Multi-Stimuli Responsive Gelators Exhibiting Molecular Logic

Hsuan-Chin (Jonathan) Wang Literature Seminar December 6th, 2012

Stimuli responsive chemical systems have found a wide range of applications because of their abilities to effect intelligent functions. The recognized "intelligence" arises because the systems appear to "process" incoming stimuli and "decide" on the proper responses, similar to a brain making logical decisions. In fact, it is from this perspective that the concept of molecular logic is established. Research into molecular logic gained momentum after de Silva published his 1993 work[1] that was considered the first true multi-input molecular logic system. Since then, a large number of molecular logic systems, demonstrating ever more complex logic functions and diverse chemistries, have appeared in the literature and encompass areas such as chemical sensing[2], gene regulation[3], controlled delivery[4], molecular actuation [5], etc.

The diverse applicability demonstrated attests to the generality of Boolean logic, which is the basis of molecular logic. Boolean logic was developed by English mathematician George Boole using a binary system (i.e., True and False, or the equivalent "1" and "0" numerical scheme) to designate the states of the input and output.[6] In molecular logic systems, the binary states are usually defined in terms of the presence/absence or high/low intensity of input stimuli that lead to a specific type of output responses (**Fig. 1**).[7] Through simple counting of possible Boolean logic outcomes[6], it can be shown that a multi-stimuli responsive molecular logic system can, in comparison to a one-input/one-output system, theoretically utilize a larger array of logic operations to perform more complex tasks, and thus show more intelligent capabilities.

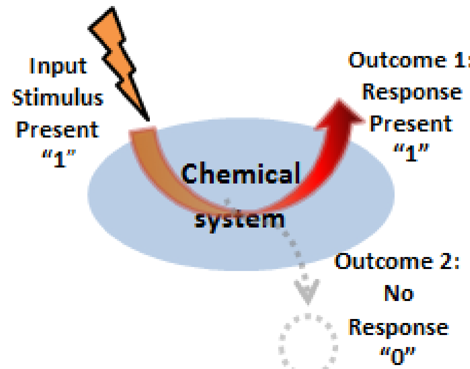

Figure 1:
One-input/one-output system with two possible outcomes: "1" & "0"

The majority of the multi-stimuli responsive molecular logic systems demonstrated so far operate in liquid solvent[8], which could hinder their applicability in cases that have difficulties retaining materials in liquid form. This limitation motivates researchers to look beyond pure solution phase for multi-stimuli responsive chemical systems, and recent implementations in solid state thin film[9], polymer matrix[8], and gels[4,5,10] have been reported. In the past three years, a few groups[4,10] have studied multi-stimuli responsive molecular logic systems based on low molecular weight gelators (LMWGs), which are solvated small molecules that self-assemble at a proper concentration and temperature to form hydro or organogels. LMWGs are particularly attractive as a component of a multi-stimuli responsive chemical system since their use of supramolecular interactions for self-assembly adds stimuli-responsive properties that could be usefully modulated.[11] Furthermore, in stimuli responsive gel materials, the ease of detection through macroscopic state transformations is another major benefit.

In 2009, Park and co-workers[10] published a fluorescent organogelator system showing "on/off" switching using thermal and optical stimuli. The organogelator (**Fig.2a**), abbreviated "SS-TFMBE," fluoresces intensely in its gel state through a process called "aggregation induced enhanced emission" (AIEE), but shows very little fluorescence when it is in solution form. Since the LMWGs undergo a gel to sol transition at their transition temperatures, heating the SS-

TFMBE gel is one way to quench fluorescence. The authors then incorporated a photochromic compound (**Fig**. **2b**) into the gel to add an optical "switch" to control fluorescence. The photo-

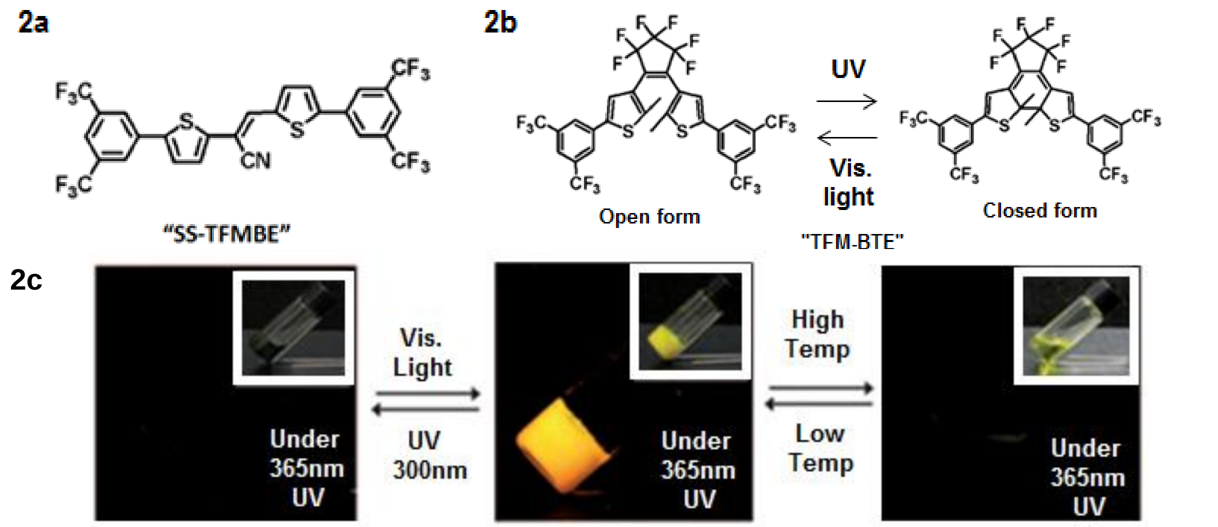

Figure 2: a) gelator with phase induced fluorescence b) photoreversible fluorescence quencher c) gelator/quencher mixture gel fluoresces (middle); loss of fluorescence under 300 nm UV exposure (left) **or** at high temperature. (right); insets: under visible light.

sensitive compound, abbreviated "TFM-BTE," undergoes reversible ring closing/opening isomerization when exposed to UV and visible light, respectively. The two isomeric forms show distinct absorption behaviors, with the closed form absorbing strongly at 577 nm, which is close to the fluorescence emission of SS-TFMBE gel. When exposed to UV, the gel containing closed form of TFM-BTE loses fluorescence by intermolecular energy transfer. Using UV and heat as fluorescence quenchers, the authors demonstrate that either stimulus can "turn off" the fluorescence from the two-component gelator system- an example of OR logic function. (**Fig. 2c**)

The same year, another team led by Hamachi[4] from Kyoto University described an aqueous molecular gelator (**Fig. 3a**) that demonstrates four basic logic operations (AND, OR, NAND, and NOR) with multiple stimuli (Ca^{2+}, pH, heat, and UV/visible light). The hydrogelator possesses two "receptor" sites, the phosphate end group sensitive to ions and the *cis-trans* isomerizable alkene unit sensitive to photoexcitation. The authors observed addition of either

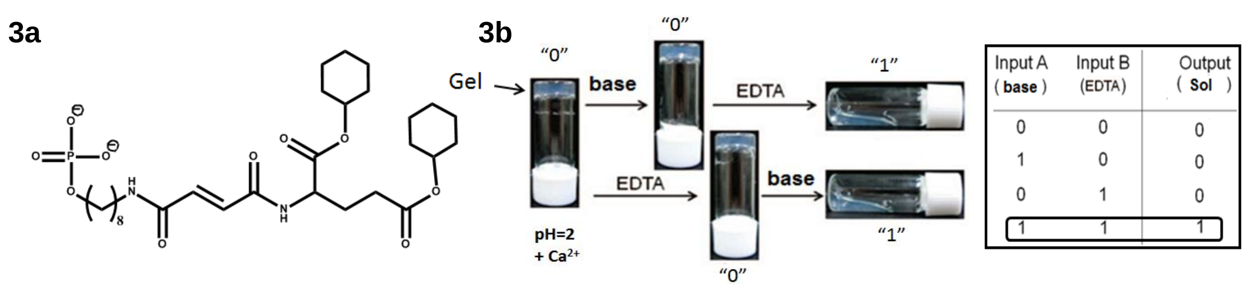

Figure 3: a) ion/photo-sensitive hydrogelator b) AND logic: EDTA **and** base (Inputs =1) needed for gel→sol transition (Output =1); table on right: AND logic in binary values.

Ca^{2+} or H^+ to gelator solution results in gelation, while its removal restores the sol. In addition to ionic stimuli, the *cis*-isomerization with UV of the hydrogelator in gel form also induces gel to sol transition that can be reversed through Br_2 catalyzed *tran*-isomerization with visible light.

Finally, as previously mentioned, adjusting temperature is another way to control phase transition. By combining these independent stimuli to effect macroscopic sol-gel transition under various conditions, the authors showed that four fundamental logic functions, AND, OR, NAND, and NOR, could be demonstrated. (AND logic shown as a representative example in **Fig. 3b**)

The two molecular gelator systems discussed here achieve different functions (optical switching and phase switching) through implementations of multiple stimuli that can be considered molecular analogues of Boolean logic operations. However, in general, the "smarter" a complex stimuli responsive system is, proportionally more complex challenges arise in its design and operation since more attributes need to be optimized. Common issues such as slow reaction time, transformation irreversibility, input-output stability are some of the major obstacles that need to be overcome before the vision of intelligent molecular logic systems efficiently integrated in complex environments can be realized. Although still early in development and largely proof of concept demonstrations, multi-stimuli responsive gelators nevertheless hold promise in applications that benefit from macroscopic transformation (e.g., phase transition, mechanical actuation, etc) while minimizing handling drawbacks associated with pure solution phase systems.

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