.; Heinemann, F. W.; Busches, M.; Daub, J.; Schunemann, V.; Trautwein, A. X. *Chem.—Eur. J.* **2002**, *8*, 3614. (k) Saalfrank, R. W.; Trummer, S.; Reimann, U.; Chowdhry, M. M.; Hampel, F.; Waldmann, O. *Angew. Chem., Int. Ed.* **2000**, *39*, 3492.

(226) Ghosh, S.; Turner, D. R.; Batten, S. R.; Mukherjee, P. S. Dalton Trans. 2007, 1869,and references therein.

(227) Chi, K. W.; Addicott, C.; Stang, P. J. *J. Am. Chem. Soc.* **2004**, *126*, 16569.

(228) Yamamoto, T.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **2003**, *125*, 12309.

(229) Megyes, T.; Jude, H.; Grosz, T.; Bako, I.; Radnai, T.; Tarkanyi, G.; Palinkas, G.; Stang, P. J. *J. Am. Chem. Soc.* **2005**, *127*, 10731.

(230) (a) Vacek, J.; Caskey, D. C.; Horinek, D.; Shoemaker, R. K.; Stang, P. J.; Michl, J. *J. Am. Chem. Soc.* **2008**, *130*, 7629. (b) Tarkanyi, G.; Jude, H.; Palinkas, G.; Stang, P. J. *Org. Lett.* **2005**, *7*, 4971. (c) Fuss, M.; Siehl, H.-U.; Olenyuk, B.; Stang, P. J. *Organometallics* **1999**, *18*, 758.

(231) (a) Park, S.-J.; Shin, D. M.; Sakamoto, S.; Yamaguchi, K.; Chung, Y. K.; Lah, M. S.; Hong, J.-I. *Chem.—Eur. J.* **2005**, *11*, 235. (b) Tiede, D. M.; Zhang, R.; Chen, L. X.; Yu, L.; Lindsey, J. S. *J. Am. Chem. Soc.* **2004**, *126*, 14054.

(232) (a) Lehn, J.-M. *Rep. Prog. Phys.* **2004**, *67*, 249. (b) Wu, A.; Isaacs, L. *J. Am. Chem. Soc.* **2003**, *125*, 4831. (c) Lehn, J.-M *Science* **2002**, *295*, 2400. (d) Hollingsworth, M. D. *Science* **2002**, *295*, 2410.

(233) (a) Zheng, Y. R.; Yang, H.-B.; Northrop, B. H.; Ghosh, K.; Stang, P. J. *Inorg. Chem.* **2008**, *47*, 4706. (b) Yang, H.-B.; Ghosh, K.; Northrop, B. H.; Stang, P. J. *Org. Lett.* **2007**, *9*, 1561. (c) Chi, K. W.; Addicott; C; Stang, P. J. *J. Am. Chem. Soc.* **2004**, *126*, 16569. (d) Addicott, C.; Das, N.; Stang, P. J. *Inorg. Chem.* **2004**, *43*, 5335. (e) Chi, K. W.; Addicott, C.; Moon, M. E.; Lee, H. J.; Yoon, S. C.; Stang, P. J. *J. Org. Chem.* **2006**, *71*, 6662. (f) Zhao, L.; Northrop, B. H.; Zheng, Y. R.; Yang, H.-B.; Lee, H. J.; Lee, Y. M.; Park, J. Y.; Chi, K. W.; Stang, P. J. *J. Org. Chem.* **2008**, *73*, 6580. (g) Zhao, L.; Northrop, B. H.; Stang, P. J. *J. Am. Chem. Soc.* **2008**, *130*, 11886.

(234) Inter alia: (a) Langner, A.; Tait, S. L.; Lin, N.; Rajadurai, C.; Ruben, M.; Kern, K. *Proc. Natl. Acad. Sci. U.S.A.* **2007**, *104*, 17927. (b) Saur, I.; Scopelliti, R.; Severin, K. *Chem.—Eur. J.* **2006**, *12*, 1058. (c) Kamada, T.; Aratani, N.; Ikeda, T.; Shibata, N.; Higuchi, Y.; Wakamiya, A.; Yamaguchi, S.; Kim, K. S.; Yoon, Z. S.; Kim, D.; Osuka, A. *J. Am. Chem. Soc.* **2006**, *128*, 7670. (d) Pinalli, R.; Cristini, V.; Sottili, V.; Geremia, S.; Campagnolo, M.; Caneschi, A.; Dalcanale, E. *J. Am. Chem. Soc.* **2004**, *126*, 6516. (e) Kondo, T.; Oyama, K.-I.; Yoshida, K. *Angew. Chem., Int. Ed.* **2001**, *40*, 894. (f) Albrecht, M.; Schneider, M.; Rötelle, H. *Angew. Chem., Int. Ed.* **1999**, *38*, 557. (g) Taylor, P. N.; Anderson, H. L. *J. Am. Chem. Soc.* **1999**, *121*, 11538. (h) Stiller, R.; Lehn, J.-M. *Eur. J. Inorg. Chem.* **1998**, 977. (i) Enemark, E. J.; Stack, T. D. P. *Angew. Chem., Int. Ed.* **1998**, *37*, 932. (j) Masood, M. A.; Enemark, E. J.; Stack, T. D. P. *Angew. Chem., Int. Ed.* **1998**, *37*, 928. (k) Caulder, D. L.; Raymond, K. N. *Angew. Chem., Int. Ed.* **1997**, *36*, 1440. (l) Krämer, R.; Lehn, J.-M; Marquis-Rigault, A. *Proc. Natl. Acad. Sci. U.S.A.* **1993**, *90*, 5394.

(235) Kay, E. R.; Leigh, D. A.; Zerbetto, F. *Angew. Chem., Int. Ed.* **2007**, *46*, 72.

(236) (a) Snyder, M. A.; Tsapatsis, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 7650. (b) Balzani, G.; Credi, A.; Venturi, M. *Chem.—Eur. J.* **2002**, *8*, 5525. (c) Seeman, N. C.; Belcher, A. M. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 6451. (d) Gates, B. G.; Xu, Q.; Stewart, M.; Ryan, D.; Wilson, C. G.; Whitesides, G. M. *Chem. Rev.* **2005**, *105*, 1171.

(237) Barth, J. V. *Annu. Rev. Phys. Chem.* **2007**, *58*, 375.

(238) Barth, J. V.; Constantini, G.; Kern, K. *Nature* **2005**, *437*, 671.

(239) Hooks, D. E.; Fritz, T.; Ward, M. D. *Adv. Mater.* **2001**, *13*, 227.

(240) Wang, D.; Wan, L. J. *J. Phys. Chem. C.* **2007**, *111*, 16109.

(241) Reviews: (a) Barlow, S. M.; Raval, R. *Surf. Sci. Rep.* **2003**, *50*, 201. (b) Wan, L. J. *Acc. Chem. Res.* **2006**, *39*, 334.

(242) Li, S. S.; Northrop, B. H.; Yuan, Q. H.; Wan, L. J.; Stang, P. J *Acc. Chem. Res.* **2009**, *42*, 000 in press.

(243) (a) Gong, J. R.; Wan, L. J.; Yuan, Q. H.; Bai, C. L.; Jude, H.; Stang, P. J. *Proc. Nat. Acad. Sci. U.S.A.* **2005**, *102*, 971. (b) Yuan, Q. H.; Wan, L. J.; Jude, H.; Stang, P. J. *J. Am. Chem. Soc.* **2005**, *127*, 16279. (c) Li, S. S.;

Yan, H. J.; Wan, L. J; Yang, H.-B.; Northrop, B. H.; Stang, P. J. *J. Am. Chem. Soc.* **2007**, *129*, 9268. (d) Yuan, Q. H.; Yan, C. J.; Wan, J. L.; Northrop, B. H.; Jude, H.; Stang, P. J. *J. Am. Chem. Soc.* **2008**, *130*, 8878.

(244) (a) Jeohn, K. S.; Shin, U.-S.; Kogej, M.; Hai, N. T. M.; Brockmann, P.; Jeong, N.; Krichner, B.; Reiher, M.; Schalley, C. *J. Am. Chem. Soc.* **2005**, *127*, 17672. (b) Menzonni, E.; Pinalli, R.; Speets, E. A.; Ravoo, B. J.; Dalcanale, E.; Reinhoudt, D. N. *Chem.—Eur. J.* **2004**, *10*, 2199. (c) Safurousky, C.; Merz, L.; Rang, A.; Brockman, P.; Hermann, B. A.; Schalley, C. A. *Angew. Chem., Int. Ed.* **2004**, *43*, 1291. (d) Semenau, A.; Spatz, J. P.; Möller, M.; Lehn, J.-M.; Sell, B.; Schubert, D.; Weidl, C. H.; Schubert, U. S. *Angew. Chem., Int. Ed.* **1999**, *38*, 2547.

(245) Review: Seidel, S. R.; Stang, P. J. *Acc. Chem. Res.* **2002**, *35*, 972.

(246) (a) Schweiger, M.; Yamamoto, T.; Stang, P. J.; Bläser, D.; Boese, R. *J. Org. Chem.* **2005**, *70*, 4861. (b) Leininger, S.; Fan, J.; Schmitz, M.; Stang, P. J. *Proc. Natl. Acad. Sci. U.S.A.* **2000**, *97*, 1380.

(247) Olenyuk, B.; Whiteford, J. A.; Fechtenkötter, A.; Stang, P. J. *Nature* **1999**, *398*, 796.

(248) Kuehl, C. J.; Yamamoto, T.; Seidel, S. R.; Stang, P. J. *Org. Lett.* **2002**, *4*, 913.

(249) (a) Radhakrishnan, U.; Schweiger, M.; Stang, P. J. *Org. Lett.* **2001**, *3*, 3141. (b) Kuehl, C. J.; Kryschenko, Y. K.; Radhakrishnan, U.; Seidel, S. R.; Huang, S. D.; Stang, P. J. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4932. (c) Kryschenko, Y. K.; Seidel, S. R.; Muddiman, D. C.; Nepo-mureno, A. I.; Stang, P. J. *J. Am. Chem. Soc.* **2003**, *125*, 9647. (d) Chi, K. W.; Addicott; C; Kryschenko, Y. K.; Stang, P. J. *J. Org. Chem.* **2004**, *69*, 964. (e) Mukherjee, P. S.; Das, N.; Stang, P. J. *J. Org. Chem.* **2004**, *69*, 3526. (f) Yang, H.-B.; Ghosh, K.; Das, N.; Stang, P. J. *Org. Lett.* **2006**, *8*, 3991. (g) Yang, H.-B.; Ghosh, K.; Arif, A. M.; Stang, P. J. *J. Org. Chem.* **2006**, *71*, 9464.

(250) (a) Olenyuk, B.; Levin, M. D.; Whiteford, J. A.; Shield, J. E.; Stang, P. J. *J. Am. Chem. Soc.* **1999**, *121*, 10434. (b) Levin, M. D.; Stang, P. J. *J. Am. Chem. Soc.* **2000**, *122*, 7428.

(251) (a) Yamauchi, Y.; Yoshizawa, M.; Fujita, M. *J. Am. Chem. Soc.* **2008**, *130*, 5832. (b) Yamaguchi, T.; Fujita, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 2067. (c) Nakabayashi, K.; Ozak, Y.; Kawano, M.; Fujita, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 2046. (d) Kikuchi, T.; Murase, T.; Sato, S; Fujita, M. *Supramol. Chem* **2008**, *20*, 81. (e) Yamashita, K.; Kawano, M.; Fujita, M. *Chem. Commun.* **2007**, 4102. (f) Suzuki, K.; Kawano, M.; Sato, S.; Fujita, M. *J. Am. Chem. Soc.* **2007**, *129*, 10652. (g) Nishioka, Y.; Yamaguchi, T.; Yoshizawa, M.; Fujita, M. *J. Am. Chem. Soc.* **2007**, *129*, 7000. (h) Suzuki, K.; Kawano, M.; Fujita, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 2819. (i) Kasai, K.; Fujita, M. *Chem.—Eur. J.* **2007**, *13*, 3089. (j) Kamija, N.; Tominaga, M.; Sato, S.; Fujita, M. *J. Am. Chem. Soc.* **2007**, *129*, 3816. (k) Ono, K.; Yoshizawa, M.; Kato, T.; Watanabe, K.; Fujita, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 1803. (l) Kobayashi, Y.; Kawano, M.; Fujita, M. *Chem Commun.* **2006**, 4377. (m) Tashiro, S.; Kobayashi, M.; Fujita, M. *J. Am. Chem. Soc.* **2006**, *128*, 9280. (n) Kawano, M.; Kobayashi, Y.; Ozeki, T.; Fujita, M. *J. Am. Chem. Soc.* **2006**, *128*, 6558. (o) Tashiro, S.; Tominaga, M.; Yamaguchi, Y.; Kato, K.; Fujita, M. *Chem.—Eur. J.* **2006**, *12*, 3211. (p) Yoshizawa, M.; Kumazawa, K.; Fujita, M. *J. Am. Chem. Soc.* **2005**, *127*, 13456. (q) Tominaga, M.; Suzuki, K.; Murase, T.; Fujita, M. *J. Am. Chem. Soc.* **2005**, *127*, 11950. (r) Nakabayashi, K.; Kawano, M.; Fujita, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 5322. (s) Yoshizawa, M.; Fujita, M. *Pure Appl. Chem.* **2005**, *77*, 1107.

(252) (a) Pluth, M. D.; Bergman, R. G.; Raymond, K. N. *J. Am. Chem. Soc.* **2008**, *130*, 6362. (b) Leung, D. H.; Bergman, R. G.; Raymond, K. N. *J. Am. Chem. Soc.* **2008**, *130*, 2798. (c) Davis, A. V.; Fiedler, D.; Ziegler, M.; Terpin, A.; Raymond, K. N. *J. Am. Chem. Soc.* **2007**, *129*, 15354. (d) Biros, S. M.; Bergman, R. G.; Raymond, K. N. *J. Am. Chem. Soc.* **2007**, *129*, 12094. (e) Pluth, M. D.; Bergman, R. G.; Raymond, K. N. *J. Am. Chem. Soc.* **2007**, *129*, 11459. (f) Pluth, M. D.; Bergman, R. G.; Raymond, K. N. *Science* **2007**, *316*, 85. (g) Leung, D. H.; Bergman, R. G.; Raymond, K. N. *J. Am. Chem. Soc.* **2006**, *128*, 9781. (h) Fiedler, D.; Bergman, R. G.; Raymond, K. N. *Angew. Chem., Int. Ed.* **2006**, *45*, 745. (i) Tiedemann, B. E. F.; Raymond, K. N. *Angew. Chem., Int. Ed.* **2006**, *45*, 83. (j) Davis, A. V.; Raymond, K. N. *J. Am. Chem. Soc.* **2005**, *127*, 7912. (k) Brumaghim, J. L.; Michels, M.; Pagliero, D.; Raymond, K. N. *Eur. J. Org. Chem.* **2004**, 5115. (l) Fiedler, D.; Leung, D. H.; Bergman, R. G.; Raymond, K. N. *J. Am. Chem. Soc.* **2004**, *126*, 3674.

(253) Reviews: (a) Moulton, B.; Zaworotko, M. J. *Chem. Rev.* **2001**, *101*, 1629. (b) Eddaouchi, M.; Moler, D. B.; Li, H.; Chen, B.; Reineke, T. M.; O'Keeffe, M.; Yaghi, O. M. *Acc. Chem. Res.* **2001**, *34*, 319. (c) Yaghi, O. M.; Li, H.; Davies, C.; Richardson, D.; Groy, T. L. *Acc. Chem. Res.* **1998**, *31*, 474.

(254) An indication of this is the nearly 1600 citations to date of our chemical review article,[223] published in 2000, and the nearly 700 citations to date of our *Acc. Chem. Res.* article,[200a] published in 1997, where we first described the directional bonding approach as summarized in Figure 2.

JO801682D