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Synthetic Approaches to Polypyridyl Bridging Ligands with Proximal Multidentate Binding Sites

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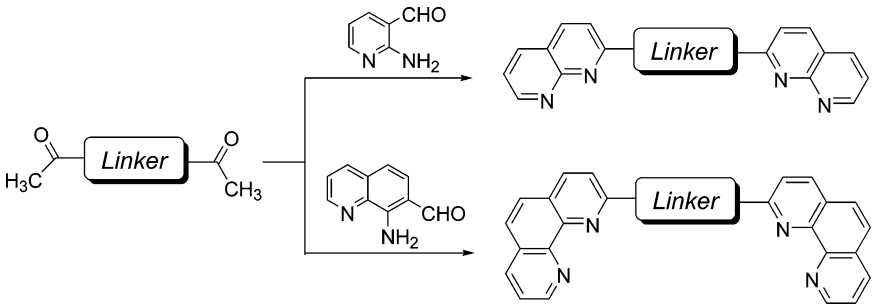

A series of 12 bridging ligands was prepared. These ligands include a central linker appended to two 1,8-naphthyrid-2-yl or two 1,10-phenanthrolin-2-yl units. The linkers include pyridazin-3,6-diyl, 1,8-naphthyrid-2,7-diyl, 2,2′-bipyrid-6,6′-diyl, 1,10-phenanthrolin-2,9-diyl, 1,2-di(2′-pyrid-6′-yl)ethyne, and 3,6-di(2′-pyrid-6′-yl)pyridazine. The ligands were synthesized from the diacetyl derivative of the central linker by a Friedländer condensation with either 2-aminonicotinaldehyde or 8-amino-7-quinolinecarbaldehyde. The precursor diacetyl derivatives were, in turn, prepared by pathways involving Stille and Sonogashira couplings. Examination of the electronic absorption spectra of the bridging ligands shows the strongest correlation to be between pairs of ligands having the same central linker. Complexation studies will follow.

Introduction

An increasingly important area of ligand design involves the synthesis and study of bridging ligands and their metal complexes.[1] Elaborate self-assembling supramolecular architectures have been constructed through the judicious utilization of bridging ligands which are predisposed to orient metals in a predictable fashion. Frequently these bridging ligands hold the metals apart from one another, often encouraging the formation of dendridic structures or linear arrays.[2] These supramolecules have been investigated for their bulk properties, including possible electrical conductivity and light harvesting.

If one considers bridging ligands found in nature, these often foster the aggregation of metal centers, bringing these centers closer together rather than holding them apart. As examples, one could consider the tetramanganese light-harvesting center of photosystem II[3] or the dinickel active site of urease.[4] Catalytic processes which may require the formation of intermediate mixed valence states or multielectron-transfer events make good use of such polymetallic clusters.

In connection with our interest in the design of potential photocatalysts for water decomposition, we became interested in the design and synthesis of bridging ligands which would hold two metals in proximal, well-defined sites. One example of such a bridging ligand is the dipyridyl pyrazole reported by Catalano and Craig,[5] which holds together two Ru(II) centers, providing a dinuclear complex which promotes the oxidation of water to dioxygen.[6] This system represents a structural improvement over the μ-oxo Ru(II) dimer reported by Meyer

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and co-workers which was one of the first examples of a potentially practical water decomposition catalyst.[7]

In earlier work, we have reported the preparation and coordination chemistry of a series of di-(1,10-phenanthrolin-2-yl) diazines which included the diphen pyridazine **7**.[8] In its syn conformation, this molecule presents two adjacent tridentate sites which could hold two metals in close proximity. With a view toward modifying the size, shape, and denticity of the binding pocket, we have undertaken the preparation of the series of bisbidentate, tridentate, and tetradentate bridging ligands **1**−**12** illustrated in Figure 1. These ligands consist of two terminal moieties, 1,8-naphthyridine (nap) or 1,10-phenanthroline (phen), connected by an intervening heteroaromatic species. In **1**−**5** and **7**−**11**, this species is a diaza-aromatic in which the separation between the nitrogens varies from one bond (**1**, **7**), to two bonds (**2**, **8**), to three bonds (**3**, **4**, **9**, **10**), to five bonds (**5**, **11**). Systems **6** and **12** have their terminal groups separated by a 3,6-di-(pyrid-2′-yl)pyridazine.

The target ligands are shown in their all-syn planar conformation, which would be the one providing the greatest interaction between two bound metal centers. Rotation about the single bond connecting the terminal nap or phen to the linker would provide other conformations of the ligand. Furthermore, six systems (**3**, **5**, **6**, **9**, **11**, **12**) have single bonds in the linker, which would afford additional conformational freedom.

The pyridazine **7** can be made by a unique approach that involved the conversion of 2-cyanophen (**21**) to a diphen-tetrazine intermediate that underwent a [4 + 2] cycloaddition with acetylene followed by the extrusion of dinitrogen.[8a] The overall yield for the three steps was low (14%) and the route is not generally applicable to other systems. In this paper, we consider several alternative approaches to such systems involving Stille or Sonogashira couplings and Friedländer condensations (Scheme 1). The relative merits of these different pathways is explored as is the preparation of some unique and synthetically important diacetyl heteroaromatic intermediates.

Two general approaches to the target ligands can be envisioned. One approach would involve coupling reactions such as the Stille coupling, which would append the phen or nap subunits onto the central bridge. A serious disadvantage to this approach is that coupling methodologies involve metal catalysts or reagents which give rise to metal cation byproducts. These cations are strongly complexed by the target ligands. The standard protocol for decomplexing the metals involves extraction with a stronger ligand such as cyanide.[9] However, for these multidentate, strongly binding systems, such methodology works poorly, at best. The approach which we prefer involves a final Friedländer condensation between the appropriate diacetyl-heteroaromatic system and 8-amino-7-quinolinecarbaldehyde (**20**).[10] This reaction is a double dehydration which does not involve any transition-metal cations and therefore avoids purification problems associated with coupling methodologies. The synthetic routes that we present to ligands **1**−**12** mainly concern access to the precursor diketones **13**−**18**. The subsequent Friedländer reactions of these species to provide the corresponding nap and phen derivatives generally proceed without difficulty (Figure 2).

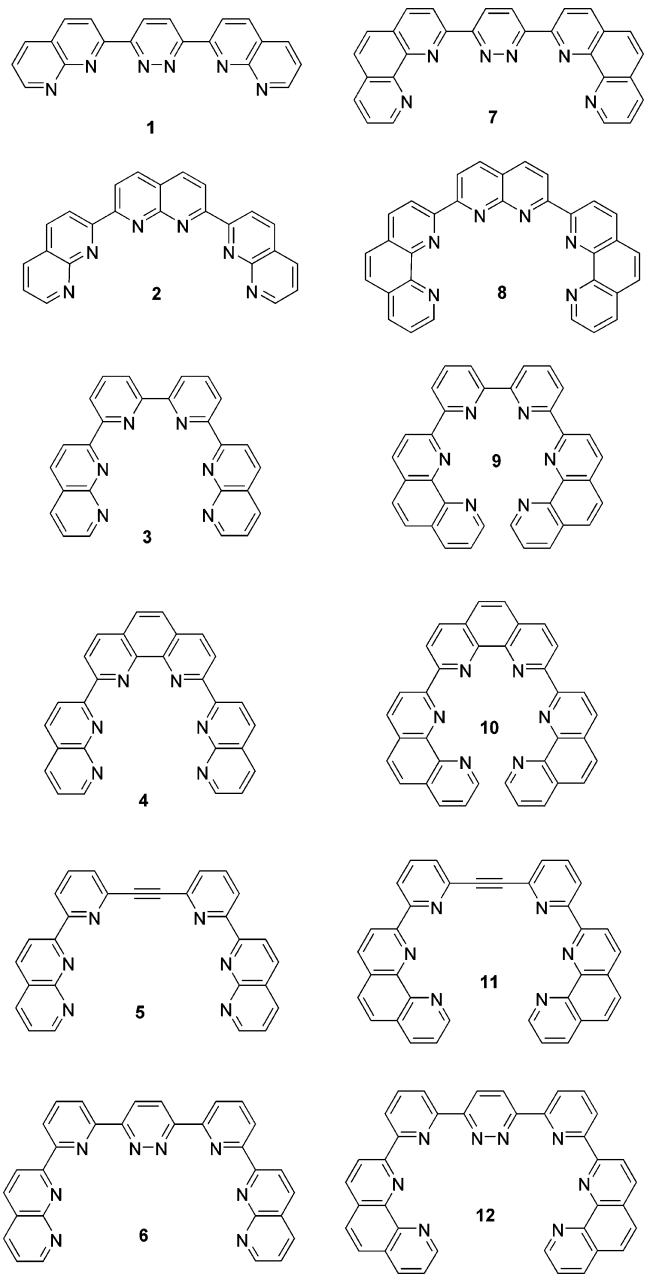

FIGURE 1. Target bridging ligands in their planar all-syn conformation.

Results and Discussion

In the case of ligand **7**, we were unable to efficiently prepare stannane derivatives of either 2-chlorophen (**22**)[11] or 3,6-dichloropyridazine (**23**). On the other hand, treatment of **23** with

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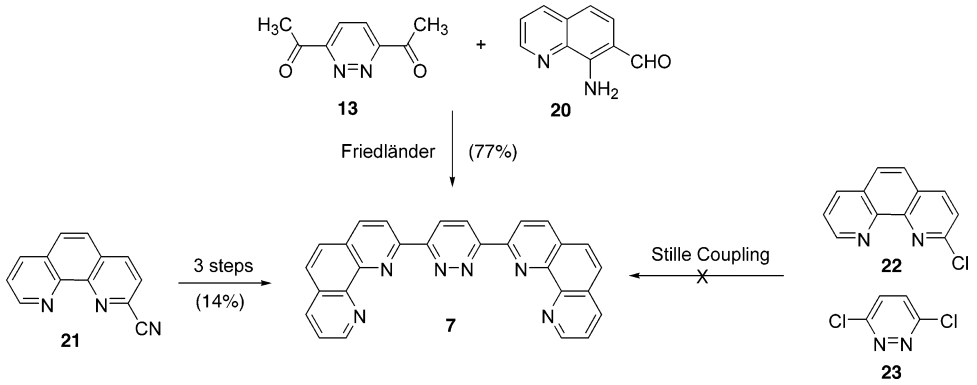
SCHEME 1. Synthetic Approaches to Bridging Ligand 7



tri-*n*-butyl-1-ethoxyvinylstannane provided the 3,6-di(1-ethoxy)-vinyl derivative which could be readily hydrolyzed to the corresponding 3,6-diacetylpyridazine (**13**).[12] Subsequent Friedländer reaction of this diketone with the quinoline aminoaldehyde **20** provided **7** in a much better yield than the previously reported tetrazine route (Scheme 1).

For the 1,8-naphthyridine-bridged ligands **2** and **8** as well as the 1,10-phenanthroline-bridged ligands **4** and **10**, the same approach was employed involving the initial conversion of either 2,7-dichloro-1,8-naphthyridine (**25**) or 2,9-dichloro-1,10-phenanthroline (**26**) to the corresponding diacetyl derivatives **14** and

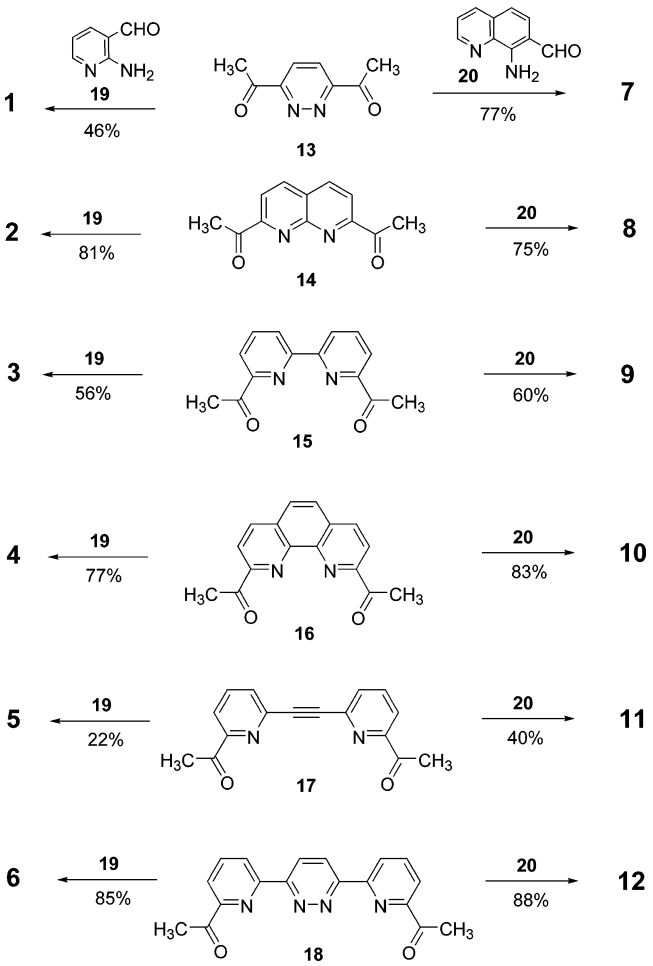
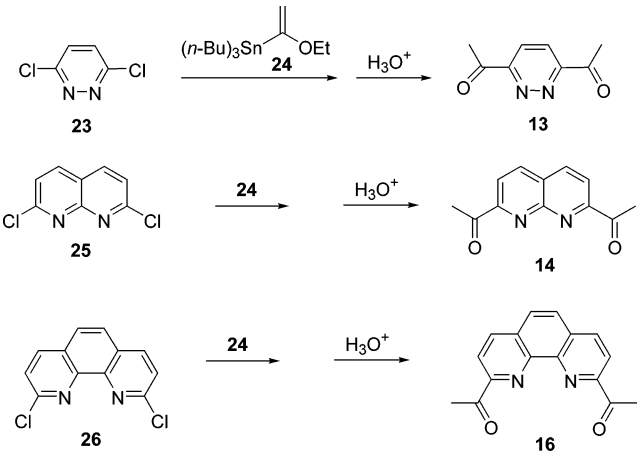


FIGURE 2. Friedländer reaction of diacetyl precursors leading to bridging ligands **1**−**12**.

SCHEME 2. Synthesis of Diacetyl Derivatives 13, 14, and 16



16. These species then underwent Friedländer condensations with **19** and **20** to provide ligands **2**, **8** and **4**, **10** respectively.

For the bipyridine-bridged systems **3** and **9**, the prerequisite diketone is 6,6′-diacetyl-2,2′-bipyridine (**15**). This diketone was prepared earlier by Potts and co-workers by the oxidative dimerization of 2,6-dibromopyridine followed by metalation of the remaining 6,6′-dibromo-substituents with *n*-BuLi and subsequent acetylation with *N*,*N*-dimethylacetamide.[13] We found that reversing the order of these steps was more convenient (Scheme 3). First 2,6-dibromopyridine was acetylated with *n*-BuLi and *N*,*N*-dimethylacetamide to give **28**.[14] The attempted conversion of this material to its stannane provided only 30% of **29** along with 57% of the desired diacetylbipyridine **15**. The stannane **29** was coupled with **23** to provide the diacetyldipyridyl-pyridazine **18** in 30% yield. A somewhat longer but more efficient route to **18** involved prior protection of the acetyl group of **28** as its ethylenedioxy ketal followed by stannylation to provide **30**. Coupling of this species with dichloropyridazine **23** followed by hydrolysis of the ketals gave the diketone **18**. Friedländer condensation of aminoaldehyde **19** with either **15** or **18** provided the bisnap derivatives **3** and **6** while a similar condensation with aminoaldehyde **20** provided the bisphen derivatives **9** and **12**.

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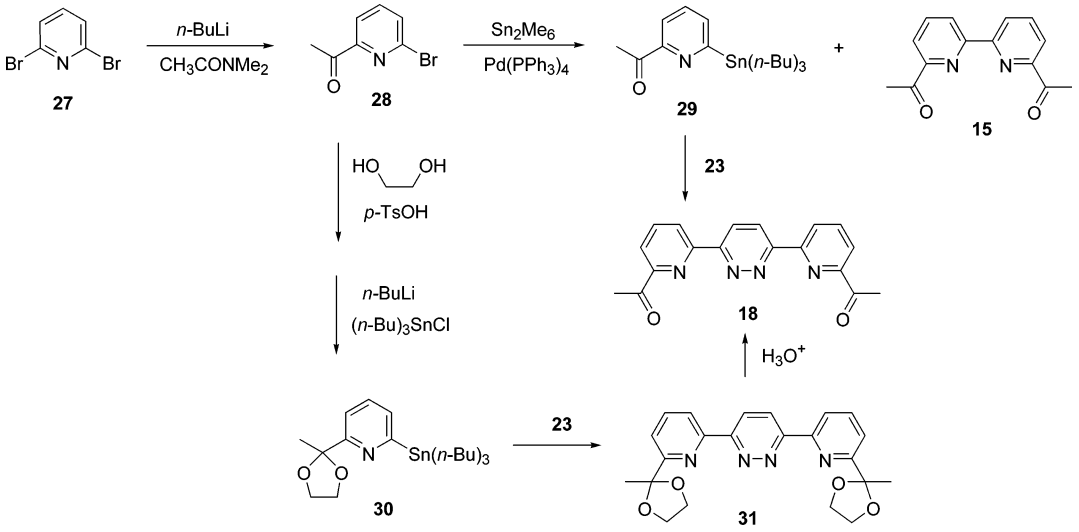
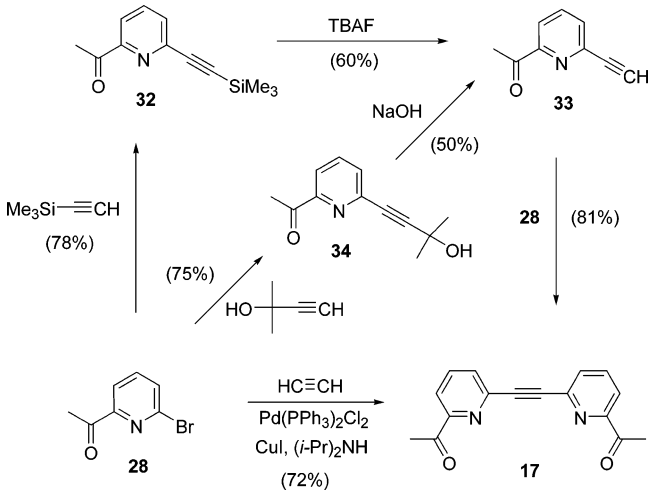
SCHEME 3. Synthesis of Diacetyl Derivatives 15 and 18



SCHEME 4. Synthesis of 1,2-Di(6′-acetylpyrid-2′-yl)ethyne (17)



The ethynyl-linked bridging ligand **11** was prepared by three different routes depending on the sequence of the Sonagashira coupling and condensation steps (Scheme 4). Direct coupling of the bromoketone **28** with acetylene provided a 72% yield of the diketone **17** which condensed in 40% yield with **20** to provide the bistridentate ligand **11**. The diketone **17** could also be prepared by the Sonogashira coupling of 6-ethynyl-2-acetylpyridine (**33**) with the bromoketone **28**. The prerequisite **33** was prepared from **28** through the intermediacy of either the trimethylsilylethynyl derivative **32** or the 3-hydroxy-3-methyl-1-butynyl derivative **34**. The Friedländer condensation of **17** with 2-aminonicotinaldehyde led to bisnap ligand **5**.

Alternatively, bromoketone **28** could be condensed with **20** to give 90% of the 2-(6′-bromopyrid-2′-yl)phen (**35**) which could be directly coupled with acetylene to give **11** in 15% yield. The same 6′-bromopyridylphen could also be converted to its 6′-ethynyl derivative **36** which could then be coupled with its precursor to afford **11** in 65% yield.

Properties of the Ligands. The most important property of the family of polypyridine ligands prepared in this work is their predicted ability to act as a bridging ligands by binding two or more metal atoms. Although it is possible for 1,8-naphthyridine to act as a chelating bidentate ligand,[15] for the 2-(pyrid-2′-yl)-1,8-naphthyridine motif found in systems **1**−**6**, it is far more likely that bidenate metal binding will involve N1 of naphthyridine and the pyridine (or pyridazine) nitrogen. This would leave one nitrogen of the naphthyridine uncomplexed and available to facilitate other chemistry such as pH dependent behavior or sensitized binding of analytes such as other metals. This property is being exploited in studies aimed at the photooxidation of water assisted by photosensitized intramolecular proton transfer.[16]

From a conformational point of view the freedom provided by the single and triple bonds in **1**−**12** can have interesting consequences. The molecules in Figure 1 are depicted in their all-syn planar conformations to emphasize potential cooperativity on metal binding. The free ligands in solution, however, more likely exist in conformations that would minimize H−H and nitrogen lone pair−lone pair repulsions about single bonds. Binding two metals will, in every case, restrict this rotational

SCHEME 5. Sonogashira routes to bridging ligand 11.

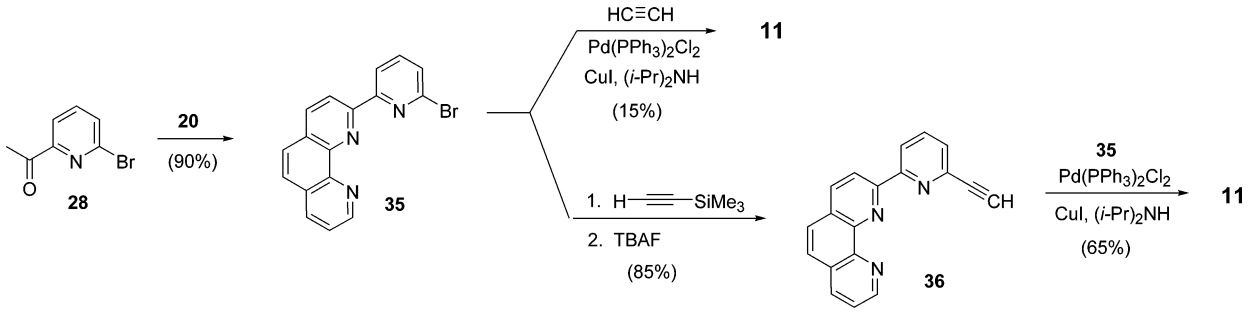


TABLE 1. Electronic Absorption Data for Ligands 1−12[a]

compound	λ_{max}, nm (ϵ, M^{-1} cm^{-1})
1	226 (22 300), 256 (24 500), 334 (30 540), 345 (31 060)
2	218 (26 260), 251 (39 220), 348 (32 110), 364 (33 140)
3	233 (42 180), 324 (21 590), 337 (21 090)
4	234 (51 810), 250 (46 920), 301 (24 930), 330 (33 880), 348 (40 150), 361 (36 720)
5	229 (45 590), 241 (44 090), 325 (33 880), 335 (32 000)
6	228 (51 470), 243 (53 980), 323 (50 020)
7	228 (42 520), 275 (28 400), 295 (30 200), 327 (27 950), 338 (29 160), 358 (28 590)
8	223 (43 170), 235 (53 450), 286 (46 910), 357 (37 220), 374 (39 540)
9	236 (78 070), 290 (47 620), 318 (45 840), 350 (9 820), 328 (27 350)
10	235 (72 240), 247 (64 450), 289 (52 710), 318 (34 520), 332 (36 300), 345 (37 040), 365 (37 310)
11	223 (61 540), 236 (82 630), 277 (55 880), 322 (53 010), 331 (52 230), 349 (11 640)
12	223 (58 580), 236 (76 390), 277 (52 880), 321 (54 980), 332 (51 820), 349 (12 560)

[a] Measured in 1.0×10^{-5} M CH_2Cl_2 solution.

freedom. Nevertheless, ligands such as **3**, **5**, **9**, and **11**, even with two bound metals, can still rotate about their central bond and thus modulate the interaction between the metal centers. Several of the prepared ligands have a variety of different denticities available. For example we have shown that **10** can act as a hexadentate with K^+ or a tris-bidentate with Cu^+.[17]

The spectroscopic and electronic properties of metal complexes derived from **1**−**12** will depend to a great extent on ligand structure. We have measured the electronic absorption properties for these systems and that data is compiled in Table 1. The strongest correlation that one finds in these data involves pairs of ligands having the same central linker between the terminal phen or nap moieties. Figure 3 compares systems having a nap linker (A) or a di-(pyrid-2-yl)acetylene linker (B). The spectra of the phen and nap derivatives are similar with the phen systems showing slightly higher absorbances. Also the phen systems show a third component at about 275−290 nm.

Future work will investigate the metal binding properties of these systems. Preliminary results indicate an interesting helical Cu(I) trimer from ligand **10**[17] and a Ru(II) dimer from ligand **6** that is very effective in water oxidation.[18]

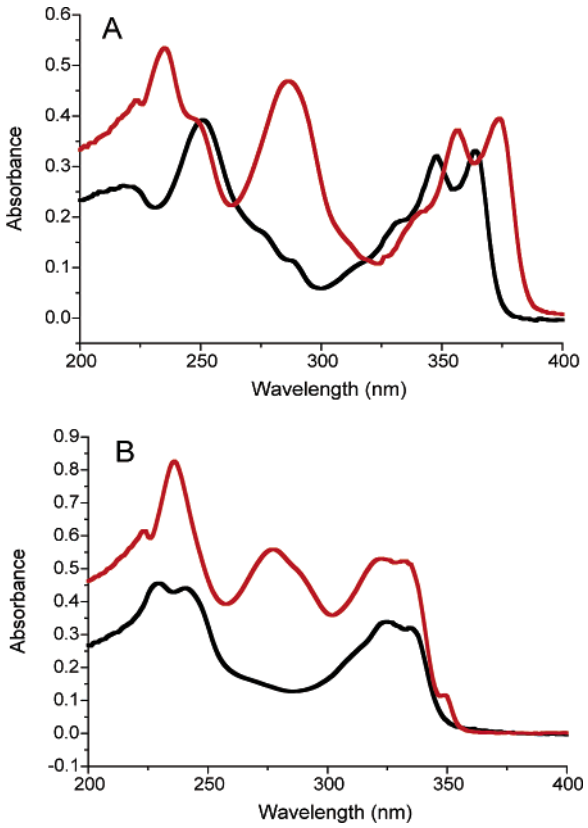


FIGURE 3. Electronic absorption spectra (10^{-5} M CH_2Cl_2). (A) **2**, black; **8**, red. (B) **5**, black; **11**, red.

Experimental Section

NMR spectra were recorded at 300 or 800 MHz for ^1H and 75 MHz for ^{13}C. Chemical shifts are reported in parts per million referenced to the solvent peak (7.26 and 77.0 in $CHCl_3$ for ^1H and ^{13}C respectively). The ligands **2**−**12** were too poorly soluble in common solvents for ^{13}C NMR. Melting points were obtained on a capillary melting point apparatus and are uncorrected. THF and diethyl ether were distilled from sodium, and DMF and dimethylacetamide were distilled from CaH_2. The 2-aminonicotinaldehyde (**19**),[19] 8-amino-7-quinolinecarbaldehyde (**20**),[10a] 2,7-dichloro-1,8-naphthyridine (**25**),[20] 2,9-dichloro-1,10-phenanthroline (**26**),[11] 6-(1′,1′-ethylenedioxyethyl)-2-bromopyridine,[21] 1-ethoxyethenyl-tri-*n*-butylstannane (**24**),[22] $Pd(PPh_3)_2Cl_2$,[23] and $Pd(PPh_3)_4$[24] were prepared according to literature procedures. For the combustion analyses, it is not unusual for strong polydentate chelators to retain water even after rigorous drying.

3,6-Bis-(1′-ethoxyvinyl)pyridazine.[12] Bis(triphenylphosphine)-palladium chloride (436 mg, 0.62 mmol), 1-ethoxyethenyl-tri-*n*-butylstannane (**24**, 5.15 g, 14.3 mmol), 3,6-dichloropyridazine (**23**, 997 mg, 6.69 mmol), and DMF (14 mL) were combined in a 50-mL round-bottom flask. The reaction mixture was stirred at 80 °C under Ar for 18 h. The resulting dark solution was poured into a flask containing KF (2.8 g) in water (20 mL). Diethyl ether (35 mL) was then added, and the mixture was stirred vigorously for 15 min, filtered, and the solid washed well with diethyl ether. The organic phase was collected, washed with water, dried over Na_2-

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SO_4, and concentrated under vacuum. The residue was purified by chromatography on silica eluting with hexanes/ethyl acetate (85:15) to afford an orange oil (880 mg, 60%): ^{1}H NMR ($CDCl_3$) δ 7.73 (s, 2H), 5.73 (d, 2H, J = 2.4 Hz), 4.43 (d, 2H, J = 2.4 Hz), 3.94 (q, 4H, J = 6.9 Hz), 1.39 (t, 6H, J = 6.9 Hz).

3,6-Diacetyl-pyridazine (13).[12] In acetone (3 mL) was dissolved 3,6-bis-(1′-ethoxyvinyl)-pyridazine (620 mg, 2.82 mmol) and hydrochloric acid (2 M, 1.8 mL). The solution was stirred overnight at room temperature. The resulting precipitate was collected, washed with water, and dried under vacuum at 50 °C. A light-yellow solid (370 mg, 80%) was obtained, mp 151−152 °C (lit.[12] mp 150.4−150.8 °C): ^{1}H NMR ($CDCl_3$) δ 8.26 (s, 2H), 2.94 (s, 6H).

3,6-Di-(1′,8′-naphthyrid-2′-yl)pyridazine (1). A suspension of 3,6-diacetylpyridazine (**13**, 29 mg, 0.18 mmol), 2-aminonicotinaldehyde (**19**, 57 mg, 0.53 mmol), EtOH (2.5 mL), and pyrrolidine (0.1 mL) was refluxed under Ar for 15 h. Additional **19** (19 mg, 0.18 mmol) was added and the solution was refluxed for 5 h. The solvent was removed in vacuo, and the residue was purified by chromatography on alumina eluting with MeOH/CH_2Cl_2 (1:20). Further purification by recrystallization from CH_2Cl_2 yielded a yellow solid (27 mg, 46%), mp > 270 °C: ^{1}H NMR ($CDCl_3$) δ 9.23 (s, 2H), 9.21 (dd, J = 1.8, 3.9 Hz, 2H), 9.07 (d, J = 8.4 Hz, 2H), 8.45 (d, J = 8.1 Hz, 2H), 8.31 (dd, J = 2.1, 8.4 Hz, 2H), 7.58 (dd, J = 4.2, 8.1 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 172.8, 158.3, 156.5, 155.8, 138.4, 137.1, 126.7, 123.5, 122.8, 120.3; MS (ESI) m/z 337 $(M + 1)^+$. Anal. Calcd for $C_{20}H_{12}N_6 \cdot 0.25H_2O$: C, 70.48; H, 3.67; N, 24.67. Found: C, 70.69; H, 3.50; N, 24.48.

2,2′:7′,2″-Ter[1,8]naphthyridine (2). A solution of 2,7-diacetyl-1,8-naphthyridine (**14**, 37 mg, 0.17 mmol), 2-aminonicotinaldehyde (45 mg, 0.37 mmol) in ethanol (10 mL), and a saturated solution of KOH in ethanol (0.3 mL) was refluxed overnight. The precipitate was collected and washed with ethanol and ether to give a beige solid (54 mg, 81%), mp > 280 °C: ^{1}H NMR ($CDCl_3$ + CH_3OD) δ 9.20 (dd, J = 2.1, 4.2 Hz, 2H), 9.18 (d, J = 8.4 Hz, 2H), 9.12 (d, J = 8.1 Hz, 2H), 8.53−8.49 (m, 4H), 8.43 (dd, J = 1.5, 7.8 Hz, 2H), 7.66 (dd, J = 4.5, 7.8 Hz, 2H); MS (ESI) m/z 387 $(M + 1)^+$. Anal. Calcd for $C_{24}H_{14}N_6 \cdot 1.5H_2O$: C, 69.73; H, 4.11; N, 20.33. Found: C, 69.76; H, 3.89; N, 19.68.

6,6′-Di-(1″,8″-naphthyrid-2″-yl)-2,2′-bipyridine (3). A suspension of 6,6′-diacetyl-2,2′-bipyridine (**15**, 50 mg, 0.21 mmol), 2-aminonicotinaldehyde (**19**, 62 mg, 0.57 mmol), EtOH (2.5 mL), and pyrrolidine (0.1 mL) was refluxed under Ar for 23 h. The suspension was filtered, and the residue was washed with EtOH (10 mL). Recrystallization of the residue from $CHCl_3/Et_2O$ (1:1) afforded a yellow solid (48 mg, 56%), mp > 300 °C: ^{1}H NMR ($CDCl_3$) δ 9.22 (dd, J = 1.5, 3.6 Hz, 2H), 9.06 (d, J = 8.7 Hz, 2H), 8.97 (dd, J = 0.9, 7.8 Hz, 2H), 8.80 (d, J = 7.8 Hz, 2H), 8.44 (d, J = 8.4 Hz, 2H), 8.36 (dd, J = 0.9, 8.1 Hz, 2H), 8.12 (t, J = 7.8 Hz, 2H), 7.60 (dd, J = 3.9, 7.8 Hz, 2H); MS (ESI) m/z 413 $(M)^+$.

2,9-Di-(1′,8′-naphthyrid-2′-yl)-1,10-phenanthroline (4). To a suspension of 2,9-diacetyl-1,10-phenanthroline (**16**, 166 mg, 0.63 mmol) and 2-aminonicotinaldehyde (156 mg, 1.28 mmol) in absolute ethanol (15 mL) at 80 °C was added KOH (100 mg) in ethanol (2 mL). The mixture immediately turned red and the resulting solution was refluxed overnight. After cooling to room temperature, the precipitate was collected and washed with ethanol (95%), absolute ethanol, and ether to afford a gray solid (211 mg, 77%), mp > 280 °C: ^{1}H NMR ($CDCl_3$ + CH_3OD) δ 9.39 (d, J = 8.7 Hz, 2H), 9.22 (d, J = 8.7 Hz, 2H), 9.13 (dd, J = 4.2, 1.8 Hz, 2H), 8.53 (d, J = 9.3 Hz, 2H), 8.50 (d, J = 8.1 Hz, 2H), 8.34 (dd, J = 8.7, 1.8 Hz, 2H), 7.93 (s, 2H), 7.57 (dd, J = 8.7, 4.2 Hz, 2H); MS (ESI) m/z 437 $(M + 1)^+$. Anal. Calcd for $C_{28}H_{16}N_6 \cdot H_2O$: C, 76.02; H, 3.77; N, 19.00. Found: C, 76.05; H, 3.53; N, 18.85.

1,2-Di[6′-(1″,8″-naphthyrid-2″-yl)pyrid-2′-yl]ethyne (5). A suspension of 1,2-di(6′-acetylpyrid-2′-yl)ethyne (**17**, 152 mg, 0.57 mmol), 2-aminonicotinaldehyde (**19**, 159 mg, 1.49 mmol), EtOH (9 mL), CH_2Cl_2 (3 mL), and pyrrolidine (0.3 mL) was stirred at 25 °C for 3 days. The suspension was filtered, and the residue was washed with EtOH (5 mL). Recrystallization of the residue from $CHCl_3/Et_2O$ (1:1) afforded a beige solid (55 mg, 22%), mp > 300 °C: ^{1}H NMR ($CDCl_3$) δ 9.18 (dd, J = 2.1, 4.2 Hz, 2H), 8.92 (dd, J = 0.9, 8.1 Hz, 2H), 8.91 (d, J = 8.1 Hz, 2H), 8.37 (d, J = 8.7 Hz, 2H), 8.27 (dd, J = 1.8, 7.8 Hz, 2H), 7.96 (t, J = 7.5 Hz, 2H), 7.78 (dd, J = 0.9 Hz, 7.8 Hz, 2H), 7.54 (dd, J = 4.2, 8.1 Hz, 2H); MS (ESI) m/z 437 $(M)^+$, 495 $(M + 58)^+$. Anal. Calcd for $C_{28}H_{16}N_6 \cdot 0.75\ H_2O$: C, 74.74; H, 3.92; N, 18.68. Found: C, 74.75; H, 3.38; N, 18.40.

3,6-Di-(6′-[1″,8″-naphthyrid-2″-yl]-pyridin-2′-yl)pyridazine (6). A suspension of 3,6-di-(6′-acetylpyrid-2′-yl)pyridazine (**18**, 55 mg, 0.17 mmol), 2-aminonicotinaldehyde (52 mg, 0.43 mmol), and saturated ethanolic KOH (0.3 mL) in absolute ethanol (15 mL) was refluxed for 24 h. The resulting mixture was concentrated to about 3 mL, water (3 mL) was added, and the precipitate was filtered and washed with ethanol (2 mL) and ether (2 mL) to afford an off-white solid (72 mg, 85%), mp > 300 °C: ^{1}H NMR ($CDCl_3$ + CH_3OD) δ 9.15 (dd, J = 4.2, 2.4 Hz, 2H), 8.98−8.91 (m, 6H), 8.86 (d, J = 8.1 Hz, 2H), 8.40 (dd, J = 8.7 Hz, 2H), 8.30 (dd, J = 8.1, 1.5 Hz, 2H), 8.14 (t, J = 8.1 Hz, 2H), 7.55 (dd, J = 8.1, 4.2 Hz, 2H); MS (ESI) m/z 491 $(M + 1)^+$. Anal. Calcd for $C_{30}H_{18}N_8 \cdot H_2O$: C, 70.86; H, 3.96; N, 22.03. Found: C, 70.49; H, 3.66; N, 21.86.

3,6-Di-(1′,10′-phenanthrolin-2′-yl)pyridazine (7).[8] To a stirred solution of **13** (308 mg, 1.88 mmol) and 8-amino-7-quinolinecarbaldehyde (800 mg, 4.64 mmol) in ethanol (10 mL) was added pyrrolidine (0.4 mL). The reaction was heated at reflux for 30 h under Ar. The resulting precipitate was filtered, washed with ethanol, and dried to give a light-orange solid (634 mg, 77%), mp >260 °C: ^{1}H NMR ($CDCl_3$) δ 9.36 (s, 2H), 9.31 (dd, 2H, J = 1.5 Hz, 4.5 Hz), 9.12 (d, 2H, J = 8.4 Hz), 8.51 (d, 2H, J = 8.4 Hz) 8.33 (dd, 2H, J = 8.4, 1.5 Hz), 7.91 (AB pattern, 4H, J = 9.0 Hz), 7.72 (dd, 2H, J = 8.4 Hz, 4.5 Hz), identical to material prepared previously.[8]

2,7-Di-(1′,10′-phenanthrolin-2′-yl)-1,8-naphthyridine (8). A mixture of 2,7-diacetyl-1,8-naphthyridine (36 mg, 0.168 mmol), 8-amino-7-quinolinecarbaldehyde (58 mg, 0.337 mmol), and pyrrolidine (0.3 mL) in ethanol (20 mL) was refluxed for 18 h. The solvents were evaporated, and the residue was purified by chromatography on alumina eluting with CH_2Cl_2 followed by CH_2Cl_2-EtOAc (95:5) to afford **8** (62 mg, 75%), mp > 270 °C: ^{1}H NMR ($CDCl_3$) δ 9.42 (d, J = 8.7 Hz, 1H), 9.35 (d, J = 8.1 Hz, 1H), 9.32 (dd, J = 4.5, 1.8 Hz, 1H), 8.53 (d, J = 8.4 Hz, 1H), 8.52 (d, J = 8.1 Hz, 1H), 8.35 (dd, J = 7.8, 1.8 Hz, 1H), 7.91 (AB, 2H), 7.72 (dd, J = 7.5, 4.2 Hz, 1H); MS (ESI) m/z 487 $(M + 1)^+$. Anal. Calcd for $C_{32}H_{18}N_6$-1.5 H_2O: C, 74.85; H, 4.09; N, 16.37. Found: C, 74.30; H, 3.83; N, 16.22.

6,6′-Di-(1″,10″-phenathrolin-2″-yl)-2,2′-bipyridine (9). A mixture of 6,6′-diacetyl-2,2′-bipyridine (92 mg, 0.38 mmol) and 8-amino-7-quinolinecarbaldehyde (134 mg, 0.78 mmol) in absolute ethanol (15 mL) and pyrrolidine (0.3 mL) was heated at 80 °C for 15 h to produce a precipitate. The solid was collected, washed with ethanol (5 mL) and ether (5 mL), and dried to afford a beige powder (118 mg, 60%), mp > 310 °C: ^{1}H NMR (800 MHz, DMSO-d_6) δ 9.24 (broad, 2H), 9.10 (broad, 2H), 9.00 (broad, 2H), 8.91 (broad, 2H), 8.76 (broad, 2H), 8.58 (broad, 2H), 8.38 (broad, 2H), 8.13 (broad, 2H), 8.10 (broad, 2H), 7.87 (broad, 2H); MS (ESI) m/z 377 $(M - 135)^+$, 513 $(M + 1)^+$. Anal. Calcd for $C_{34}H_{20}N_6 \cdot 0.5\ H_2O$: C, 78.31; H, 4.03; N, 16.12. Found: C, 77.73; H, 3.91; N, 15.67.

2,2′:9′,2″-Ter[1,10]phenanthroline (10).[17] A mixture of 2,9-diacetyl-1,10-phenanthroline (31.5 mg, 0.12 mmol), 8-amino-7-quinolinecarbaldehyde (45 mg, 0.26 mmol), and pyrrolidine (0.30 mL) in absolute ethanol (10 mL) was refluxed under Ar for 40 h. The precipitate was collected, washed with ethanol, and dried under vacuum to afford a beige solid (53 mg, 83%), mp > 300 °C: ^{1}H NMR (DMSO-d_6): δ 9.48 (d, J = 8.1 Hz, 2H), 9.32 (d, J = 8.1 Hz, 2H), 9.24 (dd, J = 4.5, 1.5 Hz, 2H), 8.88 (d, J = 8.4 Hz, 2H), 8.84 (d, J = 8.4 Hz, 2H), 8.58 (dd, J = 8.1, 1.5 Hz, 2H), 8.20 (s,

2H), 8.14 (AB, 4H), 7.86 (dd, J = 8.1, 4.5 Hz, 2H); MS (ESI) m/z 537 $(M + 1)^+$, 559 $(M + Na)^+$. Anal. Calcd for $C_{36}H_{20}N_6 \cdot 2H_2O$: C, 75.51; H, 4.22; N, 14.68. Found: C, 76.02; H, 4.14; N, 14.77.

1,2-Di-[(6′-(1″,10″-phenanthrolin-2″-yl))pyrid-2′-yl)]ethyne (11). Method A: To a stirred solution of **17** (57 mg, 0.22 mmol) and 8-amino-7-quinolinecarbaldehyde (116 mg, 0.67 mmol) in ethanol (4 mL) was added pyrrolidine (0.45 mL). The reaction was heated to 70−80 °C for 24 h under Ar. The resulting precipitate was filtered, washed with ethanol, and dried to give a gray solid (45 mg, 40%), mp > 300 °C: ^{1}H NMR ($CDCl_3$) δ 9.30 (dd, 2H, J = 1.8 Hz, 4.5 Hz), 9.12 (d, 2H, J = 8.1 Hz), 8.98 (d, 2H, J = 8.7 Hz), 8.44 (d, 2H, J = 8.7 Hz), 8.34 (dd, 2H, J = 1.8 Hz, 8.1 Hz), 7.99 (dd, 2H, J = 8.1 Hz), 7.87 (AB pattern, 4H, J = 9.0 Hz), 7.78 (dd, 2H, J = 0.9 Hz, 8.1 Hz), 7.71 (dd, 2H, J = 4.5 Hz, 8.1 Hz); MS (ESI) m/z 537 $(M + 1)^+$, 559 $(M + Na)^+$. Anal. Calcd for $C_{36}H_{20}N_6 \cdot 0.5\ H_2O$: C, 79.18; H, 3.84; N, 15.39. Found: C, 79.09; H, 3.29; N, 15.26.

Method B: To a degassed solution of **35** (398 mg, 1.18 mmol) and **36** (303 mg, 1.08 mmol) in THF (30 mL) were added CuI (22 mg, 0.11 mmol), $Pd(PPh_3)_2Cl_2$ (42 mg, 0.060 mmol), and $(i\text{-Pr})_2NH$ (1.2 mL). The reaction mixture was heated at reflux overnight under Ar. The resulting precipitate was collected and purified by chromatography on alumina, eluting with CH_2Cl_2/CH_3OH (95:5) to give a light-orange solid. The solid was washed well with hexanes to obtain **11** (378 mg, 65%), mp > 300 °C: ^{1}H NMR ($CDCl_3$) identical to the material obtained by method A.

Method C: Into an Ar-degassed solution of **35** (170 mg, 0.506 mmol), CuI (12 mg, 0.063 mmol), $Pd(PPh_3)_2Cl_2$ (23 mg, 0.033 mmol), and $(i\text{-Pr})_2NH$ (0.38 mL) in THF (30 mL) was bubbled acetylene gas at 60 °C for 3 h. The acetylene bubbling was stopped and another portion of **35** (99 mg, 0.295 mmol) was added to the reaction. The dark solution was heated to reflux overnight, and then the solvent was removed in vacuo. The crude material was purified by chromatography (silica, CH_2Cl_2/ CH_3OH, 95:5) to give a light-orange solid. The solid was washed well with hexanes to provide **11** (25 mg, 11%), mp > 300 °C: ^{1}H NMR ($CDCl_3$) identical to the material obtained by method A.

3,6-Di-(6′-(1″,10″-phenanthrolin-2″-yl)pyrid-2′-yl)-pyridazine (12). A suspension of **18** (66 mg, 0.206 mmol), 8-amino-7-quinolinecarbaldehyde (71 mg, 0.412 mmol), and KOH (50 mg) in absolute ethanol (15 mL) was heated at 80 °C for 24 h. The mixture was concentrated to about 3 mL, and water (5 mL) was added. The precipitate was collected, washed with water (2 mL), and ethanol (2 mL) and dried to give **12** (108 mg, 88%), mp > 270 °C: ^{1}H NMR ($CDCl_3$) δ 9.27 (d, J = 8.1 Hz, 2H), 9.15 (dd, J = 5.6, 1.8 Hz, 2H), 9.00 (d, J = 8.7 Hz, 2H), 8.94 (s, 2H), 8.41 (d, J = 8.7 Hz, 2H), 8.29 (dd, J = 7.8, 1.8 Hz, 2H), 8.17 (t, J = 7.5 Hz, 2H), 7.84 (AB, 4H), 7.67 (dd, J = 8.7, 4.5 Hz, 2H); MS (ESI) m/z 513 $(M - 77)^+$, 591 $(M + 1)^+$. Anal. Calcd for $C_{38}H_{22}N_8 \cdot 2H_2O$: C, 72.84; H, 4.15; N, 17.89. Found: C, 72.39; H, 3.70; N, 17.40.

2,7-Diacetyl-1,8-naphthyridine (14). A mixture of 2,7-dichloro-1,8-naphthyridine (**25**, 400 mg, 2.0 mmol), 1-ethoxyethenyl tri-*n*-butylsyannane (**24**, 1.5 g, 4.11 mmol), $Pd(PPh_3)_2Cl_2$ (125 mg, 0.18 mmol), and DMF (5 mL) was heated at 80 °C for 70 h to afford a red solution. The solution was poured into an aqueous solution of KF (3.5 g, 25 mL). The precipitate was filtered and washed with ether. The filtrate was extracted with ether (3 × 30 mL). The combined organic extracts were dried over $MgSO_4$, treated with charcoal, and concentrated. Chromatography of the crude product on alumina eluting with CH_2Cl_2 gave 2,7-di-(1′-ethoxylethenyl)-1,8-naphthyridine as an oil (290 mg, 54%): ^{1}H NMR ($CDCl_3$) δ 8.05 (d, J = 8.1 Hz, 2H), 7.82 (d, J = 8.1 Hz, 2H), 5.80 (d, J = 2.1 Hz, 2H), 4.47 (d, J = 2.1 Hz, 2H), 3.95 (m, 4H), 1.41 (t, J = 6.9 Hz, 6H). Without further purification, this material (270 mg, 1.0 mmol) was dissolved in acetone (10 mL) and mixed with aqueous HCl (2 N, 3 mL) at room temperature. After stirring overnight, the solvent was evaporated and the residue was extracted with CH_2Cl_2 (15 mL). The extract was washed with water (20 mL) and dried over $MgSO_4$. Chromatography of the crude product (210 mg) on alumina eluting with CH_2Cl_2−EtOAc (95:5) afforded a colorless solid (155 mg, 72%), mp 136−140 °C: ^{1}H NMR ($CDCl_3$) δ 8.31 (d, J = 8.7 Hz, 2H), 8.17 (d, J = 8.7 Hz, 2H), 2.84 (s, 6H); ^{13}C NMR ($CDCl_3$): δ 199.6, 156.4, 153.9, 138.1, 126.0, 120.3, 25.7. Anal. Calcd for $C_{12}H_{10}N_2O_2 \cdot 0.25\ H_2O$: C, 65.90; H, 4.80; N, 12.81. Found: C, 66.22; H, 4.94; N, 12.22.

2,9-Diacetyl-1,10-phenanthroline (16).[17] A suspension of 2,9-dichloro-1,10-phenanthroline (1.0 g, 4.0 mmol), 1-ethoxyethenyl tri-*n*-butylsyannane (**24**, 3.0 g, 8.3 mmol), and $Pd(PPh_3)_2Cl_2$ (250 mg, 0.36 mmol) in DMF (10 mL) was stirred at 80 °C for 60 h to give a dark-red suspension. The mixture was poured into a KF solution (7.0 g in 50 mL of water) and a gray precipitate was obtained. Et_2O was added to extract the product. CH_2Cl_2 (60 mL) was added to the ether extract, and the mixture was washed with water (2 × 60 mL) and dried over Na_2SO_4. Chromatography on alumina eluting with hexanes−ether (10:1 to 5:1) afforded 2,9-di-(1′-ethoxyvinyl)-1,10-phenanthroline as a colorless solid (888 mg, 69%), mp 140−141 °C: ^{1}H NMR ($CDCl_3$) δ 8.20 (d, J = 8.1 Hz, 2H), 8.05 (d, J = 8.4 Hz, 2H), 7.69 (s, 2H), 6.07 (d, J = 1.8 Hz, 2H), 4.57 (d, J = 1.5 Hz, 2H), 4.07 (q, J = 6.9 Hz, 4H), 1.50 (t, J = 6.9 Hz, 6H). ^{13}C NMR ($CDCl_3$) δ 158.5, 153.4, 145.3, 136.4, 128.4, 126.0, 118.7, 86.4, 63.6, 14.6.

A solution of 2,9-di-(1′-ethoxyvinyl)-1,10-phenanthroline (888 mg, 2.77 mmol) in acetone (10 mL) and HCl (15 mL, 2 M) was stirred for 20 h at room temperature. Solvents were removed, and the residue was treated with CH_2Cl_2 (20 mL) and water (20 mL). The organic phase was washed with an aqueous solution of $NaHCO_3$ (10 mL) and water (10 mL) and dried over $MgSO_4$. The residue from evaporation of the organic phase was purified by chromatography on alumina eluting with CH_2Cl_2 to afford **16** (400 mg, 55%), mp 251−252 °C: ^{1}H NMR ($CDCl_3$) δ 8.37 (s, 4H), 7.91 (s, 2H), 3.06 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 200.4, 153.1, 145.1, 137.2, 130.8, 128.4, 120.5, 25.5; IR (ATR, cm^{-1}) $\nu_{C=O}$ 1690. Anal. Calcd for $C_{16}H_{12}N_2O_2$: C, 72.72; H, 4.58; N, 10.60. Found: C, 72.35; H, 4.61; N, 10.44.

1,2-Di-(6′-acetylpyrid-2′-yl)ethyne (17). Method A: To a degassed solution of **28** (100 mg, 0.5 mmol) and **33** (65 mg, 0.45 mmol) in THF (16 mL) were added CuI (9.5 mg, 0.05 mmol), $Pd(PPh_3)_2Cl_2$ (17.5 mg, 0.025 mmol), and $(i\text{-Pr})_2NH$ (0.25 mL). The reaction mixture was heated at reflux overnight, and then the solvent was removed in vacuo. The crude material was purified by chromatography on silica eluting with CH_2Cl_2 to give a red solid (96 mg, 81%), mp 179−182 °C: ^{1}H NMR ($CDCl_3$) δ 8.04 (dd, 2H, J = 7.8, 1.5 Hz), 7.88 (dd, 2H, J = 7.8 Hz), 7.80 (dd, 2H, J = 7.8, 1.5 Hz), 2.77 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 199.8, 154.1, 142.0, 137.4, 131.2, 121.6, 87.9, 26.1.

Method B: Into an Ar-degassed solution of **28** (130 mg, 0.65 mmol), CuI (12 mg, 0.063 mmol), $Pd(PPh_3)_2Cl_2$ (23 mg, 0.033 mmol), and $(i\text{-Pr})_2NH$ (0.38 mL) in THF (25 mL) was bubbled acetylene gas at room temperature. After 3 h, the acetylene bubbling was stopped and another portion of **28** (100 mg, 0.5 mmol) was added to the reaction. The dark solution was heated to reflux overnight, and then the solvent was removed in vacuo. The crude material was purified by chromatography on silica eluting with CH_2Cl_2 to give a red solid (110 mg, 72%), mp 179−182 °C: ^{1}H and ^{13}C NMR were identical to those of material prepared by method A. Anal. Calcd for $C_{16}H_{12}N_2O_2$: C, 72.72; H, 4.58; N, 10.60. Found: C, 72.12; H, 4.30; N, 10.43.

3,6-Di-(6′-acetylpyrid-2′-yl)pyridazine (18). Method A: A mixture of **29** (644 mg, 2.2 mmol), 3,6-dichloropyridazine (**23**, 80 mg, 0.53 mmol), $Pd(PPh_3)_4$ (98 mg, 0.085 mmol), and 1,2-dimethoxyethane (10 mL) was heated at 80 °C for 2 days. After evaporation of the solvent, the oily red residue was purified by chromatography on alumina, eluting with CH_2Cl_2 to afford **18** (50 mg, 30%), mp 269−270 °C: ^{1}H NMR ($CDCl_3$) δ 8.97 (dd, J = 7.8, 1.2 Hz, 2H), 8.83 (s, 2H), 8.17 (dd, J = 7.8, 1.2 Hz, 2H), 8.08 (t, J = 7.5 Hz, 2H), 2.85 (s, 6H); ^{13}C NMR ($CDCl_3$) 199.6, 157.8, 153.2, 152.5, 138.3, 125.2, 124.9, 122.6, 25.7; IR (ATR, cm^{-1})

$\nu_{C=O}$ 1698. Anal. Calcd for $C_{18}H_{14}N_4O_2 \cdot 0.25H_2O$: C, 66.98; H, 4.50; N, 17.36. Found: C, 67.10; H, 4.24; N, 16.85.

Method B: A suspension of **31** (717 mg, 1.76 mmol) in acetone (45 mL) and HCl (2 N, 6 mL) was stirred at room temperature for 40 h. The mixture was concentrated to about 5 mL, carefully neutralized with saturated $NaHCO_3$, and extracted with CH_2Cl_2 (20 mL) and $CHCl_3$ (30 mL). The organic phase was washed with saturated $NaHCO_3$ (20 mL) and brine (20 mL), dried over $MgSO_4$, and evaporated to give an off-white solid. Chromatography on alumina, eluting with CH_2Cl_2, afforded **18** as a colorless solid (535 mg, 96%). ^{1}H and ^{13}C NMR were identical to those of material prepared by method A.

2-Acetyl-6-bromopyridine (28).[14] To a suspension of 2,6-dibromopyridine (13.33 g, 56.27 mmol) in diethyl ether (172 mL) was added *n*-BuLi (2.5 M in hexane, 25 mL, 62 mmol) over 30 min at −78 °C under Ar. The solution was stirred for 1 h at −40 °C and cooled to −78 °C. Dimethylacetamide (8.5 mL, 95 mmol) was then added, and the solution was allowed to warm to room temperature. The resulting yellow solution was hydrolyzed with saturated NH_4Cl (60 mL). Extraction of the aqueous solution with diethyl ether, drying over Na_2SO_4, and evaporation of the solvent gave a brown solid. The crude product was purified by chromatography on silica eluting with hexanes/ethyl acetate (95:5) to afford white crystals of **28** (9.1 g, 80%), mp 55−56 °C (lit. mp[14] 54−55 °C): ^{1}H NMR ($CDCl_3$) δ 7.99 (dd, 1H, J = 1.8 Hz, 6.9 Hz), 7.73−7.63 (m, 2H), 2.71 (s, 3H).

2-Acetyl-6-trimethylstannylpyridine (29) and 6,6′-diacetyl-2,2′-bipyridine (15). A solution of 2-acetyl-6-bromopyridine (400 mg, 2.0 mmol), hexamethylditin (700 mg, 2.14 mmol), and Pd(PPh_3)$_4$ (102 mg, 0.088 mmol) in dimethoxyethane (15 mL) was heated at 80 °C for 24 h. The resulting dark-red solution was evaporated to give an oil. Chromatography on alumina, eluting with hexanes−ether (85:15), produced two fractions. The first fraction was a colorless oil, 2-acetyl-6-trimethylstannylpyridine (**29**, 180 mg, 32%): ^{1}H NMR ($CDCl_3$) δ 7.86 (dd, J = 7.8, 2.1 Hz, 1H), 7.64 (t, J = 7.5 Hz, 1H), 7.58 (dd, J = 7.2, 2.1 Hz, 1H), 2.74 (s, 3H), 0.37 (s, 9H); ^{13}C NMR ($CDCl_3$) δ 201.2, 173.2, 153.9, 134.4, 134.1, 120.0, 25.6, −9.5. The second fraction was an off-white solid, identified as 6,6′-diacetyl-2,2′-bipyridine (**15**, 137 mg, 57%), mp 175−176 °C (lit[13] mp 182−184 °C): ^{1}H NMR ($CDCl_3$) δ 8.73 (dd, J = 7.8, 1.5 Hz, 2H), 8.08 (d, J = 7.8 Hz, 2H), 8.00 (t, J = 7.8 Hz, 2H), 2.84 (s, 6H).

6-(1′,1′-Ethylenedioxyethyl)-2-tri-*n*-butylstannylpyridine (30). To an ether solution of 6-(1′,1′-ethylenedioxyethyl)-2-bromopyridine (3.06 g, 12.5 mmol) was added dropwise *n*-BuLi (2.0 M in cyclohexane, 6.0 mL) at −78 °C, giving a yellow suspension. The mixture was stirred for an additional 50 min at −78 °C, followed by the addition of a solution of tri-*n*-butyltin chloride (3.4 mL, 12 mmol) in ether (20 mL). The reaction was kept at −78 °C for 4 h and overnight at room temperature. The colorless turbid mixture turned to a solution upon the addition of water (35 mL). The organic phase was separated, and the aqueous solution was extracted with ether (3 × 15 mL). The combined organic phase was washed with brine (15 mL), dried over $MgSO_4$, evaporated, and kugelrohr distilled (0.2 mmHg, 160−170 °C) to afford a colorless oil (4.7 g, 86%): ^{1}H NMR ($CDCl_3$) δ 7.47 (t, J = 8.1 H_Z, 1H), 7.36−7.29 (m, 2H), 4.11−3.93 (m, 4H), 1.78 (s, 3H), 1.62−0.84 (m, 27H); ^{13}C NMR ($CDCl_3$) δ 173.5, 160.4, 133.4, 131.4, 117.5, 109.2, 65.0, 29.0, 27.3, 24.4, 13.7, 10.0.

3,6-Di-(6′-(1",1"-ethylenedioxyethyl)-pyrid-2′-yl)pyridazine (31). A mixture of 6-(1′,1′-ethylenedioxyethyl)-2-tri-*n*-butylstannylpyridine (**30**, 2.60 g, 5.73 mmol), 3,6-dichloropyridazine (360 mg, 2.4 mmol), Pd(PPh_3)$_4$ (236 mg, 0.20 mmol), and 1,2-dimethoxyethane (30 mL) was heated at 80 °C for 7 d to afford a dark-red solution. The solvent was evaporated, and the residue was chromatographed on alumina, eluting with hexanes−CH_2Cl_2 (1:1). After recrystallization from dichloromethane and ether, **31** was obtained as a colorless solid (371 mg, 38%), mp 165−166 °C: ^{1}H NMR ($CDCl_3$): δ 8.75 (s, 2H), 8.70 (dd, J = 9.0, 1.2 Hz, 2H), 7.91 (t, J = 8.1 Hz, 2H), 7.67 (dd, J = 7.8, 1.2 Hz, 2H), 4.22−4.10 (m, 4H), 4.06−3.95 (m, 4H), 1.87 (s, 6H); ^{13}C NMR ($CDCl_3$): δ 160.4, 158.0, 152.9, 137.6, 125.2, 120.76, 120.1, 108.6, 65.1, 24.8.

2-Acetyl-6-(trimethylsilylethynyl)pyridine (32). To a degassed solution of **28** (210 mg, 1.05 mmol) in THF (10 mL) were added CuI (14.5 mg, 0.076 mmol), Pd(PPh_3)$_2Cl_2$ (41 mg, 0.058 mmol), (*i*-Pr)$_2$NH (0.4 mL), and trimethylsilylacetylene (118 mg, 1.2 mmol). The reaction mixture was heated at reflux overnight and then the solvent was removed in vacuo. The crude material was purified by chromatography on silica eluting with hexane/ethyl acetate (95:5) to give a yellow oil (178 mg, 78%): ^{1}H NMR ($CDCl_3$) δ 7.92 (dd, 1H, J = 8.1, 1.2 Hz), 7.75 (dd, 1H, J = 8.1 Hz), 7.59 (dd, 1H, J = 8.1, 1.2 Hz), 2.70 (s, 3H), 0.26 (s, 9H); ^{13}C NMR ($CDCl_3$) δ 199.9, 153.8, 142.6, 137.1, 131.0, 121.0, 103.4, 95.8, 26.0, −0.1.

2-Acetyl-6-ethynylpyridine (33). Method A: To a solution of **32** (159 mg, 0.733 mmol) in acetonitrile (8 mL) was added tetrabutylammonium fluoride (TBAF, 0.75 mL, 1.0 M THF solution). After stirring at room temperature for 1 h, the solvent was removed and the residue was purified by chromatography on silica eluting with hexane/ethyl acetate (90:10) to give needlelike crystals (64 mg, 60%), mp 94−95 °C: ^{1}H NMR ($CDCl_3$) δ 7.98 (dd, 1H, J = 7.8, 1.5 Hz), 7.80 (dd, 1H, J = 7.8 Hz), 7.62 (dd, 1H, J = 7.8, 1.5 Hz), 3.22 (s, 1H), 2.71 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 199.7, 153.9, 141.8, 137.3, 130.9, 121.4, 82.4, 77.9, 26.0. Anal. Calcd for C_9H_7NO: C, 74.47; H, 4.86; N, 9.65. Found: C, 74.29; H, 4.66; N, 9.58.

Method B: An ethanol (10 mL) solution containing **34** (500 mg, 2.46 mmol) and NaOH (150 mg, 3.75 mmol) was heated to 50 °C for 4 h. Water (20 mL) was added, and the reaction mixture was extracted with CH_2Cl_2 (3 × 20 mL). The combined extracts were washed with water, dried over Na_2SO_4, and concentrated to give an orange oil. The crude material was purified by chromatography on silica eluting with hexane/ethyl acetate (90:10) to give needlelike crystals (202 mg, 50%), mp 94−95 °C: ^{1}H and ^{13}C NMR identical to those of material prepared by method A.

2-Acetyl-6-(3′-methyl-3′-hydroxybutyn-1′-yl)pyridine (34).[12] To a degassed solution of **28** (1.34 g, 6.7 mmol) in THF (20 mL) were added CuI (100 mg, 0.53 mmol), Pd(PPh_3)$_2Cl_2$ (150 mg, 0.21 mmol), (*i*-Pr)$_2$NH (2.5 mL), and 2-methyl-3-butyn-2-ol (0.72 g, 8.6 mmol). The reaction mixture was heated to reflux overnight under Ar and then the solvent was removed in vacuo. The crude product was purified by chromatography on silica eluting with hexane/ethyl acetate (55:45) to give an orange oil (1.03 g, 75%): ^{1}H NMR ($CDCl_3$) δ 7.91 (dd, 1H, J = 7.8, 1.2 Hz), 7.74 (dd, 1H, J = 7.8 Hz), 7.52 (dd, 1H, J = 7.8, 1.2 Hz), 2.70 (s, 3H), 1.64 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 199.8, 133.3, 142.3, 136.9, 130.3, 120.5, 94.6, 80.8, 65.1, 31.0, 25.7.

2-(6′-Bromopyrid-2′-yl)-1,10-phenanthroline (35). To a stirred solution of **28** (429 mg, 2.14 mmol) and **20** (445 mg, 2.58 mmol) in ethanol (8 mL) was added pyrrolidine (0.21 mL, 2.6 mmol). The reaction was heated to reflux for 30 h under Ar. The resulting precipitate was filtered, washed with ethanol, and dried to give an off-white solid (630 mg, 87%), mp > 238 °C: ^{1}H NMR ($CDCl_3$) δ 9.24 (dd, 1H, J = 4.5, 1.8 Hz), 9.00 (dd, 1H, J = 8.1, 0.9 Hz), 8.80 (d, 1H, J = 8.1 Hz), 8.37 (d, 1H, J = 8.1 Hz), 8.28 (dd, 1H, J = 8.1, 1.8 Hz), 7.83 (AB pattern, 2H, J = 9.0 Hz), 7.76 (dd, 1H, J = 8.1 Hz), 7.67 (dd, 1H, J = 8.1, 4.5 Hz), 7.55 (dd, 1H, J = 8.1, 0.9 Hz); ^{13}C NMR ($CDCl_3$) δ 157.2, 154.5, 150.4, 146.1, 145.5, 141.3, 139.3, 137.0, 136.3, 129.0, 128.4, 127.1, 126.5, 123.0, 122.5, 121.4, 121.0. Anal. Calcd for $C_7H_{10}BrN_3$: C, 60.73; H, 3.00; N, 12.50. Found: C, 60.59; H, 2.71; N, 12.34.

2-(6′-Ethynylpyrid-2′-yl)-1,10-phenanthroline (**36**). To a degassed solution of **35** (505 mg, 1.50 mmol) in THF (25 mL) were added CuI (28 mg, 0.15 mmol), Pd(PPh_3)$_2Cl_2$ (57 mg, 0.081 mmol), (*i*-Pr)$_2$NH (1.2 mL), and trimethylsilylacetylene (215 mg, 2.19 mmol). The reaction mixture was heated to reflux overnight under Ar and cooled to room temperature. TBAF (1 M, 1.8 mL) was then added to the reaction and the stirring continued for 30 min. After the solvent was removed in vacuo, the residue was purified

by chromatography on silica, eluting with CH_2Cl_2, to give a brown solid (360 mg, 85%), mp 124 °C (dec): ^{1}H NMR ($CDCl_3$) δ 9.22 (dd, 1H, J = 4.5, 1.8 Hz), 9.00 (dd, 1H, J = 8.1, 0.9 Hz), 8.85 (d, 1H, J = 8.4 Hz), 8.33 (d, 1H, J = 8.4 Hz), 8.24 (dd, 1H, J = 8.1, 1.8 Hz), 7.87 (dd, 1H, J = 8.1 Hz), 7.78 (AB pattern, 2H, J = 9.0 Hz), 7.63 (dd, 1H, J = 8.1, 4.5 Hz), 7.55 (dd, 1H, J = 8.1, 0.9 Hz), 3.22 (s, 1H); ^{13}C NMR ($CDCl_3$) δ 156.7, 155.5, 150.5, 146.4, 145.7, 141.6, 137.4, 137.2, 136.5, 136.1, 129.2, 128.1, 127.1, 126.7, 123.1, 122.8, 121.3, 83.3, 77.6. Anal. Calcd for $C_{19}H_{11}N_3 \cdot 0.25H_2O$: C, 79.85, H, 3.85, N, 14.71. Found: C, 80.35; H, 3.80; N, 14.79.

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