Control of Hydrogen Bond Strengths through Push–Pull Effects Triggered by a Remote Reaction Center: A Theoretical Study

Tsong-Song Hwang, Ning Juan, Hsing-Yin Chen, Cheng-Chung Chen, Shih-Jung Lo, and Ito Chao*[a]

Abstract: In an effort to manipulate the bond strengths of hydrogen bonds, we have studied a three-component chemical system consisting of a reaction center, a conjugated bridge, and a hydrogen-bonding site. Protonation of the reaction center triggers intramolecular charge transfer from the hydrogen-bonding site, altering its affinity to bind to an acceptor. Previously, we had found that this communication (signal transduction) between the reaction center and the hydrogen-bonding site does not necessarily die out with increasing length of the conjugated bridge. In certain cases, this signal transduction is maintained—and even amplified—over long distances (I. Chao, T.-S. Hwang, *Angew. Chem.* **2001**, *113*, 2775–2777; *Angew. Chem. Int. Ed.* **2001**, *40*, 2703–2705). In this study we report the results of an extensive theoretical investigation of this problem to provide insights into this intriguing phenomenon. In the systems we investigated it was found that the push–pull process between the hydrogen-bonding site and the protonatable reaction center was mediated with the greatest facility by conjugated bridges with low-lying π and π* orbitals.

Keywords: HOMO · hydrogen bonds · intramolecular charge transfer · LUMO · supramolecular chemistry

Introduction

Supramolecular chemistry and self-assembly are playing increasingly important roles in the assembly of novel devices through a bottom-up approach.[1–3] The strength, directionality, and selectivity of binding interactions form the foundations of such assemblies. If the binding ability or the recognition pattern of a molecule could be altered at will, this could be exploitable in the design of novel sensors, signal transducers, or supramolecular assemblies with tunable structures. Hydrogen bonding represents one of the most important interactions that could be used for molecular recognition. Several attempts to modulate the strengths of hydrogen bonds in synthetic host–guest systems[4] and in biologically related structures[5] have been made by different approaches. In view of the large differences in the substituent effects between neutral and charged substituents (e.g., the Hammett-type substituent constants σ_p for $-NH_2$ and for $-NH_3^+$ are -0.57 and 0.60, respectively),[6] we felt that it might be possible to tune the strength of the hydrogen bond effectively by linking the hydrogen-bonding site to a reaction center through a conjugated spacer, and by altering the charge state of the reaction center in the solution. Protonation, metalation, oxidation and reduction, or chemical transformation are among the reactions that could cause such charge alterations at the reaction center, and it is thought that the binding ability of the remote hydrogen-bonding site might respond to such reactions at the reaction center in significant and interesting ways. We have recently undertaken a theoretical study of these systems directed towards testing this thesis. As a prototype, we have selected the three-component molecular system depicted in Scheme 1, in which a π-conjugated bridge has been used to link a pyrrole (the hydrogen-bonding center) with an imine (the reaction center). For reasons of computational efficiency and ease of experimental execution we limited the study to protonation reactions at the imine.[7] At the hydrogen-bonding end, ammonia is used as a proton acceptor to form a hydrogen bond with the N–H group of pyrrole,[7] and we simulated the effects of protonation of the imine on the strength of the hydrogen bond of the pyrrole with the ammonia as a function of the length of the π-conjugated bridge.

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Supporting information for this article is available on the WWW under http://www.chemeurj.org/ or from the author. Binding results at different theory levels (Part I). Correlation between $\Delta E_{b,\,protonated}$ and Q_H (Part II). Table of values of E_{HOMO} (pyrrole), E_{LUMO} (two-component system), ΔE, q_{LUMO}, and MEP of systems with all bridges (Part I-II).

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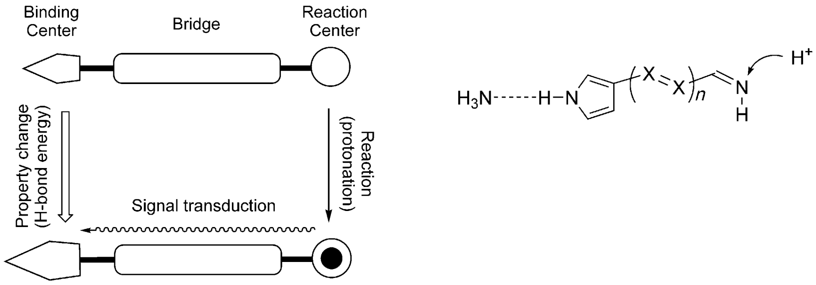
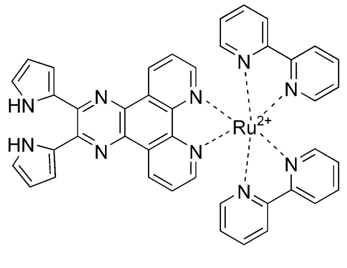


Scheme 1. The three-component system investigated in this work.

In the literature there are examples of charge-influenced hydrogen-bonding systems in which the charge center and the hydrogen-bonding center are covalently coupled as in our three-component system.[8] Organic and organometallic redox-switched hydrogen-bonded complexes have been reported, for example.[9–11] A number of anion binders based on hydrogen bonding have been designed by the metallation (M^{n+}) strategy.[11,12] In several ditopic receptors[13] (i.e., receptors that bind both cations and anions), allosteric effects have been observed.[14] In addition to the through-space electrostatic effects of a charge center on the hydrogen-bonding site, the acidity of a proton donor could also be enhanced by polarization of a nearby cationic center.[10,14c] However, when the charge center and the binding center are in close proximity, the strong electrostatic effect of the charge center overshadows the polarization of the hydrogen-bonding site. In light of this, the cooperative effect observed in allosteric ditopic receptors is very often ascribed to electrostatic and structural pre-organization effects.[11]

In the earlier study, we deliberately picked a π-conjugated bridge of sufficient size to curtail the through-space electrostatic effect, and the reaction-induced polarization of the hydrogen-bonding site was varied by increasing the number of double bonds in the π-conjugated bridge between the hydrogen-bonding and reaction centers. In other words, the calculations were designed to highlight the remote communication. Interestingly, while ammonia binding in some protonated three-component systems (pyrrole–$(CH{=}CH)_n$–iminium; $n = 1$–4) showed a distance-dependent decay as expected, systems with pure azo bridges (pyrrole–$(N{=}N)_n$–iminium; $n = 1$–4) exhibited an enhanced charge polarization effect as the bridge got longer.[7] That is, we have observed signal amplification with the longer bridges, as if the reaction and binding centers were behaving as signal input and output centers, respectively. Subsequent tests with more synthetically feasible bridge systems—namely, the pyrrole–$(CH{=}CH)_n$–$N{=}N)_x$–iminium system ($n = 1$–4, $x = 1$–2)—also revealed signal amplifying/maintaining effects as x was increased from 1 to 2.[7] Therefore, if the components are appropriately chosen, efficient remote communication is achievable, not just limited to a system with a pure azo bridge.

Since we published our original theoretical work, we have uncovered two relevant experimental reports in which the reaction and binding centers were also not in close proximity. In these reports, the anion-binding ability of a pyrrole was enhanced when metal coordination occurred on the polycyclic heteroaromatic ligand to which pyrrole was attached (**1** and **2**).[12] With F^- as the common anion, for example, increases in the binding constants of about tenfold[12b] to 30-fold[12a] were observed upon the formation of Ru^{2+} complexes. These results support the idea that remote communication between charge and binding centers is experimentally feasible even in solution. In Sessler's phenanthroline-containing DPQ anion sensor (**2**),[12a] the hydrogen bond center (pyrrole ring) and the metal coordination site (pyridine ring) are separated by four fused aromatic rings.



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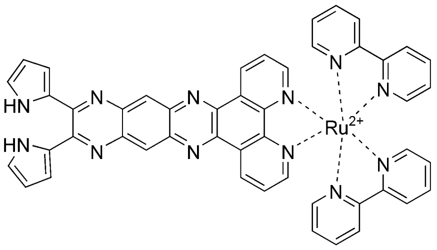

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It is of crucial importance to elucidate the mechanism(s) for the signal-maintaining or signal-amplifying behavior of the longer bridges, so that a design strategy for customized three-component systems may be formulated. Previously, we had interpreted the signal-amplifying effect of the azo-containing three-component systems in terms of the weak double bond character of an azo group and its cumulative electron-withdrawing effects in the longer bridges.[7,15] In the current work, we have extended our study to include a large variety of hybrid C- and N-containing bridges, and have found a molecular orbital approach that has proven to be valuable for understanding the phenomenon. While some of the bridges may not be readily amenable to direct chemical synthesis, we nevertheless need a large data set in order to deduce and confirm the underlying principles. The results of these hybrid bridges not only provide insights into, but also provide certain guidelines for the design of effective remote charge-controlled binding systems.

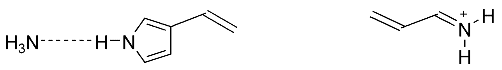
Computational Details

As in reference [7], ammonia was used as the proton acceptor in this work. All the three-component systems were studied in their most extended forms: that is, the bridge double bonds were in s-*trans* relationships. Calculations were carried out with Gaussian 98[16] and the listed binding energies included counterpoise correction for basis set superposition errors.[17] Stationary points were confirmed to be local minima by frequency analysis.

Both neutral and protonated systems were closed-shell, ground-state species. The theory level of RHF/6-31G* was used throughout to obtain the trends of binding energies in all the three-component systems of different bridge lengths. We had previously shown that the *trend* of binding energies (i.e., whether a given bridge series belongs to a signal-maintaining or -reducing system) observed at this level is consistent with that obtained at the DFT, MP2, and MP4 levels.[7] Subsequently, we carried out more calculations at higher levels (the highest level is CCSD(T)/6-31G*//MP4(SDQ)/6-31G*) with the same conclusions as reached at the RHF/6-31G* level, indicating that the latter is good enough to give the proper binding trends. (See Supporting Information for binding energies calculated at different levels; Table S1 and S2.)

Results

$(X{=}Y)_n$ and $(X{=}Y{-}X'{=}Y')_n$ bridges: An electron-withdrawing bridge would be expected to increase the acidity of a proton donor and hence increase its binding ability. As the electron-withdrawing character of an azo group may be relevant to the interesting signal-amplifying behavior noted earlier,[7] in this study we calculated pyrrole–$(CH{=}N)_n$–imine and pyrrole–$(N{=}CH)_n$–imine systems, in which the effects of the bridges are electron-withdrawing and electron-donating, respectively. As $(C{\equiv}C)_n$ bridges have been often used in study of molecular wires, we have included calculations on a system with these bridges for comparison between systems containing the $(CH{=}CH)_n$ and $(C{\equiv}C)_n$ bridges. The results for the various bridges are shown in Table 1. It can be seen that for a given series of bridges, the ammonia binding energies change little for the neutral three-component systems.[18] Taking the series with the largest binding change, $(CH{=}N)_n$, as an example, we found that the binding energies ($\Delta E_{b,neutral}$) are -7.27 and $-8.09\,kcal\,mol^{-1}$ for $n = 1$ and 4 bridges, respectively. Therefore, the length of the bridge has a limited effect on the binding strength of these neutral three-component systems, even though small cumulative electron-withdrawing effects of the CH=N and N=N units, and electron-releasing effects of CH=CH and N=CH are at work, according to the trend of $\Delta E_{b,neutral}$. (For N=N and CH=N, the $\Delta E_{b,neutral}$ increases as n becomes larger. The reverse is observed for N=CH and CH=CH.) Upon protonation, the positive charge at the reaction center has a strong influence on the binding ability of the pyrrole unit. All three-component systems with an $n = 1$ bridge show an increase in binding energies of ca. 6 to $8\,kcal\,mol^{-1}$ upon protonation (see $\Delta\Delta E_{b(P\text{-}N)}$ in Table 1). When the bridges are longer, the binding energies ($\Delta E_{b,protonated}$) show a distance-dependent decrease for all bridges, except for the systems with azo bridges. To elucidate the importance of the through-bond polarization effect in the charge-bearing system, we undertook a calculation for a system in which the two middle double bonds of the bridge in pyrrole–$(CH{=}CH)_4$–iminium were removed (**3**).[19] The calculated ammonia binding energy of system **3** was $-7.27\,kcal\,mol^{-1}$, which was not very different from that of neutral pyrrole–$(CH{=}CH)_4$–imine ($-6.57\,kcal\,mol^{-1}$), but significantly weaker than that of cationic pyrrole–$(CH{=}CH)_4$–iminium ($-10.47\,kcal\,mol^{-1}$). Therefore, the through-bond polarization effect plays an important role in our fully conjugated cationic systems.



3•NH$_3$

For the protonated three-component systems with CH=CH, CH=N, and N=CH sp^2-hybrized bridging units, the elec-

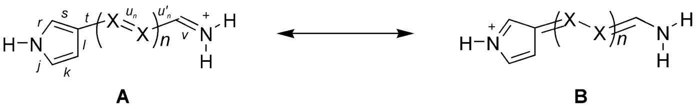
Table 1. Ammonia binding energies (ΔE_b) and binding energy differences ($\Delta\Delta E_{b(P\text{-}N)}$) between protonated and neutral three-component systems with different bridges at the HF/6-31G* level.

Bridge		$n = 1$	$n = 2$	$n = 3$	$n = 4$
$(N{=}N)_n$	$\Delta E_{b,neutral}$	−7.39	−7.66	−7.84	−7.95
	$\Delta E_{b,protonated}$	−15.50	−16.45	−17.99	−19.07
	$\Delta\Delta E_{b(P\text{-}N)}$	−8.11	−8.79	−10.15	−11.12
$(CH{=}N)_n$	$\Delta E_{b,neutral}$	−7.27	−7.61	−7.88	−8.09
	$\Delta E_{b,protonated}$	−13.88	−13.24	−12.75	−12.37
	$\Delta\Delta E_{b(P\text{-}N)}$	−6.61	−5.63	−4.87	−4.28
$(N{=}CH)_n$	$\Delta E_{b,neutral}$	−6.85	−6.69	−6.55	−6.43
	$\Delta E_{b,protonated}$	−13.56	−11.98	−9.88	−8.61
	$\Delta\Delta E_{b(P\text{-}N)}$	−6.71	−5.29	−3.33	−2.18
$(CH{=}CH)_n$	$\Delta E_{b,neutral}$	−6.84	−6.73	−6.64	−6.57
	$\Delta E_{b,protonated}$	−13.17	−12.04	−11.18	−10.47
	$\Delta\Delta E_{b(P\text{-}N)}$	−6.33	−5.31	−4.54	−3.90
$(C{\equiv}C)_n$	$\Delta E_{b,neutral}$	−7.20	−7.35	−7.43	−7.47
	$\Delta E_{b,protonated}$	−13.15	−11.79	−10.66	−9.80
	$\Delta\Delta E_{b(P\text{-}N)}$	−5.95	−4.44	−3.23	−2.33

tron-withdrawing $(CH{=}N)_n$ series show less binding reduction with increasing bridge length (1.51 kcal mol^{-1} from $n = 1$ to $n = 4$) than $(N{=}CH)_n$ and $(CH{=}CH)_n$ bridges. Systems with the electron-donating $(N{=}CH)_n$ bridges, on the other hand, exhibited a significant reduction in the binding affinity as n was increased (4.95 kcal mol^{-1} from $n = 1$ to $n = 4$). As, in a given bridge series, the change in $\Delta E_{\mathrm{b,neutral}}$ is small, the trend of $\Delta\Delta E_{\mathrm{b(P\text{-}N)}}$ is basically determined by the change in $\Delta E_{\mathrm{b,protonated}}$.

To obtain high sensitivity for remote signal transduction, two requirements have to be met. First, the change in binding strength, $\Delta\Delta E_{\mathrm{b(P\text{-}N)}}$, in response to a reaction at the reaction center should be large. Second, the distance-dependent decay in $\Delta\Delta E_{\mathrm{b(P\text{-}N)}}$ should be kept minimal. For the above three-component systems, the efficiency of sp^2-hybrized bridges in achieving remote communication with better sensitivity is $(N{=}N)_n > (C{=}NH)_n > (CH{=}CH)_n > (N{=}CH)_n$. Comparison of the sp^2-hybrized $(CH{=}CH)_n$ and sp-hybridized $(C{\equiv}C)_n$ bridges reveals that the stronger electron-withdrawing ability of sp-hybridized carbon atoms makes the $\Delta E_{\mathrm{b,neutral}}$ values of systems with $(C{\equiv}C)_n$ somewhat stronger than those with $(CH{=}CH)_n$ bridges. Meanwhile, as electrons are held more tightly by the sp-hybridized carbons, the $(C{\equiv}C)_n$ bridges are less responsive to the polarization of a charge center; $\Delta E_{\mathrm{b,protonated}}$ drops more rapidly as the bridge gets longer in the $(C{\equiv}C)_n$ series than in the $(CH{=}CH)_n$ series. Therefore, the $(CH{=}CH)_n$ bridges are better than the $(C{\equiv}C)_n$ bridges in terms of remote signal transduction.

Structural details are important for understanding of molecular properties. The three-component systems with $(N{=}N)_n$ and $(CH{=}CH)_n$ have been taken as representatives of signal-amplifying and -reducing systems, respectively, and their bond length data are tabulated in Table 2. In comparison with the corresponding neutral systems, the degree of bond length alternation (BLA) in protonated systems is significantly increased in the pyrrole ring. In the three-component system with $(N{=}N)_1$, for example, the bond lengths of r, s, j, k, and l are within 1.350 to 1.432 Å for the neutral species, but 1.305 to 1.452 Å after protonation (Scheme 2, Table 2). In the protonated $(N{=}N)_n$ systems, those with the longer bridges lead to more BLA in the pyrrole ring. Furthermore, the BLA pattern of the systems with the azo bridge shifts from that of structure **A** in Scheme 2 (i.e., $u_n <$



Scheme 2. Labels for the geometric parameters listed in Table 2. **A** and **B** represent two possible resonance structures for the three-component systems.

Table 2. Bond lengths [Å] of three-component systems with $(N{=}N)_n$ and $(CH{=}CH)_n$ bridges.

	Neutral				Protonated			
N	1	2	3	4	1	2	3	4
Pyrrole–$(N{=}N)_n$–imine								
r	1.350	1.347	1.346	1.346	1.305	1.298	1.287	1.281
s	1.365	1.366	1.366	1.367	1.413	1.427	1.447	1.461
j	1.373	1.374	1.375	1.375	1.408	1.417	1.429	1.437
k	1.351	1.351	1.351	1.350	1.335	1.332	1.327	1.324
l	1.432	1.432	1.433	1.433	1.452	1.458	1.466	1.471
t	1.391	1.387	1.385	1.384	1.308	1.294	1.275	1.266
u_1	1.226	1.221	1.222	1.223	1.291	1.312	1.347	1.369
u'_1	1.419	1.395	1.391	1.390	1.325	1.271	1.241	1.224
u_2		1.215	1.213	1.214		1.288	1.336	1.370
u'_2		1.424	1.399	1.396		1.322	1.253	1.228
u_3			1.213	1.211			1.305	1.357
u'_3			1.426	1.401			1.309	1.240
u_4				1.213				1.322
u'_4				1.427				1.298
v	1.247	1.245	1.245	1.244	1.297	1.298	1.306	1.314
Pyrrole–$(CH{=}CH)_n$–imine								
r	1.356	1.357	1.358	1.358	1.325	1.331	1.336	1.340
s	1.365	1.366	1.365	1.365	1.390	1.385	1.380	1.377
j	1.366	1.365	1.365	1.365	1.385	1.381	1.377	1.374
k	1.354	1.354	1.354	1.354	1.344	1.346	1.348	1.349
l	1.435	1.435	1.435	1.435	1.444	1.441	1.439	1.438
t	1.458	1.459	1.459	1.459	1.407	1.417	1.426	1.432
u_1	1.329	1.331	1.332	1.331	1.375	1.368	1.360	1.354
u'_1	1.468	1.457	1.456	1.456	1.390	1.399	1.409	1.418
u_2		1.331	1.333	1.333		1.384	1.376	1.368
u'_2		1.468	1.456	1.455		1.382	1.392	1.401
u_3			1.331	1.333			1.390	1.383
u'_3			1.468	1.456			1.377	1.385
u_4				1.331				1.395
u'_4				1.468				1.372
v	1.257	1.257	1.257	1.257	1.306	1.312	1.316	1.320

u'_n) to that of structure **B** ($u'_n < u_n$) with increasing bridge length. (For the protonated system with $(N{=}N)_1$ bridge, u_1 and u'_1 are 1.291 and 1.325 Å, respectively; the corresponding values for the protonated $(N{=}N)_4$ system are 1.369 and 1.224 Å.) These structural features imply that pyrrole is involved in intramolecular charge transfer (ICT) upon protonation of the imine reaction center. Once protonated, the electron-rich pyrrole moiety of the three-component system is effectively a "push" (donor) group and the electron-withdrawing iminium moiety is a "pull" (acceptor) group. As a result of this electron push–pull process, partial positive charge is delocalized on the pyrrole. In agreement with the increased BLA (and thus the increased positive charge delocalization on pyrrole) in the $(N{=}N)_n$ systems, the gains in positive charge on the pyrrole group are 0.417, 0.473, 0.587, and 0.664 for $n = 1$–4, respectively.[20] With the increased positive charge delocalization on pyrrole, the acidity of the pyrrole proton donor (N−H group) is also increased.[21] Therefore, in the $(N{=}N)_n$ series, the longer three-component systems have stronger hydrogen-bonding ability. The corresponding $(CH{=}CH)_n$ systems showed the opposite trends in structure (Table 2) as well as the gains in positive charge on the pyrrole (0.267, 0.223, 0.184, 0.152 for $n = 1$–4). Accordingly, the longer $(CH{=}CH)_n$ bridges thwart the push–pull process, and the hydrogen-bonding ability of the pyrrole decreases for the systems with the longer bridges. The reason for the different behavior of the systems with $(N{=}N)_n$ and $(CH{=}CH)_n$ bridges is discussed in the next section.

We have previously shown that the hybrid bridge systems (pyrrole-$((CH{=}CH)_n{-}N{=}N)_x$−iminium; $n = 1$–4, $x = 1$–2) exhibit a signal-amplifying/-maintaining effect as x changes from 1 to 2.[7] It may seem that addition of an azo group to the repeating unit of a bridge offers a strategy for creating a signal-amplifying/-maintaining system. Figure 1 shows the ammonia binding energies of different hybrid systems (pyrrole−$(X{=}Y{-}X'{=}Y')_n$−iminium; $n = 1$–2). It is apparent that all of the five signal-amplifying/-maintaining bridges (see the top five bridges in Figure 1) contain an N=N unit. However, the bridge with the largest binding reduction is also an azo-containing bridge, the $(N{=}N{-}N{=}CH)_n$ bridge. Interestingly, the bridge that enjoys the largest binding increase, $(N{=}CH{-}N{=}N)_n$, and that suffering the largest binding reduction, $(N{=}N{-}N{=}CH)_n$, have the same constituents, except that the order of N=N and N=CH units is exchanged. It is also noteworthy that the $(N{=}CH)_n$ bridges are the most strongly signal-reducing of the simple X=Y bridges, but when N=CH and N=N units are incorporated in the correct order, they constitute the most impressive $X{=}Y{-}X'{=}Y'$ bridge. These findings illustrate the importance of arranging the bridge units in an appropriate order and that addition of azo groups to a three-component system may be beneficial, but does not necessarily guarantee efficient signal transduction.

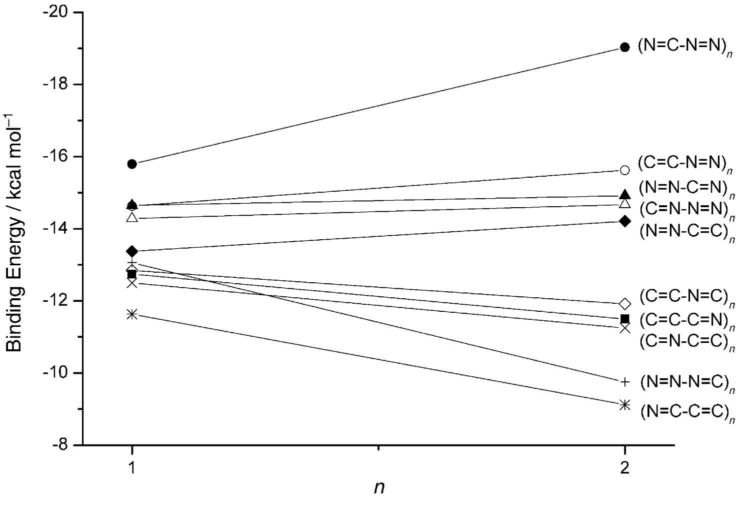
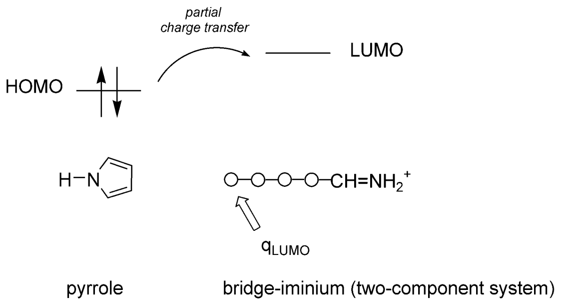


Figure 1. Binding energies of three-component systems containing $(X{=}Y{-}X'{=}Y')_n$ bridges. For simplicity, the hydrogen atoms next to carbon atoms are not shown.

Fragmental molecular orbital (MO) analysis: In this section we attempt to understand the efficiency of pyrrole in delocalizing the positive charge in different protonated three-component systems. We pointed out in the previous section that an electron push–pull process in the cationic three-component system resulted in positive charge delocalization on pyrrole. The extent of positive charge delocalization on pyrrole thus influences the acidity of the N−H group and its hydrogen-bonding ability. We checked the relationship between the atomic Mulliken charge of the H atom of the pyrrole N−H bond (Q_H) and the hydrogen-bonding energy ($\Delta E_{b,protonated}$), and observed a good linear correlation between $\Delta E_{b,protonated}$ and Q_H ($R^2 = 0.9687$; 40 data points).[22] We therefore view Q_H as a convenient indicator that reflects the extent of positive charge delocalization on pyrrole and the strength of binding energy; larger positive Q_H values imply more charge delocalization and better binding ability.

To understand why a bridge is signal-amplifying or -reducing, we sought help from MO-based analyses. From molecular orbital interaction theory it is known that efficient charge transfer should be observed if the energy gap (ΔE) between occupied and virtual orbitals is small and the overlap between these orbitals is large. The problem one then faces is how to dissect the fully conjugated protonated three-component system into electron-donor and -acceptor parts. As the bridge is right next to the protonation center, it should be strongly influenced by the added H^+, either through space or through bond. Therefore, rather than dissecting the system into three parts, we assume that the electron is donated from the HOMO of the pyrrole unit into the *combined* LUMO of the other two components (bridge-iminium; see Scheme 3). Using pyrrole and two-component structures frozen in the optimized geometry of protonated three-component systems,[23] we calculated the energies of occupied and virtual orbitals of pyrrole and the two-component system. It was found that the range of the HOMO energy of frozen pyrrole is fairly invariant (−7.5 to −7.9 eV), while that of the two-component LUMO spans the range −3.3 to −7.0 eV. The LUMO energies of the two-component systems with signal-reducing $(CH{=}CH)_n$ bridges are in the range of −3.83 to −3.29 eV (n from 1 to 4; note that the longer the bridge, the higher the LUMO energy).



Scheme 3. The proposed charge transfer model. Note that we presume charge transfer from the HOMO of the pyrrole to the LUMO of the remaining bridge-iminium.

The corresponding values of the $(N{=}N)_n$ series are −5.13 to −7.04 eV (n from 1 to 4), much lower than that of the $(CH{=}CH)_n$ series. Therefore, the energy gap between occupied and virtual orbitals of the donor and acceptor is significantly smaller for the $(N{=}N)_n$ series than for the $(CH{=}CH)_n$ series. These results explains well: i) why the azo-containing systems are more efficient than the $(CH{=}CH)_n$ systems in delocalizing the positive charge by donating electron from pyrrole, and ii) why systems with longer $(N{=}N)_n$ bridges are still successful in helping pyrrole to delocalize the positive charge (signal-maintaining), but the systems with longer $(CH{=}CH)_n$ bridges fail to do so (signal-reducing).

A further test of the soundness of the above simple donor–acceptor model comes from the following analysis. We plotted Q_H of all protonated three-component systems against the energy gap (ΔE) of the donor and acceptor. A smaller energy gap should lead to more charge transfer from pyrrole and hence a more positive Q_H value. It is shown in Figure 2 that smaller energy gaps (e.g., <3 eV) do indeed lead to more positive Q_H values, as expected. Of course, the extent of charge transfer is influenced not only by ΔE, but also by orbital overlap. A large LUMO coefficient at the atom connecting to pyrrole (see the terminal atom of the two-component part in Scheme 3) would afford better orbital overlap and facilitate charge transfer. Using the LUMO Mulliken population of the terminal atom (q_{LUMO}) to classify the data points in Figure 2, we found good linear correlations between ΔE and Q_H for large q_{LUMO} values (i.e., $R^2 > 0.97$ when q_{LUMO} in the 0.350–0.510 or 0.250–0.349 ranges). When q_{LUMO} is small, the correlation coefficients drop significantly. Basically, there is no correlation between ΔE and Q_H when q_{LUMO} is in the 0.000–0.049 range ($R^2 = 0.0258$). When the wave function amplitude at the connecting atom is so small, charge transfer is not efficient and contributes little to the charge-enhanced hydrogen bonding of pyrrole. The five systems with q_{LUMO} smaller than 0.049 are those bearing $(N{=}CH)_3$, $(C{\equiv}C)_4$, $(N{=}N{-}N{=}CH)_2$, $(N{=}CH{-}CH{=}CH)_2$, and $(N{=}CH)_4$ bridges; they are the only protonated systems with ammonia binding energies weaker than $-10\,\mathrm{kcal\,mol^{-1}}$ (Table 1 and Figure 1). For these cases, the through-space electrostatic effect exerted on pyrrole by the protonated reaction center is examined by calculation of the molecular electrostatic potential (MEP) of a two-component system at the position in which the N atom of pyrrole is supposed to be in a complete three-component system.[24] The good correlation between MEP and ammonia binding energy ($\Delta E_{b,protonated}$) of systems with small q_{LUMO} values (see Figure 3; $R^2 = 0.9850$) demonstrates that when charge transfer involving pyrrole is not at work, the through-space electrostatic effect is playing an important role.

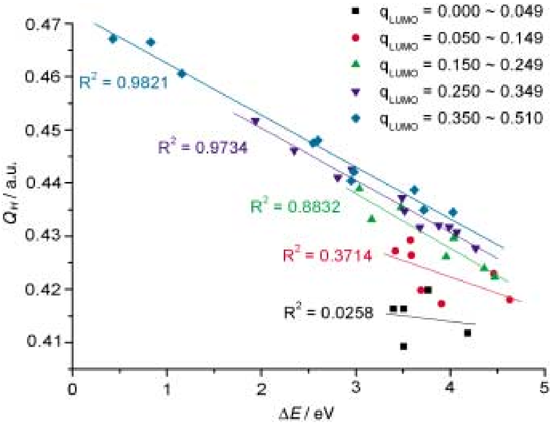


Figure 2. Correlation of charges at the H atom of the pyrrole N−H bond and the energy gap between pyrrole HOMO and two-component LUMO.

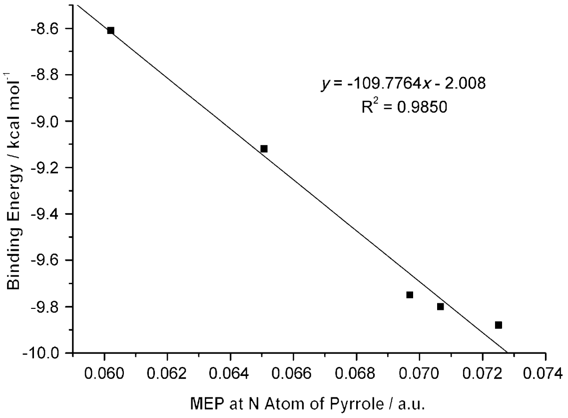


Figure 3. Correlation of binding energy and MEP at the N atom of pyrrole.

With the reasonableness of the simple donor–acceptor model in Scheme 3 seemingly in place, we can now transform our original questions of "why are some three-component systems more efficient in signal transduction than others and why can signal transduction be maintained even when the bridge is long?" into new ones: "how can a low-lying two-component LUMO be achieved and how may raising of the LUMO energy be avoided as the bridge in the two-component system gets longer?" We have mentioned that LUMO energies of two-component systems containing $(N{=}N)_n$ are lowered with larger n, but the opposite is observed for the $(CH{=}CH)_n$-containing systems.[25] Normally, more extended double bond conjugation results in lowering of the LUMO. However, this is not necessarily true in the presence of a very low-lying LUMO of a charge center. In Figure 4 we plotted the orbital energies of closed-shell systems relevant to the two-component systems.[26] Since the LUMO of the charge center ($H_2C{=}NH_2^+$) is of π-symmetry, we only show the highest occupied π-orbital (π-HOMO) and lowest unoccupied π-orbital (π-LUMO) of bridges in Figure 4, ignoring the nonbonding orbitals of $(N{=}N)_n$. When the LUMO of a charge center is low enough, it will not only interact with the π-LUMO of a bridge, but also with the π-HOMO. For the $(N{=}N)_n$ series, π-HOMO is low-lying in energy, so the LUMO of the charge center interacts primarily with π-LUMO of the bridge. Therefore, the resultant two-component LUMO is lower in energy as the number of bridge double bonds increases, as in most conjugated systems. On the other hand, the π-HOMO of $(CH{=}CH)_n$ is high-lying, so the LUMO of the charge center also interacts significantly with π-HOMO when forming a combined two-component LUMO (Figure 4). Systems with longer bridges have higher π-HOMOs and these π-HOMOs interact even more readily with the charge center LUMO. Because the resultant two-component LUMO is strongly influenced by the π-HOMO, the energy trend of two-component LUMOs in the $(CH{=}CH)_n$ series is no longer the same as in the $(N{=}N)_n$ systems. One can think of the high-lying HOMO of $(CH{=}CH)_n$ as more and more effective in deterring ICT from pyrrole when the bridge gets longer. Therefore, a bridge with a low-lying π-HOMO and π-LUMO would be expected to behave quite differently from a common bridge such as $(CH{=}CH)_n$. It is conceivable that addition of electronegative atoms to the bridge as we did, or of electron-withdrawing groups to the two-component part, would help to achieve a low-lying two-component LUMO and to avoid raising its energy as the bridge gets longer.

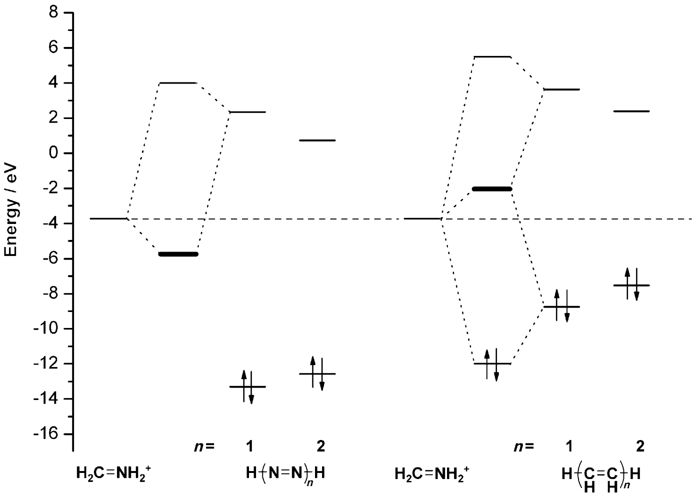


Figure 4. Energy level diagram of the LUMO of $H_2C{=}NH_2^+$ and the π-HOMOs and π-LUMOs of $H{-}(CH{=}CH)_n{-}H$, $H{-}(N{=}N)_n{-}H$, $n = 2$ and 4. The orbitals relevant to the two-component LUMO are shown in bold.

Figure 5 shows the π-HOMOs and π-LUMOs of different hybrid X=Y−X′=Y′ bridges. The orbitals are lower-lying with more electronegative N atoms in the bridge. For the five three-component systems that are signal-amplifying/-maintaining in Figure 2 (the top five systems of Figure 2), the π-HOMOs and π-LUMOs of their bridges ($(CH{=}CH{-}N{=}N)_n$, $(CH{=}N{-}N{=}N)_n$, and $(N{=}CH{-}N{=}N)_n$) are indeed lower-lying than those of $(CH{=}N{-}CH{=}CH)_n$ and $(N{=}CH{-}CH{=}CH)_n$. Therefore, this finding reinforces the idea that low-lying π-HOMOs and π-LUMOs could facilitate ICT from pyrrole to iminium. With this kind of bridge, the involvement of the π-HOMO can be minimized when a three-component system is protonated. According to the above finding and reasoning, we modified the $(CH{=}CH)_n$ bridge to $(CF{=}CF)_n$, expecting the electron-withdrawing fluorine atoms to lower orbital energies and improve the signal reduction phenomenon. The orbital energies of fluorinated systems were indeed lowered,[27] and the ammonia binding energies of pyrrole−$(CF{=}CF)_n$−iminium ($\Delta E_{\mathrm{b,protonated}}$) were −14.00, −13.31, −12.82, and −12.51 kcal mol^{-1} for $n = 1$–4, respectively. In relation to those of their $(CH{=}CH)_n$ counterparts (−13.17 to −10.47 kcal mol^{-1}, $n = 1$–4; see Table 1), the signal reduction phenomenon was indeed improved by replacement of the H atoms with F atoms. The $\Delta\Delta E_{\mathrm{b(P\text{-}N)}}$ values were in the −6.93 to −4.97 and −6.33 to −3.90 kcal mol^{-1} ranges for systems containing $(CF{=}CF)_n$ and $(CH{=}CH)_n$, respectively. Therefore, modification of the carbon bridge on the basis of our rationale improves both the sensitivity and the signal-maintaining ability of three-component systems.

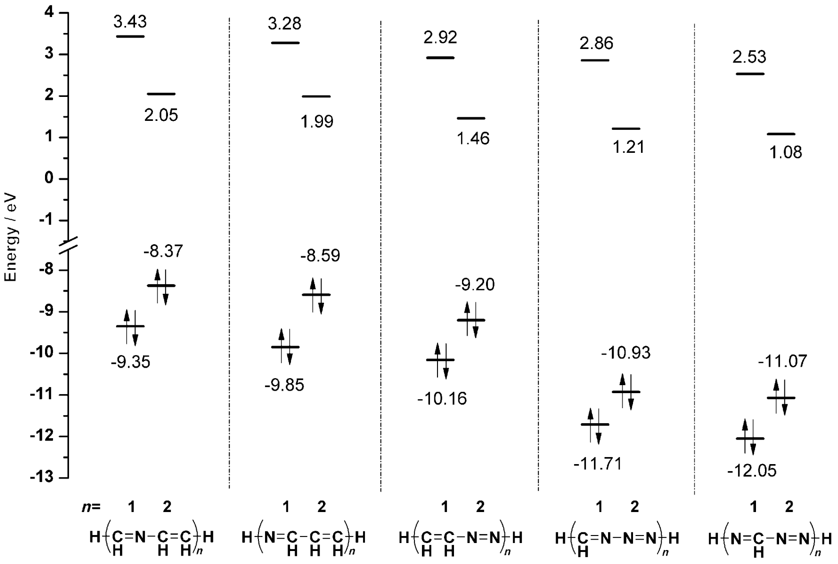


Figure 5. The π-HOMOs and π-LUMOs of different hybrid bridges.

Discussion

A proton exerts a strong electric field. The action of protonation causes strong polarization of a molecule; the electron cloud is redistributed and nucleus positions are relocated. During the reorganization of the molecule, orbital energies and the shapes of the electronic wave functions of our hypothetical donor/acceptor parts will vary. If q_{LUMO} and ΔE were not derived from the frozen geometry adapted from the protonated three-component system (which is the outcome of charge transfer), but from optimized two-component geometry (which has not been subjected to charge transfer from pyrrole), the correlations shown in Figure 2 would become inferior. The following example illustrates the difficulty in predicting the response of a bridge in advance of charge transfer by simply considering a fully optimized two-component system: the LUMO energies of two-component systems containing $(N{=}CH)_3$ and $(CH{=}N{-}N{=}N)_2$ are similar (−4.30 and −4.32 eV, respectively) and their q_{LUMO} values are both small (0.034 and 0.050, respectively). However, when the protonated three-component geometry is adapted, the two-component LUMO energy of the $(CH{=}N{-}N{=}N)_2$ system (−4.97 eV) is significantly lower than that of $(N{=}CH)_3$ (−4.43 eV) and q_{LUMO} is also much larger for the former system (0.293 vs. 0.045). Because of the significant difference in response to charge transfer, the $\Delta E_{b,protonated}$ values for the $(CH{=}N{-}N{=}N)_2$ and $(N{=}CH)_3$ three-component systems are −14.67 and $-9.88\,kcal\,mol^{-1}$, respectively. Therefore, although the donor/acceptor model in Scheme 3 provides a simple and insightful conceptual model, one has to be aware that quantitative analysis (e.g., Figure 2) is suitable only under specific circumstances.

With the simple donor/acceptor model, it seems intuitively simple to understand the directional effects of X=Y bridges. The $(CH{=}N)_n$ bridges are superior to the $(N{=}CH)_n$ bridges because the electron-withdrawing power of CH=N units helps to pull out the electron from pyrrole and the electron-donating power of N=CH deters electron from leaving pyrrole. However, it is difficult to apply similar arguments to the complicated hybrid X=Y−X′=Y′ bridges. These considerations point to the need for more sophisticated analyses for rationalization and prediction of protonation-induced push–pull behavior in conjugated systems. We are currently pursuing the problem along this direction.

Finally, we comment on the influence of the weak double bond character of an azo group. We had proposed that the weak double bond character may be relevant to the larger contribution of resonance form **B** in the azo-containing three-component systems.[7,15] For a three-component system containing a pure azo bridge, the net change in bonding pattern between resonance forms **A** and **B** is that one weak N=N and one strong C=C double bonds in form **A** are turned into two strong C=N double bonds (Scheme 2).[15] For the $(CH{=}CH{-}N{=}N)_2$ and $(N{=}N{-}CH{=}CH)_2$ bridges, twice the number of bonds are changed in converting form **A** to **B** (two N=N and two C=C bonds turned into four C=N bonds). No other three-component system involves as many N=N double bonds in converting form **A** to **B**. If a weak N=N bond strength is playing a dominant role in facilitating the molecule into form **B**, these two systems should have the largest positive charges on pyrrole and show the best binding ability. However, the binding energies of three-component systems containing $(CH{=}CH{-}N{=}N)_2$ and $(N{=}N{-}CH{=}CH)_2$ are not very different from those of other hybrid azo bridges (Figure 1). Therefore, when designing a three-component system, it is more effective to consider an azo group as the means of lowering orbital energies of a bridge, rather than as the source of a weak bond strength to facilitate bond alternation.

Conclusions

In this study, we have employed a protonation-triggered push–pull system to achieve control over hydrogen bonding. Before protonation, the binding site is only weakly influenced by the rest of the molecule. Upon protonation, the low-lying LUMO of the protonated reaction center creates a strong push–pull drive for charge redistribution. With a suitable bridge, the binding site can contribute its electron in response to the push–pull drive, and this causes the change in its binding ability. Among different ways of building up a molecular orbital model, we have developed a reasonable approach toward understanding the extent of charge transfer in terms of the HOMO of the binding site (donor) and the combined LUMO of the two remaining components (acceptor). When the pyrrole and the two-component parts are frozen in the protonated three-component geometry to derive orbital details, the best correlations can be obtained between orbital interaction and charge transfer. This geometry limitation reflects that much electronic and structural reorganization is in process before the positive charge is equilibrated within the system, so the charge-equilibrated geometry has to be used for a model in its simplest form. For systems in which charge transfer from pyrrole is not important, the through-space electrostatic effect dominates the binding ability of pyrrole.

Our MO model, though simple, helps to clarify the factors that could facilitate effective remote communication in protonated push–pull conjugated systems. A bridge with low-lying filled and unoccupied π-orbitals not only has the potential to facilitate charge transfer with its low-lying unoccupied orbital, but its low-lying filled orbital also makes it less likely to deter charge transfer as the bridge gets longer. Modification of the $(CH{=}CH)_n$ bridges along these lines (to $(CF{=}CF)_n$) has been shown fruitful. Aside from this rule of thumb, the way the bridge units are arranged (e.g., CH=N vs. N=CH) also greatly influences the behavior of a three-component system. It is noteworthy that if it were to be attempted to construct bridges with vastly different communicating ability, this could be achieved easily with the use of a few building units, as demonstrated in our (X=Y−X′=Y′) results.

The study of protonated push–pull conjugated systems has value in its own right. Rather than emphasize the electric or optical properties of these conjugated systems, we choose to examine their binding properties. This is because control over intermolecular binding is an important issue in the construction of novel functional molecular assemblies, machines, or devices. Moreover, the potential of conjugated molecules in this regard has been explored only to a limited extent in the literature. We have demonstrated that some of our three-component systems can be viewed as molecular sensors/switches with remote sensing/communication ability. Current experimental evidence supports the feasibility of remote binding control through charge alteration in conjugated systems.[12] Our work thus serves to provide insights into how these systems can be analyzed, and of how to identify potential bridge types that facilitate remote communication. Armed with the knowledge acquired in this study, the design of new three-component systems with commonly available building blocks is now in progress.

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[18] All reported energies are at the HF/6-31G* level. See the second paragraph of the Computational Details section for the reason for this choice of theory level.

[19] H atoms were added to fulfill the valence requirement. The two molecules in system **3** were constrained to be in the same plane and the N···N distance was fixed at 14.43 Å as in the ammonia complex of pyrrole–$(CH{=}CH)_4$–iminium.

[20] The values are the differences in the Mulliken group charge of pyrrole between protonated and neutral three-component systems.

[21] The Mulliken charge of the H atom of the pyrrole N–H group increases from 0.448 to 0.467 in the pyrrole–$(N{=}N)_n$–iminium series (n = 1–4). It has been established that charge values correlate with the pK_a values of the proton donors. For a recent example, see C. A. Holingsworth, P. G. Seybold, C. M. Hadad, *Int. J. Quantum. Chem.* **2002**, *90*, 1396–1403.

[22] See Supporting Information. A correlation coefficient (R^2) of 0.9983 is obtained if the four deviating data points are not included in the correlation.

[23] H atoms were added (1.0 Å from the heavy atom along the original bond direction) to fulfill the valency requirement of pyrrole and the two-component system. In doing so, we avoided the spin-contamination problem of open-shell systems. This approximation appears to work well as evidenced by the reasonable results.

[24] Geometries used in calculation of MEP are the same as those used in calculation of q_{LUMO} and ΔE.

[25] LUMO energies of all two-component systems (used to obtain ΔE in Figure 2) are provided in the Supporting Information. It is to be noted that the same LUMO energy trends are observed with fully optimized or frozen $(N{=}N)_n$ and $(CH{=}CH)_n$ two-component systems.

[26] Since we want to illustrate a general phenomenon with Figure 4, we have used optimized geometries of closed-shell molecules, rather than the geometry found in the protonated three-component system.

[27] The π-HOMO and π-LUMO for planar H–$(CF{=}CF)_n$–H are −9.44 and 3.07 eV for n = 2, and −8.69 and 1.38 eV for n = 4. The corresponding values for H–$(CH{=}CH)_n$–H are −8.75 and 3.63 eV for n = 2, and −7.53 and 2.39 eV for n = 4. An imaginary frequency is observed for planar H–$(CF{=}CF)_4$–H. However, because the geometry of the protonated three-component system containing $(CF{=}CF)_4$ is planar, the π-HOMO and π-LUMO of planar H–$(CF{=}CF)_4$–H are reported.

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