Molecular Logic

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A Simple Unimolecular Multiplexer/Demultiplexer**

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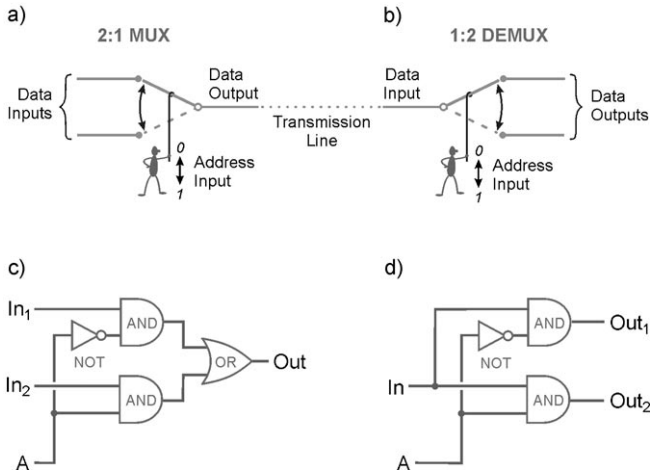
In living organisms information is processed, transferred, and stored using molecular or ionic substrates.[1] The design and construction of molecular systems capable of elaborating information[2] could lead to the development of radically new computing paradigms and, in the long term, to the realization of useful devices. Leaving aside speculation related to the construction of a chemical computer, molecular logic systems could perform relatively simple computing tasks that cannot be accomplished with silicon-based devices, e.g. in nanoscale spaces[3] or in vivo.[4]

Molecular switches convert input stimuli into output signals.[5] Hence, the principles of binary logic[6] can be applied to signal transduction operated by molecules under appropriate conditions.[7] Many chemical systems that mimic the operation of semiconductor logic gates and circuits have been reported.[8–15]

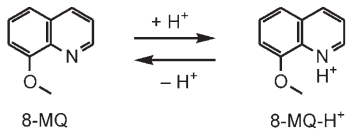
An important function in information technology is signal multiplexing/demultiplexing. A 2:1 multiplexer (MUX) is a circuit with two data inputs, one address input, and one output. The MUX selects the binary state from one of the data inputs and directs it to the output; the selected input depends on the binary state of the address input (Scheme 1a). Conversely, a 1:2 demultiplexer (DEMUX) is a circuit that possesses one data input, one address input, and two outputs. The DEMUX routes the data input to one of the output lines, and the selected output is determined by the binary state of the address input (Scheme 1b). Hence a multiplexer allows the encoding of multiple data streams into a single data line for transmission, and a demultiplexer can decode entangled data streams from a single signal (Scheme 1a, b). The combinational circuits corresponding to a 2:1 multiplexer and 1:2 demultiplexer are shown in Schemes 1c and d, respectively.

Molecules that can mimic the function of a 2:1 multiplexer[16] or a 1:2 demultiplexer[17,18] have recently been reported. However, these systems either rely on carefully designed multicomponent species[16,17] and coupling to an external optical device,[17] or imply a dependence of the data input on the binary state of the address input.[18] Demultiplexers based on solid-state nanostructures have also been described.[19] Here we show that the reversible acid/base switching of the absorption and photoluminescence properties of a fluorophore as simple as 8-methoxyquinoline in solution can form the basis for molecular 2:1 multiplexing and 1:2 demultiplexing with a clear-cut digital response.



Scheme 1. Operation scheme (top) and combinational logic network (bottom) corresponding to a 2:1 multiplexer (a and c) and a 1:2 demultiplexer (b and d).

8-Methoxyquinoline (8-MQ, Scheme 2) is related to the well-known fluorogenic compound 8-hydroxyquinoline (8-HQ).[20] The absorption spectrum of 8-MQ in CH_3CN (Figure 1a) shows a band with $\lambda_{max} = 301$ nm, assigned to a π–π^* transition.[21] In contrast with 8-HQ, 8-MQ is strongly fluorescent ($\lambda_{max} = 388$ nm, Figure 1b) because the presence of the methoxy group prevents the intramolecular proton transfer process in the excited state responsible for the strong fluorescence quenching in 8-HQ.[21,22] The addition of one equivalent of triflic acid (CF_3SO_3H) to 8-MQ affords the protonated form 8-MQ-H^+ (Scheme 2), the absorption and fluorescence spectra of which are markedly different from those of 8-MQ.[21] Specifically, the absorbance in the region of the 8-MQ absorption band (270–320 nm) decreases substantially, and a new absorption band ($\lambda_{max} = 358$ nm, Figure 1c) is observed in a spectral region where 8-MQ does not absorb light. The fluorescence band of 8-MQ, which has a maximum



Scheme 2. Acid/base-controlled switching between 8-methoxyquinoline (8-MQ) and its protonated form (8-MQ-H^+).

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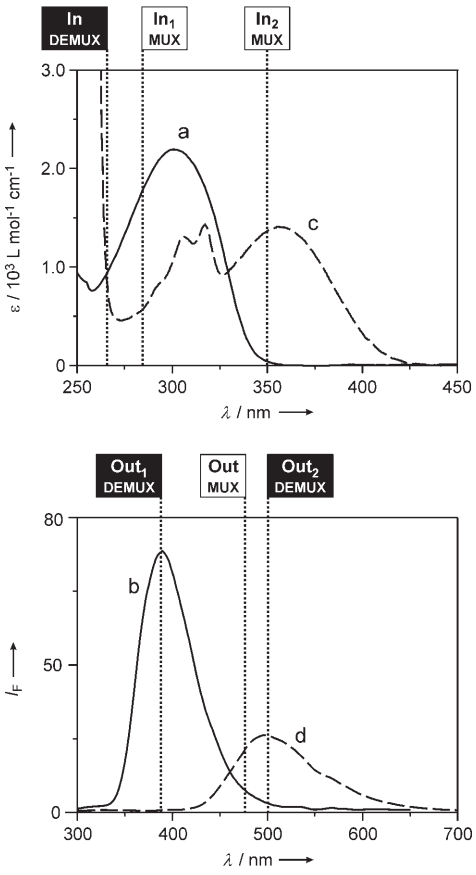

Figure 1. Absorption (top) and fluorescence ($\lambda_{ex} = 262$ nm, bottom) spectra of 8-MQ (a and b) and 8-MQ-H^+ (c and d). The wavelengths of the inputs and outputs signals relevant for the MUX/DEMUX binary functions are indicated. Conditions: 1.5×10^{-5} mol L^{-1}, air-equilibrated MeCN, RT.

at 388 nm, is replaced by a weaker emission band with $\lambda_{max} =$ 500 nm (Figure 1d). The unprotonated form can be regenerated on addition of one equivalent of tris-*n*-butylamine (*n*Bu_3N). The acid/base-controlled switching between 8-MQ and 8-MQ-H^+ is fully reversible and can be repeated many times with the same solution without appreciable reduction in intensity in the absorption and fluorescence spectra. This particular spectroscopic behavior and the chemical reversibility of the acid/base switching can be used to obtain both 2:1 MUX and 1:2 DEMUX functions, using proton concentration as the address input (A), and excitation and emission optical signals as the data inputs and outputs, respectively.

In the case of the 2:1 multiplexer the incident light intensities at 285 nm (In_1) and 350 nm (In_2) were used as the data inputs; these wavelengths were chosen in order to achieve selective excitation of 8-MQ and 8-MQ-H^+, respectively (Figure 1a–c). The output (Out) was monitored using the fluorescence intensity at 474 nm, a wavelength at which both 8-MQ and 8-MQ-H^+ fluoresce (Figure 1b–d). The fluorescence output levels measured for a solution containing 8-MQ in MeCN under the conditions corresponding to the eight combinations of the binary data and address inputs are listed in Table 1. A threshold value could be easily identified in order to assign binary output states so that the truth table

Table 1: Truth table for the 2:1 multiplexer function.

Data inputs		Address input	Data output
In_1	In_2	A	Out
I_{ex} (285 nm)[a]	I_{ex} (350 nm)[a]	[H^+]/[8-MQ]	I_F (474 nm)[b]
0	0	0	0 *(0)*
1	0	0	1 *(21)*
0	1	0	0 *(5.1)*
1	1	0	1 *(26)*
0	0	1	0 *(0)*
1	0	1	0 *(9.2)*
0	1	1	1 *(21)*
1	1	1	1 *(30)*

[a] Binary state 1 corresponds to irradiation with the excitation lamp of the spectrofluorimeter; state 0 corresponds to no excitation (lamp off). [b] The values in parentheses indicate the experimental fluorescence intensity values in arbitrary units; the corresponding binary states are determined by applying a threshold value of $I_F = 15$ arbitary units.

corresponds to that of a 2:1 multiplexer. If the address input is 0 (no H^+ added, 8-MQ form), the output reports the state of data input In_1, whereas if the address input is 1 (1 equivalent of H^+ added, 8-MQ-H^+ form), the output mirrors the state of data input In_2.

The system can be easily reconfigured to behave as a 1:2 demultiplexer by changing the optical input and output channels. In this case, the data input (In) was the incident light intensity at 262 nm, which is an isosbestic point in the absorption spectra of 8-MQ and 8-MQ-H^+. The two output signals were represented by the fluorescence intensity at 388 nm (λ_{max} for 8-MQ, Out_1) and 500 nm (λ_{max} for 8-MQ-H^+, Out_2), respectively. Table 2 shows the fluorescence output

Table 2: Truth table for the 1:2 demultiplexer function.

Data input	Address input	Data outputs	
In	A	Out_1	Out_2
I_{ex} (262 nm)[a]	[H^+]/[8-MQ]	I_F (388 nm)[b]	I_F (500 nm)[b]
0	0	0 *(0)*	0 *(0)*
1	0	1 *(71)*	0 *(0.5)*
0	1	0 *(0)*	0 *(0)*
1	1	0 *(2.1)*	1 *(21)*

[a] Binary state 1 corresponds to irradiation with the excitation lamp of the spectrofluorimeter; state 0 corresponds to no excitation (lamp off). [b] The values in parentheses indicate the experimental fluorescence intensity values in arbitrary units; the corresponding binary states are determined by applying a threshold value of $I_F = 10$ arbitary units.

levels measured for a solution of 8-MQ in MeCN under the conditions corresponding to the four combinations of the binary data and address inputs. On fixing an appropriate threshold for the fluorescence output, the truth table of the 1:2 demultiplexer is obtained. If the address input is 0 (8-MQ form), the binary state of the data input is transmitted to Out_1; conversely, if the address input is 1 (8-MQ-H^+ form), the binary data input is transmitted to Out_2.

Although the construction of a practical device was not the overall purpose of this work, we investigated whether the acid/base switching of the 8-MQ fluorescence observed in solution could also be obtained in a solid-state environment.

To this end, we embedded 8-MQ into polystyrene thin films and recorded the fluorescence spectra of the resulting materials upon exposure to acidic and basic reagents. The result of a typical experiment is shown in Figure 2. Upon

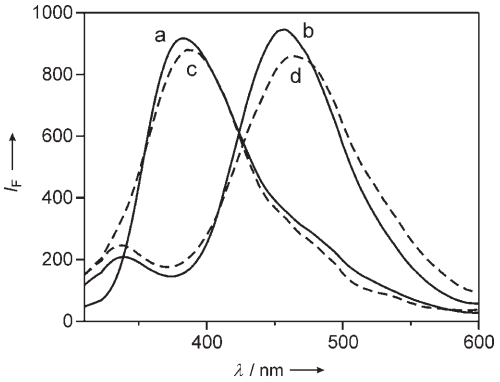

Figure 2. Fluorescence spectra ($\lambda_{ex} = 262$ nm, RT) of a 0.7 μm-thick polystyrene film containing 8-MQ as prepared (a) and subjected to the following sequence of treatments: 10^{-2} mol L^{-1} solution of CF_3COOH in MeCN followed by drying (b), 10^{-2} mol L^{-1} solution of nBu_3N in MeCN followed by drying (c), 10^{-2} mol L^{-1} solution of CF_3COOH in MeCN followed by drying (d).

excitation at 262 nm the unmodified embedded film exhibited the fluorescence band of 8-MQ ($\lambda_{max} = 383$ nm, Figure 2a). After treatment of the film with a solution of CF_3COOH in MeCN followed by drying, the fluorescence band of 8-MQ was replaced by a band with $\lambda_{max} = 465$ nm (Figure 2b), showing that the quantitative conversion of 8-MQ into 8-MQ-H^+ within the plastic material had occurred. Successive exposure of the film to a MeCN solution of nBu_3N regenerated the fluorescence spectrum of 8-MQ (Figure 2c), and a second switching cycle could be started (Figure 2d). Therefore, our observations indicate that the protonation–deprotonation reactions of 8-MQ/8-MQ-H^+ also take place reversibly when such molecules are embedded in a polystyrene matrix.

In summary, we have shown that the proton-driven reversible modulation of two complementary absorption and fluorescence signals allows the implementation of both 2:1 multiplexer and 1:2 demultiplexer digital functions with an unsophisticated fluorophore. This work demonstrates that functions achieved by combinational circuits whose logic design requires the interconnection of several basic elements can be implemented with simple molecules, taking advantage of logic reconfiguration.[9,12–14] Our next goal is to develop a system mimicking a real communication network, in which the output of a multiplexer is sent as the input to a separate demultiplexer. Observation of switching at the single-molecule level[23] and control of the address input with light by intermolecular proton transfer from a photoacid[24] in order to obtain complete optical operation[11] are also under investigation.

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[1] D. S. Goodsell, *Bionanotechnology—Lessons from Nature*, Wiley, Hoboken, **2004**.
[2] a) V. Balzani, A. Credi, M. Venturi, *Chem. Eur. J.* **2008**, *14*, 26; b) J.-M. Lehn, *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 4763.
[3] A. Prasanna de Silva, D. Y. James, B. O. F. McKinney, D. A. Pears, S. M. Weir, *Nat. Mater.* **2006**, *5*, 787.
[4] K. Rinaudo, L. Bleris, R. Maddamsetti, S. Subramanian, R. Weiss, Y. Benenson, *Nat. Biotechnol.* **2007**, *25*, 795.
[5] *Molecular Switches* (Ed.: B. L. Feringa), Wiley-VCH, Weinheim, **2001**.
[6] J. R. Gregg, *Ones and Zeros: Understanding Boolean Algebra, Digital Circuits, and the Logic of Sets*, Wiley, New York, **1998**.
[7] A large number of chemical switches exhibiting interesting properties from a binary logic viewpoint have been reported. In many cases the authors were either not aware of such behavior in their systems, or they published the work before the notion of molecular logic gates became popular. For the first explicit description of the analogy between molecular switches and logic gates, see: A. P. de Silva, H. Q. N. Gunaratne, C. P. McCoy, *Nature* **1993**, *364*, 42.
[8] a) V. Balzani, A. Credi, M. Venturi, *Molecular Devices and Machines—Concepts and Perspectives for the Nanoworld*, 2nd ed., Wiley-VCH, Weinheim, **2008**, chap. 9; b) V. Balzani, A. Credi, M. Venturi, *ChemPhysChem* **2003**, *4*, 49.
[9] A. P. de Silva, S. Uchiyama, *Nat. Nanotechnol.* **2007**, *2*, 399.
[10] D. Gust, T. A. Moore, A. L. Moore, *Chem. Commun.* **2006**, 1169.
[11] F. M. Raymo, M. Tomasulo, *Chem. Eur. J.* **2006**, *12*, 3186.
[12] U. Pischel, *Angew. Chem.* **2007**, *119*, 4100; *Angew. Chem. Int. Ed.* **2007**, *46*, 4026.
[13] A. Credi, *Angew. Chem.* **2007**, *119*, 5568; *Angew. Chem. Int. Ed.* **2007**, *46*, 5472.
[14] a) S. J. Langford, T. Yann, *J. Am. Chem. Soc.* **2003**, *125*, 11198; b) D. H. Qu, Q. C. Wang, H. Tian, *Angew. Chem.* **2005**, *117*, 5430; *Angew. Chem. Int. Ed.* **2005**, *44*, 5296; c) K. Szaciłowski, W. Macyk, G. Stochel, *J. Am. Chem. Soc.* **2006**, *128*, 4550; d) F. Remacle, R. Weinkauf, R. D. Levine, *J. Phys. Chem. A* **2006**, *110*, 177; e) D. Margulies, G. Melman, A. Shanzer, *J. Am. Chem. Soc.* **2006**, *128*, 4865; f) U. Pischel, B. Heller, *New J. Chem.* **2008**, *32*, 395.
[15] a) T. Niazov, R. Baron, E. Katz, O. Lioubashevski, I. Willner, *Proc. Natl. Acad. Sci. USA* **2006**, *103*, 17160; b) H. Lederman, J. Macdonald, D. Stefanovic, M. N. Stojanovic, *Biochemistry* **2006**, *45*, 1194; c) G. Seelig, D. Soloveichnik, D. Y. Zhang, E. Winfree, *Science* **2006**, *314*, 1585; d) B. M. Frezza, S. L. Cockroft, M. R. Ghadiri, *J. Am. Chem. Soc.* **2007**, *129*, 14875.
[16] J. Andréasson, S. D. Straight, S. Bandyopadhyay, R. H. Mitchell, T. A. Moore, A. L. Moore, D. Gust, *Angew. Chem.* **2007**, *119*, 976; *Angew. Chem. Int. Ed.* **2007**, *46*, 958.
[17] J. Andréasson, S. D. Straight, S. Bandyopadhyay, R. H. Mitchell, T. A. Moore, A. L. Moore, D. Gust, *J. Phys. Chem. C* **2007**, *111*, 14274.
[18] E. Perez-Inestrosa, J.-M. Montenegro, D. Collado, R. Suau, *Chem. Commun.* **2008**, 1085.
[19] a) A. Drezet, D. Koller, A. Hohenau, A. Leitner, F. R. Aussenegg, J. R. Krenn, *Nano Lett.* **2007**, *7*, 1697; b) W. Macyk, G. Stochel, K. Szaciłowski, *Chem. Eur. J.* **2007**, *13*, 5676.
[20] For examples of molecular switches based on 8-MQ derivatives, see: a) R. T. Bronson, M. Montalti, L. Prodi, N. Zaccheroni, R. D. Lamb, N. K. Dalley, R. M. Izatt, J. S. Bradshaw, P. B. Savage, *Tetrahedron* **2004**, *60*, 11139; b) P. Singh, S. Kumar, *Tetrahedron Lett.* **2006**, *47*, 109; c) H. Zhang, Q.-L. Wang, Y.-B. Jiang, *Tetrahedron Lett.* **2007**, *48*, 3959.

[21] a) M. Goldman, E. L. Wehry, *Anal. Chem.* **1970**, *42*, 1178; b) S. G. Schulman, *Anal. Chem.* **1971**, *43*, 285; c) S. G. Schulman, A. C. Capomacchia, *J. Am. Chem. Soc.* **1973**, *95*, 2763.
[22] E. Bardez, I. Devol, B. Larrey, B. Valeur, *J. Phys. Chem. B* **1997**, *101*, 7786.
[23] For recent examples of single-molecule fluorescence switching, see: a) S. Habuchi, R. Ando, P. Dedecker, W. Verheijen, H. Mizuno, A. Miyawaki, J. Hofkens, *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 9511; b) S. S. White, H. T. Li, R. J. Marsh, J. D. Piper, N. D. Leonczek, N. Nicolaou, A. J. Bain, L. M. Ying, D. Klenerman, *J. Am. Chem. Soc.* **2006**, *128*, 11423; c) R. O. Al-Kaysi, J. L. Bourdelande, I. Gallardo, G. Guirado, J. Hernando, *Chem. Eur. J.* **2007**, *13*, 7066; d) B. Kolaric, M. Sliwa, M. Brucale, R. A. L. Vallée, G. Zuccheri, B. Samorì, J. Hofkens, F. C. De Schryver, *Photochem. Photobiol. Sci.* **2007**, *6*, 614; e) T. Fukaminato, T. Umemoto, Y. Iwata, S. Yokojima, M. Yoneyama, S. Nakamura, M. Irie, *J. Am. Chem. Soc.* **2007**, *129*, 5932.
[24] a) F. M. Raymo, R. J. Alvarado, S. Giordani, M. A. Cejas, *J. Am. Chem. Soc.* **2003**, *125*, 2361; b) S. Silvi, A. Arduini, A. Pochini, A. Secchi, M. Tomasulo, F. M. Raymo, M. Baroncini, A. Credi, *J. Am. Chem. Soc.* **2007**, *129*, 13378.

