NJC

Cite this: *New J. Chem.*, 2011, **35**, 948–952

www.rsc.org/njc

PAPER

Molecular logics: a mixed bodipy–bipyridine dye behaving as a concealable molecular switch†

Fausto Puntoriero,[a] Francesco Nastasi,[a] Thomas Bura,[b] Raymond Ziessel,*[b] Sebastiano Campagna*[a] and Antonino Giannetto*[a]

Received (in Montpellier, France) 8th October 2010, Accepted 7th February 2011
DOI: 10.1039/c0nj00770f

A species based on a bodipy chromophore and containing bipyridine chelating sites behaves as a concealable molecular switch, featuring part of the properties of D-latch circuits by integrating two logic gates, a NOR and an INHIBIT gate, with both gates sharing the same inputs.

Introduction

Molecular logics, initially introduced in the late eighties[1] and fostered by de Silva's suggestion[2] that luminescence signals controlled by cations, protons and other chemical species could be seen to be analogous to digital responses in electronic logic gates, is a very active research field.

Molecular logics is indeed a powerful approach to process information at the molecular level. For example, molecular properties such as absorption, redox behavior, and luminescence can be affected by the presence of other molecules, ions, and/or specific light and/or redox inputs. So, by using an electronic analogy, the addition of ions, protons, *etc*. represents the inputs which are decoded by a specific molecule (or molecular assembly), giving rise to specific outputs (most commonly, luminescence at a given wavelength). The specific molecule behaves as a molecular logic gate, depending on the truth table generated by the combination of inputs and outputs.[3]

In principle, molecular logic gates are by themselves more powerful than silicon-based analogues, as the same molecule can behave as different, distinct logic gates, depending on the inputs and outputs considered.[4] Leaving aside speculation related to the construction of chemical computers, design of novel molecular logic gates is also attracting a large interest because these species can be connected to applications in the fields of sensing and labeling[5] and since the behavior of molecular logic gates could assist to understand the chemical basis of complex biological processes.[6] However, as recently mentioned by many researchers,[1,4d,5,7] probably the strongest aspect of molecular logic research is to introduce new viewpoints to look at chemical systems, so contributing to develop new ideas.

In this latter regard, molecular logics has another advantage over traditional, silicon-based electronics, as novel logic functions can be designed/performed, inspired by similar, but not identical, existing processes operating in the electronic realm.

Recently, research on molecular logics has allowed us to design systems capable to perform quite complex and valuable logic functions, based on the combination of multiple gates. Examples are the molecular half-adders,[8] full-adders,[4f] keypad lock,[9] multiplexers,[4a,10] and encoder–decoder[4d,11] systems recently reported.

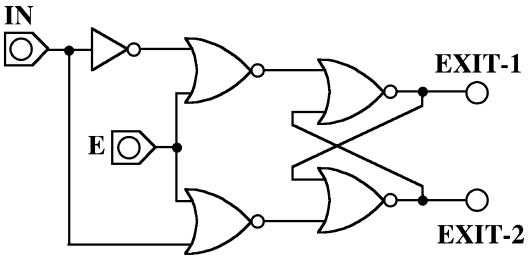
Most of the molecular logic gates reported up to now are based on combinational logic. A quite intriguing perspective in the molecular logic research field is the design of systems capable to work by a sequential logic that is a type of logic circuit whose output depends not only on the present input but also on the history of the input. This is in contrast to combinational logic, whose output is a function of, and only of, the present input. In other words, sequential logic has a sort of data storage (memory) that combinational logic does not. An example of circuits operating by a sequential logic is D-latch circuits.

In gated D-type latches,[12] two external inputs are available: one (the *exchanging input* or *data input*, named IN in Scheme 1) has the function of exchanging the output between *exit*-1 and *exit*-2; it can be thought of as a switch. The second input (the *output enabler*, named E in Scheme 1) has the function of blocking the output as it is at the time the second input is activated, disabling any successive effect of the first input IN until the second input E is removed.

Here we report on a hybrid bodipy–bipyridine dye, **1** (see Fig. 1), which is able to process two inputs, protons and Cu^{2+} ions, giving rise to luminescence outputs which resemble in

[a] *Dipartimento di Chimica Inorganica, Chimica Analitica e Chimica Fisica, Università di Messina, via Sperone 31, 98166 Vill. S. Agata, Messina, Italy. E-mail: campagna@unime.it*
[b] *Laboratoire de Chimie Organique et Spectroscopies Avancées (LCOSA), Centre National de la Recherche Scientifique (CNRS), Ecole de Chimie, Polymères Matériaux (ECPM), Université de Strasbourg (UdS), 25 rue Becquerel, 67087 Strasbourg Cedex 02, France. E-mail: ziessel@unistra.fr*

† Electronic supplementary information (ESI) available: Absorption and emission spectral changes of **1** upon Cu^{2+} complexation; interactive figure illustrating the behavior of **1**. See DOI: 10.1039/c0nj00770f



Scheme 1 The logic scheme of a possible D-latch system. E represents the enabler/disabler input, and IN is the data input.

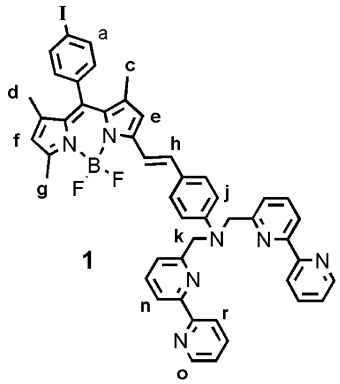


Fig. 1 Molecular formula of **1**.

some aspects the behavior of a gated D-latch system, although some essential features of an effective D-latch system behavior are not matched (so a molecular-level counterpart of D-latch circuits still remains elusive). In essence, **1** can behave as a disguised molecular switch, by integrating the behavior of two logic gates, a NOR and an INHIBIT gate, which share the same inputs.

Results and discussion

Compound **1** comprises an extended fluorescent core made of a 4,4-difluoro-4-bora-3a,4a-diaza-s-indacene (bodipy) dye, and a complexation pocket made of a tertiary amine tethered with two bipyridine subunits. The general route for the synthesis of **1** has been already reported as a preliminary communication and full synthetic details are given in the Experimental part.[13] Compound **1** has been unambiguously characterized by modern NMR techniques. In particular the splitting of the β-pyrrolic protons into two singlets at 5.97 (assigned to proton f) and at 6.58 ppm (proton e) is diagnostic for the level of substitution (Fig. 2). This is in agreement with the observation of three methyl signals at 2.47 (protons g), 1.44 (protons c) and 1.40 ppm (protons d). The presence of two bipyridine side-arms is confirmed by the integration of the methylene groups at 4.99 ppm accounting for 4H and the deshielded doublet at 8.64 ppm assigned to the protons in the *ortho* position of the pyridine rings (protons o). The 16.2 Hz proton–proton coupling constant for the vinyl protons at 7.18 ppm confirms the *E*-conformation of the double bond.

In acetonitrile solution, **1** exhibits a relatively strong emission (Φ = 0.26, τ = 2 ns), peaking at 695 nm (see Fig. 3),

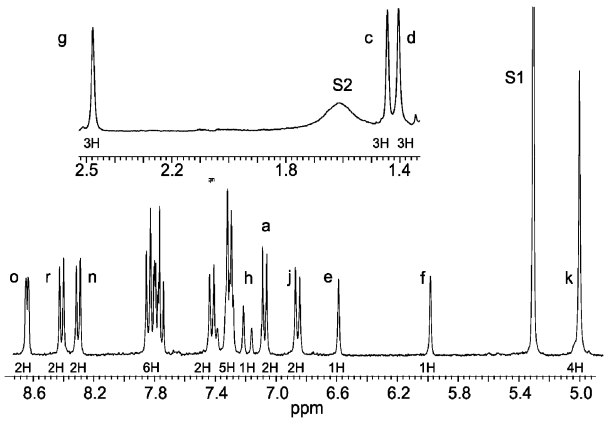


Fig. 2 Aromatic region of the proton NMR of compound **1** in CD_2Cl_2 labeled S1 in the spectra. Inset: expanded aliphatic region, S2 accounts for residual water.

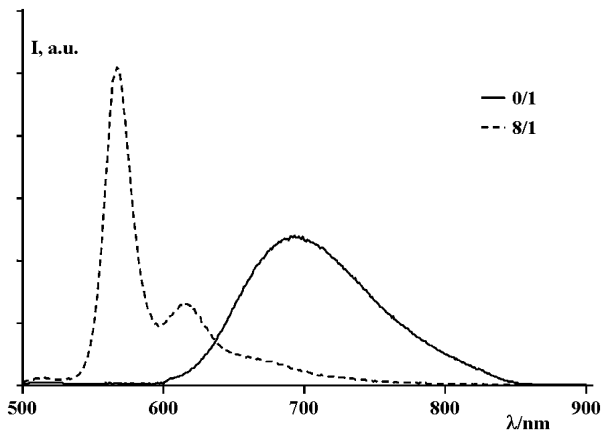


Fig. 3 Emission spectral changes of **1** upon protonation (acetonitrile solution). Concentration of **1** is 9.4×10^{-6} M; in the panel, molar ratios between added triflic acid and **1** are reported.

originated from a singlet excited state with partial charge transfer (CT) character, where the tertiary amine plays the role of the donor and the bodipy core is the acceptor. Addition of protons (triflic acid; 1 : 8 molar ratio between **1** and H^+) leads to disappearance of the 695 nm emission, with the appearance of a structured emission peaking at 570 nm (Fig. 3), as a consequence of protonation of the tertiary amine group and destabilization of the CT state, so yielding the quite intense and higher-energy emission of the bodipy core (Φ = 0.63, τ = 5 ns).‡

Protonation of the tertiary amine can be reversed by addition of a strong base, so (referring to Scheme 1) the presence of an acid is the *exchanging input* capable of switching the emission output between *exit*-1 (emission at 695 nm) and *exit*-2 (emission at 570 nm). The other input is the presence of Cu^{2+} ions: indeed Cu^{2+} is promptly coordinated by the bipyridine subunits of **1**, quantitatively, as indicated by

‡ Please note that a large excess of acid is needed to protonate the tertiary amine group of **1**, since the initial acid addition leads to protonation of the bipyridine units, with only small changes in the emission spectrum.

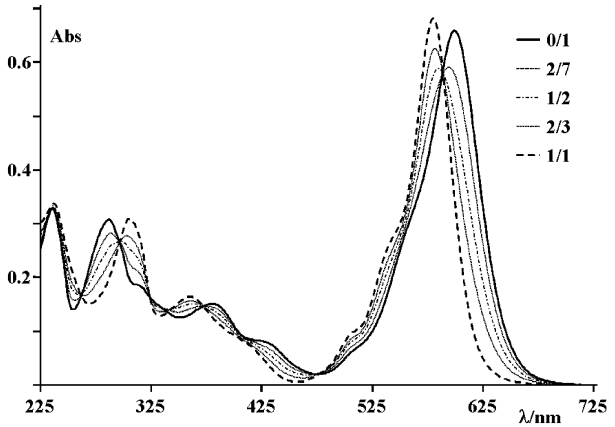


Fig. 4 Absorption spectral changes of **1** upon Cu^{II} complexation. Concentration of **1** is 8.6×10^{-6} M; in the panel, molar ratios between added $CuCl_2$ and **1** are reported. Solvent: acetonitrile.

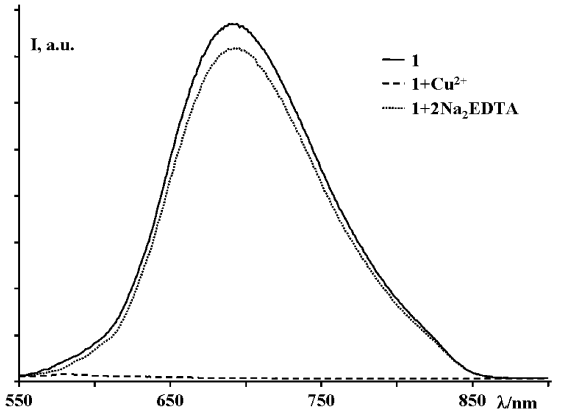
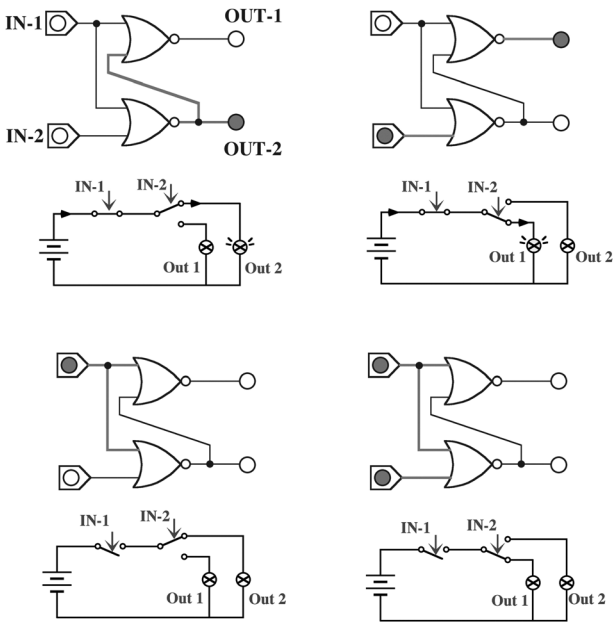


Fig. 5 Emission spectral changes of **1** upon Cu^{2+} complexation. Concentration of **1** is 2.84×10^{-6} M. Solid line, emission spectra of **1**; dashed line (mostly overlapped with baseline), emission spectra of **1** after adding $CuCl_2$ in the molar ratio 1/1; dotted line, emission spectra of **1** after adding $CuCl_2$ and (successively) Na_2EDTA in the molar ratio 1/1/3. Excitation is performed at 375 nm, an isosbestic point. Solvent: acetonitrile.

absorption spectral changes of **1** in the presence of $CuCl_2$ (see Fig. 4).§ The coordination of Cu^{2+} fully quenches the emission of **1** at any wavelengths (see Fig. 5): most likely the formation of the Cu^{2+} complex introduces a low-lying metal-centered excited state, to which all the other excited states of **1** deactivate, and which decays to the ground state by radiationless processes.¶ In the presence of Cu^{2+}, any addition/removal of protons has no effect on the emission properties, and both *exits* are deactivated. However, removal of Cu^{2+} ions, for example by EDTA, restores the emission outputs (Fig. 5). The presence of Cu^{2+} ions plays therefore the role of *output enabler/disabler* input.

The truth table of the above described system is shown in Fig. 6, which also shows the logic scheme of **1** (in this scheme, the E and IN inputs of Scheme 1 are called IN-1 and IN-2, respectively) and the corresponding switch circuit schematization, based on two NOR logic gates, with the four possible combinations of input digits (00, 01, 10, 11). When input-1 (represented by Cu^{2+}, the *enabler/disabler* input) is absent, input-2 (the *exchanging or switching input*, *i.e.* acidification) switches the system output from the output digit 01 to the output digit 10. In the presence of input-1, no exit is active (output digit is always 00), both in the presence and absence of protons.

We wish once more to clearly point out that our system *is not* a D-latch system, whose design remains an elusive task at the molecular level; however, our system is inspired by D-latches as far as the effect of the enabler/disabler input on the functioning of the "exchanging" input is concerned: both in D-type latches and in our system, the exchanging input can be made inefficient. From an operational viewpoint, the difference is that in fully-operative D latches the enabler/disabler input blocks the function of the exchanging input but leaves one output active, which now becomes independent of the state of the system as far as the exchanging input is



IN-1 Cu^{2+}	IN-2 H^+	OUT-1 λ_{em}=570 nm	OUT-2 λ_{em}=695nm
0	0	0	1
0	1	1	0
1	0	0	0
1	1	0	0

Fig. 6 Truth table, combined logic gate diagrams and circuit schematizations of **1**. All the four possible combinations of inputs are illustrated. Interactive diagrams, also showing effects on the emission spectra, are given as ESI.†

§ The quantitative complexation is shown by the fact that any successive addition of $CuCl_2$ does not modify the spectrum corresponding to the 1 : 1 molar ratio shown in Fig. 4. Also, the several isosbestic points which are maintained during all the coordination process indicate that a single process (*i.e.*, copper coordination) takes place.

¶ The bodipy luminescence could also be quenched by the Cu^{2+}-containing subunit *via* oxidative electron transfer. The mechanism of the quenching process is not investigated here.

concerned, whereas in **1** the enabler/disabler input deactivates both outputs (in this sense, a specific memory function of D-latches is missed by **1**). However the information linked to the exchanging input of the molecular system is still maintained, as removing the enabler/disabler input re-activates the circuit and its specific output, conforming to the situation determined by input-2. The enabler/disabler input in **1** can be seen as a "hide" signal, as the output (and therefore, the information embedded in the system by input-2) is temporarily hidden, but it is stored and can be made visible again at will when the enabler/disabler input is cancelled. In other words, **1** behaves as a concealable molecular switch, where one input (the addition of Cu^{2+} ions) can disguise the state of the proton switchable chromophore. In essence, **1** features the integration of two logic gates: a NOR and an INHIBIT gate, with both gates sharing the same inputs.

Finally, with reference to the connections between molecular logics and complex biological systems as far as the information processing is concerned, we would like to note that the behavior of **1** could basically recall the way in which some multifunctional enzymes (ME) work. An ME is an enzyme which can perform different functions (outputs), depending on changes of its environment (the "exchanging" input);[14] however, when a suitable inhibitor (the "enabler/disabler" input) is present, all the enzyme functions (or most of them) can be suppressed.

Conclusions

In short, we showed that **1** can exhibit a behavior which recalls in part that of a D-type latch circuit, when protons and Cu^{2+} ions are used as the chemical inputs. The complete behavior of a D-latch system (including the quite interesting memory functions typical of D-latch systems) is not matched, however a behavior allowing to include a hiding function on the output of a stored information is obtained.[15] Our results further indicate that electronic logics can inspire the design of systems towards alternative ways of processing the information at the molecular level.

This work is supported by MIUR (Prin 2008), the University of Messina, and the Centre National de la Recherche Scientifique (CNRS).

Experimental part

General methods

All reactions were performed under a dry atmosphere of argon using standard Schlenk tube techniques. All chemicals were used as received from commercial sources without further purification unless otherwise stated. Toluene was distilled from P_2O_5 under an argon atmosphere. The 200, 300, 400 (^{1}H) and 50, 75, 100 MHz (^{13}C) NMR spectra were recorded at room temperature using perdeuterated solvents as internal standards: ‰ (H) in ppm relative to the residual protiated solvent; ‰ (C) in ppm relative to the solvent. Mass spectra were measured with a ESI-MS mass spectrometer. Chromatographic purifications were performed using 40–63 μm silica gel. TLC was performed on silica gel plates coated with a fluorescent indicator.

UV-Vis absorption spectra were recorded with a Jasco 560 spectrophotometer. Steady-state luminescence spectra were recorded with a Horiba Jobin-Yvon Fluoromax P spectrofluorimeter equipped with a Hamamatsu R3896 photomultiplier, and were corrected for photomultiplier response using a program purchased with the fluorimeter. Emission lifetimes were measured with an Edinburgh OB-900 single-photon counting spectrometer equipped with a Hamamatsu PLP-2 laser diode (pulse width at 408 nm, 59 ps) and/or with a PicoQuant PDL 800-D pulsed laser diode (pulse width at 308 nm, 50 ps). The emission decay traces (emission lifetimes measured at the emission maximum wavelengths) were analyzed by the Marquadt algorithm. Experimental uncertainty for absorption spectra maxima is 2 nm, for molar absorption is 10%, for luminescence emission maxima is 4 nm, for luminescence lifetime is 10%.

Preparation and characterization of compound 1. In a round-bottomed flask equipped with a Dean stark apparatus, 4-(bis((6-(pyridin-2-yl)pyridin-2-yl)methyl)amino)benzaldehyde (85 mg, 0.185 mmol) and piperidine (2 mL) were added to a stirred solution of bodipy (5.5 mg, 0.123 mmol) in toluene (20 mL). The solution was heated at reflux for 12 h. After cooling to rt, the mixture was washed with water and brine. The organic phase was filtered over hydroscopic cotton wool and rotary evaporated. The residue was purified by column chromatography on silica gel eluting with a gradient of ethyl acetate/petroleum ether (20/80 to 40/60) to give compound **1** (72 mg, 65%). ^{1}H NMR (CD_2Cl_2, 300 MHz): δ = 1.40 (s, 3H), 1.44 (s, 3H), 2.47 (s, 3H), 4.99 (s, 4H), 5.97 (s, 1H), 6.58 (s, 1H), 6.85 (d, ^3J = 9 Hz, 2H), 7.07 (d, ^3J = 8.3 Hz, 2H), 7.18 (d, ^3J = 16.15 Hz, 1H), 7.27–7.31 (m, 5H), 7.41 (d, ^3J = 8.6 Hz, 2H), 7.73–7.84 (m, 6H), 8.29 (d, ^3J = 7.9 Hz, 2H), 8.41 (d, ^3J = 7.9 Hz, 2H), 8.64 (d, ^3J = 4.1 Hz, 2H); ^{13}C{^{1}H} NMR ($CDCl_3$, 50 MHz): δ = 14.2, 15.0, 46.3, 57.6, 78.6, 83.1, 112.9, 115.1, 118.0, 119.7, 120.8, 121.1, 121.4, 122.9, 123.9, 125.8, 128.7, 129.5, 132.8, 136.1, 137.1, 137.6, 137.9, 138.0, 141.0, 142.7, 149.3, 149.7, 153.7, 154.8, 156.2 ppm; ESI-MS: *m*/*z*: 889.2 (100) $[M]^+$; elemental analysis calcd for $C_{48}H_{39}BF_2IN_7$ (M_r = 889.58): C, 64.81; H, 4.42; N, 11.02%. Found: C, 64.52; H, 3.98; N, 10.84%.

Notes and references

1 A. Aviram, *J. Am. Chem. Soc.*, 1988, **110**, 5687.
2 A. P. de Silva, H. Q. N. Gunaratne and C. P. McCoy, *Nature*, 1993, **364**, 42.
3 For few recent books or reviews, see: (*a*) *Molecular Devices and Machines-Concepts and Perspectives for the Nanoworld*, ed. V. Balzani, A. Credi and M. Venturi, Wiley-VCH, Weinheim, 2008, ch. 9; (*b*) K. Szacilowski, *Chem. Rev.*, 2008, **108**, 3481; (*c*) A. P. de Silva and S. Uchiyama, *Nat. Nanotechnol.*, 2007, **2**, 399; (*d*) U. Pischel, *Angew. Chem., Int. Ed.*, 2007, **46**, 4026.
4 A few papers are mentioned here: (*a*) M. Amelia, M. Baroncini and A. Credi, *Angew. Chem., Int. Ed.*, 2008, **47**, 6240; (*b*) D. Gust, T. A. Moore and A. L. Moore, *Chem. Commun.*, 2006, 1169; (*c*) J. Andreasson and U. Pischel, *Chem. Soc. Rev.*, 2010, **39**, 174; (*d*) P. Ceroni, G. Bergamini and V. Balzani, *Angew. Chem., Int. Ed.*, 2009, **48**, 8516; (*e*) F. M. Raymo and M. Tomasulo, *Chem.–Eur. J.*, 2006, **12**, 3186; (*f*) D. Margulies, G. Melman and A. Shanzer, *J. Am. Chem. Soc.*, 2006, **128**, 4865; (*g*) K. Rurack,

C. Trieflinger, A. Koval'chuck and J. Daub, *Chem.–Eur. J.*, 2007, **13**, 8998; (*h*) E. Perez-Inestrosa, J. M. Montenegro, D. Collado and R. Suau, *Chem. Commun.*, 2008, 1085; (*i*) H. Tian and Q. C. Wang, *Chem. Soc. Rev.*, 2006, **35**, 361; (*j*) A.-F. Li, Y.-B. Ruan, Q.-Q. Jiang, W.-B. He and Y.-B. Jiang, *Chem.–Eur. J.*, 2010, **16**, 5794; (*k*) H. T. Baytekin and E. U. Akkaya, *Org. Lett.*, 2000, **2**, 1725.

5 O. A. Bozdemir, R. Guliyev, O. Buyukcakir, S. Selcuk, S. Kolemen, G. Gulseren, T. Nalbantoglu, H. Boyaci and E. U. Akkaya, *J. Am. Chem. Soc.*, 2010, **132**, 8029.

6 (*a*) *Bionanotechnology: Lessons from Nature*, ed. D. S. Goodsell, Wiley, Hoboken, 2004; (*b*) *Soft Machines: Nanotechnology and Life*, ed. R. A. L. Jones, Oxford University Press, New York, 2004.

7 (*a*) A. Credi, *Nat. Nanotechnol.*, 2008, **3**, 529; (*b*) A. P. de Silva, M. R. James, B. O. F. McKinney, D. A. Pears and S. M. Weir, *Nat. Mater.*, 2006, **5**, 787.

8 J. Andréasson, S. R. Straight, G. Kodis, C.-D. Park, M. Hambourger, M. Gervaldo, B. Albinsson, T. A. Moore, A. L. Moore and D. Gust, *J. Am. Chem. Soc.*, 2006, **128**, 16259.

9 (*a*) J. Andréasson, S. R. Straight, T. A. Moore, A. L. Moore and D. Gust, *Chem.–Eur. J.*, 2009, **15**, 3936; (*b*) D. Margulies, C. E. Felder, G. Melman and A. Shanzer, *J. Am. Chem. Soc.*, 2007, **129**, 347.

10 J. Andréasson, S. R. Straight, S. Bandyopadhyay, T. A. Moore, A. L. Moore and D. Gust, *Angew. Chem., Int. Ed.*, 2007, **46**, 958.

11 C. Giansante, P. Ceroni, M. Venturi, J. Sakamoto and A. D. Schlüter, *ChemPhysChem*, 2009, **10**, 495.

12 *Ones and Zeros Understanding Boolean Algebra, Digital Circuits and the Logic of Sets*, ed. J. R. Gregg, Wiley, New York, 1998.

13 T. Bura and R. Ziessel, *Tetrahedron Lett.*, 2010, **51**, 2875.

14 (*a*) M. St. Maurice, L. Reinhardt, K. H. Surinya, P. V. Attwood, J. C. Wallace, W. W. Cleland and I. Rayment, *Science*, 2007, **317**, 1076; (*b*) S. J. Wakil, *Biochemistry*, 1989, **28**, 4523; (*c*) R. Scherzer, G. Y. Gdalevsku, Y. Goldgur, R. Cohen-Luria, S. Bittner and A. H. Parola, *J. Enzyme Inhib. Med. Chem.*, 2009, **24**, 350; (*d*) L. Wu, X. Liu and D. Li, *Org. Lett.*, 2008, **10**, 2235; (*e*) M. Baes, S. Huyghe, P. Carmielet, P. E. Declerq, D. Collen, G. P. Mannaerts and P. P. Van veldhoven, *J. Biol. Chem.*, 2000, **275**, 16329; (*f*) C. Lopez-Otin and J. S. Bond, *J. Biol. Chem.*, 2008, **283**, 30433.

15 It has been recently proposed that systems operating by sequential logics, like D-latch systems, could require the integration of kinetic effects with thermodynamic parameters, see: (*a*) U. Pischel, *Angew. Chem., Int. Ed.*, 2010, **49**, 1356. For other works related to this aspect, see: ; (*b*) A. E. Keirstead, J. W. Bridgewater, Y. Terazono, G. Kodis, S. Straight, P. A. Liddell, A. L. Moore, T. A. Moore and D. Gust, *J. Am. Chem. Soc.*, 2010, **132**, 6588; (*c*) M. Semeraro and A. Credi, *J. Phys. Chem. C*, 2010, **114**, 3209; (*d*) G. Periyasamy, J.-P. Collin, J.-P. Sauvage, R. D. Levine and F. Remacle, *Chem.–Eur. J.*, 2009, **15**, 1310.

