# Chemical approaches to nanometre-scale logic gates

**A Prasanna de Silva**[1]**, Yoann Leydet**[2]**, Christophe Lincheneau**[2] **and Nathan D McClenaghan**[2]

[1] School of Chemistry, Queen's University, Belfast BT9 5AG, UK
[2] Laboratoire de Chimie Organique et Organométallique, CNRS UMR 5802, Université Bordeaux 1, 351, Cours de la Libération, 33405 Talence, France

E-mail: a.desilva@qub.ac.uk and n.mc-clenaghan@lcoo.u-bordeaux1.fr

## Abstract

External stimulus-induced changes in molecular read-out give rise to bistable nanoscopic switches. Beyond simple bistable species, multistate (multi-input/output) systems lead to the idea of molecular logic gates. Since the appearance of a prototypical molecular logic gate in 1993, different strategies have been described for developing these molecular information processors. Notably, various photophysical processes have been employed to effect the requisite changes in photonic output as a function of the input. Equally, different questions have been addressed with varying degrees of success concerning the connectivity/integration of logic gates and the superposition/multiplexing of optical logic gates. After introducing pertinent processes available in the chemist's toolbox for designing functional nanometric devices, illustrated with a few simple examples, more sophisticated combinatorial logic arrays are described, including molecular systems capable of numeracy.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Current microprocessor systems are based on bulk semiconductor logic gates which employ electronic (e.g. voltage) input and electronic output signals and power supply [1]. Data manipulation relies on the binary digital (bit) nature of these signals which protects against noise accumulated from serial operations and transmission over distances. Each type of logic gate has a specific input–output signal correlation pattern which are described by truth tables arising from George Boole's classic ideas [1]. Voltages employed can be simply high or low (above or below a threshold value): digital 1 or 0 respectively in the positive logic convention, whereas the negative logic convention reverses this relationship. Huge arrays of interconnected logic gates can be built up to achieve selected functions of varying complexity.

Despite the success of the current top-down approach of silicon-based technology (semiconductor features of 65 nm have been reported [2]) the impending, well-documented, insurmountable size barrier will soon be attained. The slowdown in miniaturization is due to cost issues [3] as well as fundamental scientific problems arising when bulk semiconductor components approach small nanometric dimensions. Among these problems are cross-talk and heat dissipation. Importantly, the logic ideas introduced above were developed before the advent of electronic computers. Current information technology systems are therefore just one manifestation of Boolean logic employing electronic coding of inputs and outputs. Different sectors of the scientific community champion atom/molecule-based bottom-up approaches to nanometre-scale logic to complement/supersede the forthcoming performance limitations of silicon-based technology [4]. Although the potential advantage of nanometre-sized devices is not a novel concept, having been put forward over 40 years ago by Nobel laureate Feynman, the implementation of concerted arrays of molecules remains challenging [5]. Equally, much debate exists concerning the way in which molecules can be deployed to achieve this goal. In one approach molecules are used as nanocomponents to replace somewhat larger solid-state components. In this case, the molecules themselves in these systems have no inherent intelligence and resulting architectures are derived from/inspired by analogous solid-state regimes where typically fragments of conjugated polymer or nanotubes span the gap between micro/nanoelectrodes. These molecular electronic approaches to electronic devices have only begun in recent years [6]. Even then some of these require bulk metal connectors (or nanotube bundles) which negates the molecular size scale [7].

In a philosophically different approach, which dominates the focus of the current article, small synthetic molecules (or adapted biomolecules) are designed to perform specific functions of varying complexity at the nanometre scale. These functions may be analogous to those of solid-state components or have a distinctly molecular aspect (e.g. acid/base reactions, conformational changes, photoinduced electron transfer, photoinduced isomerizations, redox processes and non-covalent supramolecular interactions). The resulting systems are more reminiscent of biologically based information processing systems such as those found in the human brain but often their functioning can be interpreted in a Boolean algebraic framework. Manipulation of information by molecules based on optical read-out includes: gathering (sensor, assay reagent, antenna); transmitting (wire); storing (photochrome); displaying (electrochrome); and processing (switch, logic, arithmetic system) [8]. This wealth of functions in electronic/photonic devices can be obtained using organic molecules of nanometre size. Equally, properties can be tuned through a plethora of chemical modifications and their synthesis can be carried out such that billions of these molecular information processors can be produced simultaneously at low cost.

In this paper we give an overview of some recent approaches towards molecule-based information processing systems using chemical principles in chemical, biological and physical arenas. Incorporation into organized media/nanospaces and state-of-the-art combinatorial molecular logic arrays is also described. Far from being exhaustive, the current onus is rather on the conceptual basis and processes called into play in some key nanometre/subnanometre-sized systems which have advanced this field.

## 2. Chemical approaches to molecular logic gates

In this section, some of the more promising and popular approaches available to effect switching and logic operations in designer molecules will be outlined. Also, conceptual advances underpinning molecular processes are described. Particular attention will be paid to optically based systems, which can be addressed remotely and whose output can be detected

with high sensitivity. In this context, fluorescence may be considered an ideal output because of the ease of detection even at the single-molecule limit [9].

Of course the processes described below can (and have been) combined to produce a desired effect, as highlighted through specific examples.

### 2.1. Processes used to promote switching

Although several of the more common molecule-based approaches to satisfying appropriate Boolean truth tables are addressed in this section, space precludes detailed consideration of reports based on chemical wave logic gates [10], logic operations based on optical transitions and high Rydberg states [11], combinatorial logic representation and sequential machine interpretation of a two-photon dissociation reaction [12] along with magnetic stimulations [13]. Alternative signal transduction mechanisms [14] include magnetoresistance parallel switching and gating devices with cyclic molecules [15], and chirality [16]. Even bimolecular binding of neutral hydrocarbons inside a self-assembled cage [17] and gel swelling have been interpreted in molecular logic terms [18].

For further examples of specific molecular logic gates/types (YES, NOT, AND, OR, XNOR, XOR, NAND, NOR) based on the principles outlined below see [19] and recent examples [20].

### 2.1.1.  *Photoinduced electron transfer (PET).*  Photoinduced electron transfer is of fundamental importance in natural photosynthetic systems, and has been subject to much research [21].   While natural systems are characterized by elaborate multicomponent architectures, the same principles can be applied in small designer molecular systems for the purposes of luminescence switching and logic, taking into account certain thermodynamic and kinetic parameters [22]. In this context, the basic approach to switching 'on/off' luminescence can be illustrated (see figure 1) and briefly summarized. This strategy reposes on the connection and combination of molecular subunits in a modular fashion which facilitates the combination of different modules giving rise to systems with predetermined properties.   This can be identified as one of the strengths of this approach to molecular switching with respect to other less predictable nanometre-scale systems. A lumo/fluorophore is connected to a receptor via a short (one or two carbon atoms) spacer, which could alternatively be virtual or even absent. Known redox potentials [23] can be used to choose components so that the receptor will transfer an electron to/from the excited lumo/fluorophore preventing emission.  Binding of a target species (e.g. protonation) will now change the redox potential of the receptor so that the electron transfer is no longer energetically feasible, and the excited state energy of the lumo/fluorophore gives rise to photonic emission. This is input-induced emission enhancement, where the input is an ion and the output is fluorescence. The 'on/off' emission intensity ratios can attain values of several orders of magnitude.

To exemplify control of PET switching processes in a molecular system, Zang's recent example (**1**) is considered (see figure 1). The imide nitrogen creates a node in the molecular orbital system, and so **1** [24] conforms to the 'fluorophore–spacer–receptor' (FSR) format. Indeed, PET from the anilinic unit (R) to the excited central perylenetetracarboximide (F) leads to negligible fluorescence (output 0). Protonation of the anilinic unit gives a strong fluorescence enhancement (output 1). Importantly, switching of this molecular YES logic gate **1** (with a $H^+$ input) can be observed even at the single-molecule level by confocal scanning microscopy. The time trajectory of fluorescence intensity is similar to that seen in the one previous case of a fluorescent intramolecular charge transfer (ICT) proton sensor [25].

Incorporation of additional modules within this framework leads to multistate logic systems rather than the single-input–single-output-type system described above.   In the
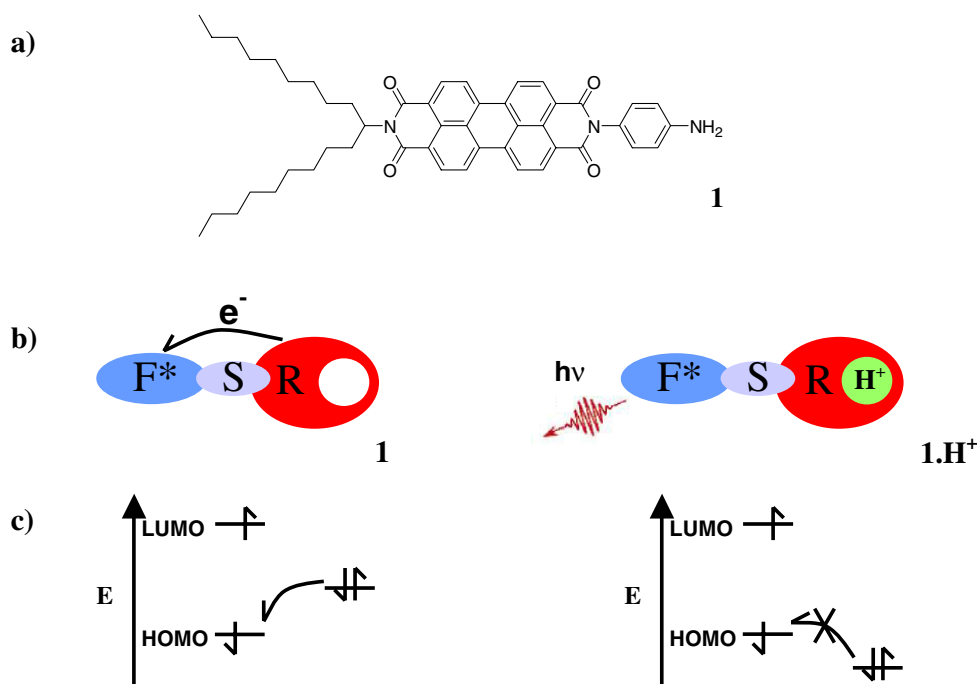
a)



**1**

b)



**1**                                              **1.H⁺**

c)



**Figure 1.** Molecular implementation of an 'off/on' fluorescent switch (or YES logic gate) (**1**) incorporating a photoinduced electron transfer (PET) mechanism (a). Modules incorporated in design (F = fluorophore; S = spacer; R = receptor), (b); pertinent frontier orbital diagram showing HOMO and LUMO energies (c).

following examples the modular format will allow an improvement in performance towards a single-molecule regime by replacing the popular fluorophores with more recent examples with higher quantum yield and absorption cross-section, while respecting the pertinent thermodynamic and kinetic parameters describing the system as a whole. Equally fluorophores are available in a variety of excitation and emission colours. Similarly the receptor can be chosen to target a particular guest in a given solvent, within a given concentration range and in the presence of a given set of potential interferents. These choices are of course subject to constraints such as availability of light sources, detectors and other optical components which are controlled by advances in optical physics and engineering. The availability of receptors is dependent on developments in coordination and supramolecular chemistry.

When the number of inputs is increased from 1 to 2, the possible number of logic types will rise to 16 [1]. One of these, AND logic, gives an output of 1 only if both inputs are held at 1 each. The prototype molecular example of this logic gate was described in 1993 according to a 'fluorophore–spacer₁–receptor₁–spacer₂–receptor₂' design format [26]. A second generation species, **2**, is presented in figure 2 [27], which uses a different arrangement of the constituent modules, namely 'receptor₁–spacer₁–fluorophore–spacer₂–receptor₂'. (In certain rare cases, rearrangement of modules changes behaviour not only quantitatively but also qualitatively; see [28].) This AND gate utilizes two discrete, selective binding sites which are weakly coupled to a fluorophore. Thermodynamically controlled, guest-modulated, PET processes from oxidizable moieties located at each receptor, across inert methylene spacers, serve to quench the fluorescence from the excited fluorophore. Only if chemical species ($H^+$ and $Na^+$) are present at both receptor₁ and receptor₂ are both oxidation potentials raised, such that the
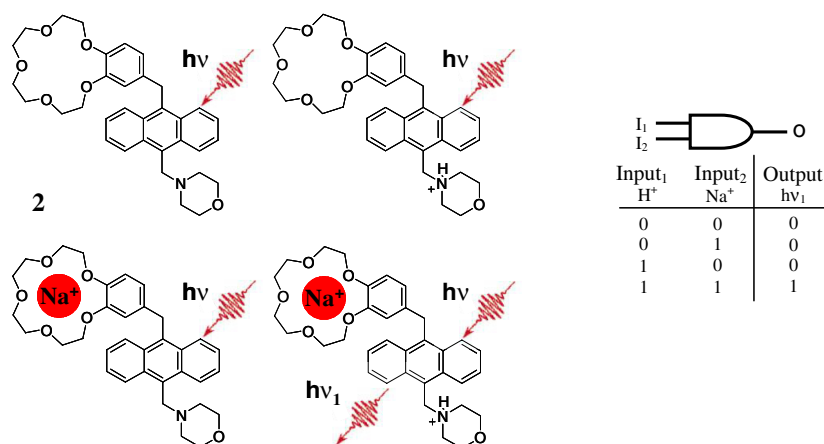
**Figure 2.** A five-module, two-input one-output fluorescent AND gate (**2**) showing four discernible states along with truth table and electronic representation.

electron transfer is abated. Then the fluorescence output from **2** is restored (output 1), and the truth table is satisfied. In this implementation, the power supply was provided by excitation light, while the inputs are chemical ($H^+$ and $Na^+$) and the output is fluorescence. Importantly, the commutative nature of this system is apparent as binding of each guest is truly independent. Such photoionic systems [26] can be considered wireless since the inputs are directed to the correct receptor of the gate unaided while the photons also find their way in and out of the fluorophore component.

Multireceptor 'fluorophore–spacer–receptor' PET systems showing AND logic can employ chemical species which are more complex than atomic ions. Cooper and James report a system targeting a diol (with a boronic acid) and an ammonium ion (with an azacrown ether). The end result is a selective sensor for glucosamine at physiological pH [29]. More recent AND gates of this type involve $Na^+$ and various phosphate species [30], $K^+$ and $F^-$ [31], and $Na^+$ and transition metal ions [32].

As well as small molecule approaches, polymeric approaches have also been described. A fluorescent polymeric AND gate has been described with biologically important temperature and pH as inputs for disabling a PET process. A modular approach prevails as thermo-/acido-sensitive domains and pendant fluorophores can be discerned. The authors propose modifications for adapting this system to a general platform for polymeric logic gates [33].

A fundamentally different bulk molecular approach to molecular logic involving PET processes was recently described. Just as older textbooks concerning computing show how two diodes can be wired to produce AND logic activity [34], Matsui used two nanosheet diodes built from polymer Langmuir–Blodgett films operated at different wavelengths to produce an AND logic gate [35] with two optical inputs and an electrical (photocurrent) output. Matsui *et al* now extend this nanosheet approach to include XOR logic [36]. Even though these nanosheets are molecule based, it is clear that logic behaviour at the level of a single molecule is not attainable by this approach. However, single-molecule logic is not essential for many envisaged applications.

*2.1.2. Electronic energy transfer (EET).*    Electronic energy transfer plays an important role in many photophysical studies/systems [37], including molecular logic systems. Like PET,

this process is under kinetic and thermodynamic control. Modulation of these parameters can therefore be used to promote switching. As regards the former, fluorescence resonance energy transfer (FRET) kinetically competes with fluorescence emission where donor–acceptor pairs are separated by around 5 nm, i.e. a large conformational change or bimolecular process. As energy runs downhill, from an excited state of high energy leading to population of a lower energy excited state, in a bichromophoric system this implies a two-colour output. A recent example based on switching involving conformational change by Shanzer is presented in section 7, while a dissociation of two-fluorophore tagged DNA strands is discussed in section 5. Interestingly Speiser concludes that cascading molecular logic gates (for the purposes of integration) via energy-wasting downhill energy transfer reactions are unfeasible [38].

Above, we considered processes involving thermally equilibrated excited states. Equally, higher energy excited states can be considered. Yeow and Steer propose molecular logic circuits based on energy transfer between higher electronic states of two organic molecules (azulene and a zinc porphyrin). Their theoretical study and computational dynamics simulation is based on the cyclic forward intermolecular $S_2$–$S_2$ energy transfer and back $S_1$–$S_1$ energy transfer reactions. Repopulation of the initial $S_2$ state is achieved by applying an additional photon. Equally it is suggested that varying the medium (viscosity) will lend control to the dynamics for forward and back energy transfer of the molecular logic system, which has its basis in Förster energy transfer theory [39]. For an earlier report on related processes to achieve number processing see section 7 [40].

Another method for incorporating switching into energy transfer systems is by a thermodynamic approach, inverting the order of the energy of lowest lying excited states in a two-component system where the energy difference is greater than the available thermal energy [41]. Gunnlaugsson and Parker use this approach in an organic chromophore appended Tb(III) complex which is the first example of a molecular logic gate corresponding to a two-input INHIBIT (INH) function. Such an INHIBIT gate can be viewed as an AND gate, one of whose inputs is the output of a NOT gate. The output, a sharp, line-like terbium emission, is only observed with two chemical inputs: (i) the presence of protons and (ii) the absence of molecular oxygen [42]. Protons serve to invert the energy ordering of excited states to allow energy transfer from the protonated strongly absorbing organic chromophore to the weakly absorbing Tb(III) atom, while triplet oxygen is a good quencher of excited states. The long excited state lifetime is a consideration here which could, in principle, be incorporated into a sequential, time-based scheme of logic events. Gunnlaugsson was also involved in an earlier report on a three-input INHIBIT gate [43].

*2.1.3. Intramolecular charge transfer (ICT).* To this point we have considered molecule-based optical devices constructed such that communication exists between formally distinct modules/molecules and switching can be effected. Here we adopt the opposite approach, in that a receptor site is integrated with the chromogenic unit; indeed atoms common to both units can often be identified [44]. In this instance arrival of a chemical input will perturb the excited state of the adjacent chromophore, signalled by a displacement of the absorption (or emission spectrum). For maximum effect the chromophore comprises electron donor and acceptor moieties which can be identified on opposite termini of a $\pi$-conjugated bridge. Due to substantial charge redistribution in these ICT systems [45], arrival of a cation next to the positive or negative pole will destabilize or stabilize the excited state, respectively. Concomitant blue or red shifts in the fluorescence emission and excitation spectral signatures, as well as in the absorption signature, are observed. The degree of alteration is still difficult to predict quantitatively, particularly where emission is concerned; however qualitative understanding permits the construction of molecular devices [46]. Although less sensitive than fluorescence
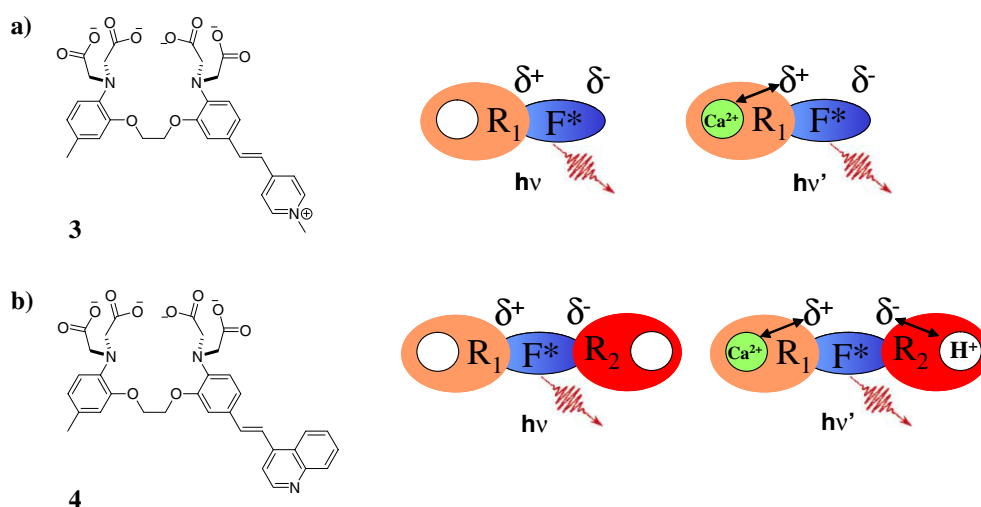
**Figure 3.** Internal charge transfer (ICT) chromophores integrated with one (a), **3**, and two receptors (b), **4**.

detection, absorbance (or transmittance) can be detected with increasing sensitivity [47]. To remain consistent with a designated photonic output, transmittance rather than absorbance can be considered as the output.

While a plethora of molecules with integrated 'receptor–chromophore' systems are known, the $Ca^{2+}$-induced colour changes in non-fluorescent ICT sensors such as **3** warrant discussion (see figure 3(a)) since they have been shown to display aspects of quantum computing [48]. Observations of such input-induced transmittance changes at four chosen wavelengths are seen to exhibit the four different logic types for a single-input–single-output device, i.e. PASS 0; PASS 1; YES; NOT. The fact that the four wavelengths can be simultaneously observed then leads us to conclude that four different computational operations can be run concurrently. This function is unavailable to electronic devices because colour (and the multiplexing capacity of light which is used to great effect in fibre optic cables for communication) is meaningless to electrons in wires.

Quantum computation deals with superposition of quantum bit strings; i.e. the string 01 say will exist simultaneously as 01, 00, 11, 10 in four parallel universes. So when the qubits are operated on by quantum logic gates all the strings are processed in parallel. These molecular processors now show a superposition of logic gates, a property which is related to, but not the same as, ideas in quantum computation. Thus we can generalize the idea of simultaneously multiply configurable logic within simple molecular systems. Cases like **4** (see figure 3(b)), resulting from a small structural modification [49], are more complex two-input versions, for example. However, it is important to note that there are individual examples which can be interpreted in this way [50, 51]. Such simultaneously configurability will allow optically functional molecular devices to enter areas where semiconductor-based electronic logic cannot easily go. For a recent example, where reconfiguring of logic gates can be achieved by considering three types of output (electrochemical, absorbance and fluorescence), see [52].

Molecule **4** acts as an XOR gate (figure 3(b)) due the input-dependent perturbations on the energy of the Franck–Condon excited state, which is manifested in a significant displacement of the absorption band from the monitoring wavelength. The two-input, one-output XOR gate can compare two digital signals. Output 1 is obtained with dissimilar signals, while a 0 results
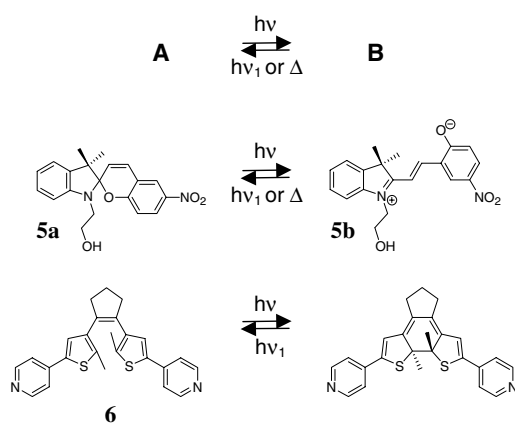
**Figure 4.** Switching between two forms of a photochromes of the types spiropyran (**5**) and diarylethene (**6**).

from 2 similar inputs. (Typically implementation of the XOR gate has proved challenging on the molecular scale [53, 54].) This approach to XOR logic promises to be rather general, as well as being free of inter-input annihilation. When two ion inputs are present, the antagonistic effects (destabilization with $Ca^{2+}$ and stabilization with $H^+$) effectively cancel each other out making the absorption (and transmittance) properties at 390 nm the same as in the ion-free case (output 0), while with only one high input the shifted absorption band results in a much smaller absorbance (and hence high transmittance value) at this wavelength (output 1). Fluorescent versions will be interesting for the future.

A recent system consolidating PET and ICT ideas in a single molecule to obtain a two-input INHIBIT gate is worthy of note [55]. For other examples of INHIBIT logic gates see [20, 42, 43, 56]. In brief, flexibility in inputs and outputs in some of the above systems leads to reconfigurability of the logic function in several ways—some of these even simultaneously. Such achievement of reconfigurable or even superposed logic has only a short history [48, 57].

*2.1.4. Photochrome-based systems.* Photochromic molecules can typically be reversibly interconverted between two forms (see figure 4), at least one form-changing reaction being light driven. Due to the changing structure of the two forms, via isomerization or cyclization/ring-opening reactions, typically the absorption spectra, and other parameters, e.g. redox potentials, differ between the two forms [58]. In a seminal paper in the 1950s, Hirshberg [59] recognized that these bistable switches could be used for molecular memories. Switching times can be fast also [60]; for example diarylethenes exhibit electrocyclic ring-opening/closing reactions of the order of a few picoseconds' duration [61]. It is therefore not surprising therefore that simple bistable switches have been elaborated for logic purposes. Two different approaches for achieving this goal are described below.

Adapting the photochrome from a bistable to a tristable species, for example, offers the possibility of performing multi-input logic operations. Identification of the presence of a receptor integrated within a photochrome such as a spiropyran **5a** (closed form) in its open, merocyanine form (**5b**) first seen by Tamaki [62] and also by Buncel [63], was developed by Raymo and Giordani into an approach towards molecular logic systems containing small scale integration with acid-sensitive spiropyrans; see section 6 [64]. Deliberately building in a receptor to a photochrome is another way to tackle related logic problems, first done by Inouye

with spiropyrans [65] and later by Diederich for dihydroazulenes [66]. Now, Tian *et al* [67] modify Irie's celebrated dithienylethene photochromics [58] with pyridyl groups, **6**, so as to benefit from a $Zn^{2+}$ input. An ICT behaviour can be assigned, owing to the 'fluorophore–receptor' integration. Compound **6** allows small scale integration, especially when different emission and absorption wavelengths are observed [57], for achieving superposed logic configurations [48].

Alternatively, the bistable switch (or switches) could be coupled with fluorophores either covalently tethered [68] or via a process of intermolecular light emission/absorption. Introducing fluorescence offers a means to obtain a more easily detectable output, although modulation techniques mean that measurements of absorption can approach the single-molecule regime [47]. Of course in bi/multichromophoric systems, EET destroying the photoactivity of the higher energy excited state is always a consideration. Irie [69] gave a nice demonstration of the power of this linked photochrome–fluorophore approach by linking a highly efficient photochrome with a highly efficient fluorophore. Studies down to the single molecule were possible. Subsequently, Guo *et al* [70] reported a fluorophore appended with two spiropyran photochromes. The usual spiropyran photochromic ring opening to merocyanine can be achieved by UV irradiation, in spite of the presence of the perylenediimide. Fluorescence is switched 'on' only if UV light, $Fe^{3+}$ and $H^+$ are all supplied in THF. This constitutes a three-input AND logic gate. For related reports using a different fluorophore see [71]. Gust and Moore successfully linked two different photochromes to a zinc porphyrin fluorophore, where only one form of each quenches fluorescence, thus giving rise to a four-state system which can be operated as an AND gate or reconfigured as an INHIBIT gate [72]. For other reports by the same team see section 7.

*2.1.5. Logic operations resulting from submolecular movement.*   Due to pioneering work from the labs of Balzani and Stoddart pseudo-rotaxanes have been encouraged to participate in molecular logic [54, 73]. Rotaxanes can be considered as the molecular equivalent of a bead on a thread with stoppers at each terminus of the thread to prevent dissociation. Related pseudo-rotaxanes lack the stopper component. Briefly, nanometre-sized systems are designed such that threading/dethreading of a molecular bead can occur in response to designated inputs and is signalled by a designated output. Typically inputs are ionic, photonic and electronic in nature. As a classic example of XOR logic we can consider **7** and **8**; see figure 5 [54]. The electron-rich bead **7** can spontaneously assemble with the electron-poor thread **8** via charge transfer (CT) interactions to give a non-fluorescent ensemble. Introduction of an acid (input$_1$) or base (input$_2$) causes dissociation of the ensemble giving an output 1 (fluorescence of the bead component). Simultaneous introductions of acid and base neutralize one another; rethreading occurs and fluorescence ceases (output 0).

An XNOR gate [73] was constructed using similar CT interactions, this time between a cationic (electron-poor) bead and an electron-rich thread in a pseudo-rotaxane. Inputs are electrochemical (oxidizing and reducing) in nature, and served to reduce the bead or oxidize the thread, either situation causing dissociation and a loss of the CT absorption at 830 nm (output 0). With no electrochemical stimulus or both applied simultaneously the CT complex would, in principle, be preserved and the absorption signature could be measured (output 1). For more in-depth discussion of the operation of these types of systems see the article by Balzani, Credi and co-workers in this Special Issue.

Most recently a new paradigm has been published based on rotaxanes where the affinity for the mobile bead shows affinity for a particular station of the thread based on hydrogen bonding. Hydrogen bonding can be disrupted and movement assured, even when localized in polymer support by vapours of DMSO (a polar, aprotic solvent). Vapours of TFA (a strong
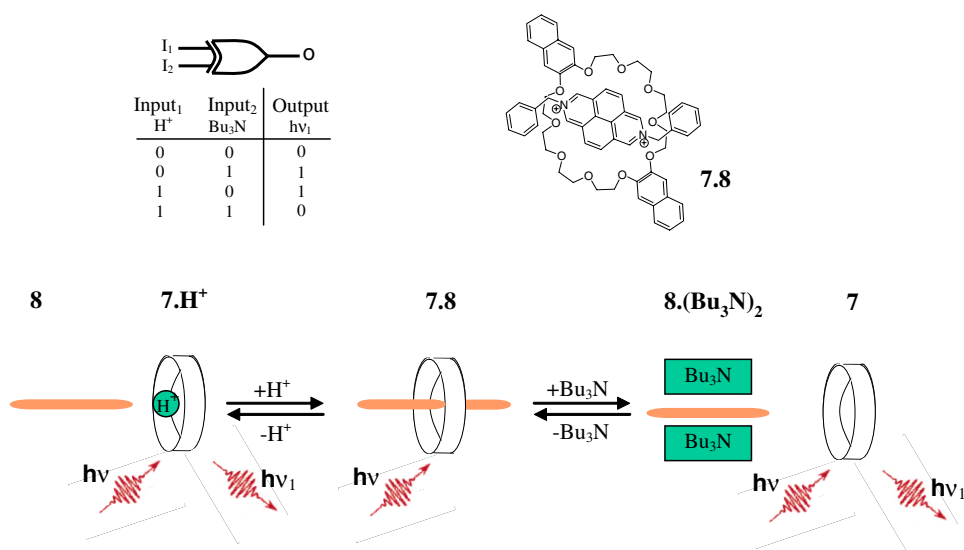
| Input$_1$ H$^+$ | Input$_2$ Bu$_3$N | Output h$\nu_1$ |
|:---:|:---:|:---:|
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

**Figure 5.** Prototype XOR gate based on the threading/dethreading of a fluorescent molecular bead (**7**) on a quencher thread (**8**).

organic acid) protonate the bead making it a good electron acceptor for participating in a PET reaction with a terminal fluorophore/electron donor on the thread. Changes in the optical output are ascribed to input-induced translation of the bead (separation of donor and acceptor) along with the fluorescence quenching PET reaction resulting in the demonstration of an INHIBIT gate with fluorescence quenching as the output (negative logic convention). While vapours are perhaps not the ideal inputs for a molecular logic gate the operation of a logic gate in a polymer support is important and this type of molecule may be of interest in a sensing system [74].

## 3. All-optical approaches to molecular logic

Initial proposals for molecular logic gates discussed AND gates with two optical inputs and an optical output [75]. However, these systems never reached the primary literature. Theoretical studies also support the idea of reversible PET reactions for fast molecular switching in devices [76]. Due to the efforts of the Wasielewski, Levine and Zhang groups, examples of all-optical molecular AND logic gates are now available [40, 77, 78]. For example, system **9** which comprises several chromophores (see figure 6(a)) uses pump laser beams of two colours as the two inputs [77]. The output, monitored at a third wavelength, is the absorption of the benzenediimide radical anion. Importantly the branched nature of the structure allows generation of long-lived output states. As a high light output results from a low absorbance, the output is based on a negative logic convention. Application of input$_1$ 1 (photon 1) provokes a PET reaction (see section 2.1.1) from the aminonaphthalimide subunit to the neighbouring naphthalenediimide. Application of input$_2$ 1 (photon 2) then causes the naphthalenediimide radical anion to transfer its additional electron to the benzenediimide via the naphthalimide subunit. These processes occur on the nanosecond timescale. The qualitative aspect of input–output homogeneity is displayed while the quantitative aspect is still not easy to achieve with molecular-scale logic. In this example the output from one molecular device could feedback as the input in the absence of wiring.

Under sufficiently high irradiation intensities, many molecules including **10** can undergo two-photon fluorescence (TPF). Application of two low power laser beams (where the two
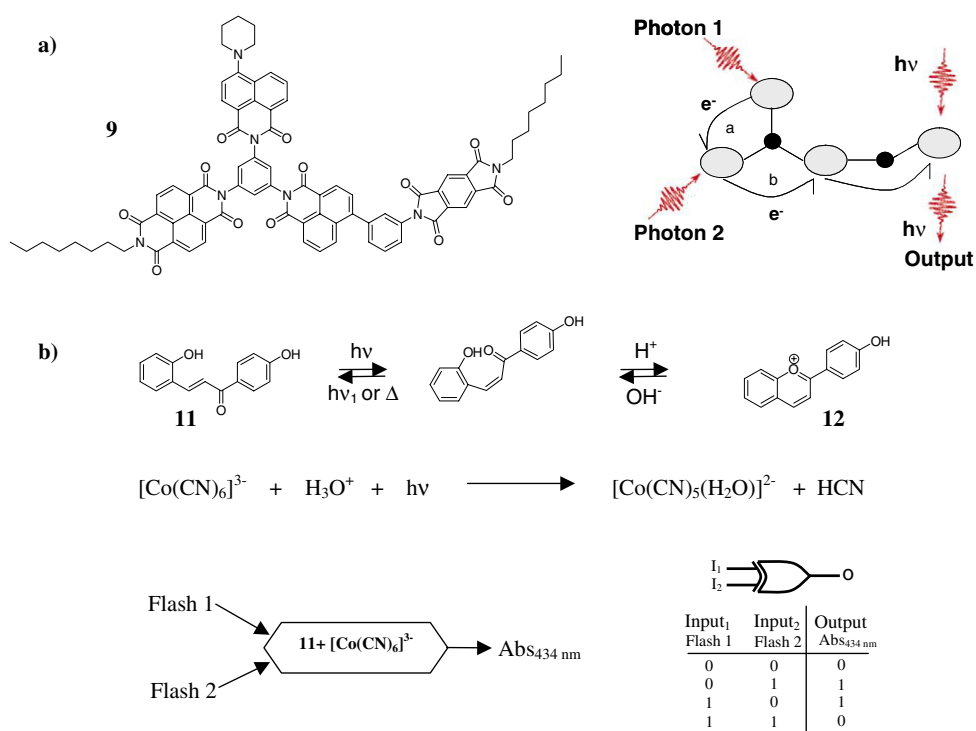
**Figure 6.** All-optical system based on: PET in **9** (a); a photocontrolled artificial neuronal system showing XOR logic (b).

light inputs are both held at 1) are necessary for TPF to occur (output 1), even though the quantum efficiency is quite small. On demonstrating AND gate action, the wavelengths of the two inputs can be the same but the output wavelength is necessarily different. Thus full input–output homogeneity is not met.

The protein bacteriorhodopsin, which presents multiple photochemically accessible states, has been shown to display all 16 possible two-input logic types, AND logic being just one example [78]. Similarly, the wavelengths of laser inputs and the output are not all the same and the intensities are also deliberately chosen to be different. Nevertheless, this example and other all-optical AND gates highlight the substantial versatility of design which is possible.

Although described above in terms of AND logic, **10** [40] shows other logic expressions (see section 7). Conventional one-photon fluorescence output corresponds to XOR behaviour, under carefully selected conditions. For example, either of the two low power laser beams (input$_1$ or input$_2$) gives rise to normal fluorescence emission (output 1). No emission results (output 0) if both laser beams are switched off (both input$_1$ and input$_2$ = 0), while if both laser beams are applied (input$_1$ and input$_2$ = 1), TPF results instead of normal fluorescence, which is under observation (output 0).

Balzani and co-workers recently described a bimolecular threshold device which not only mimics in an elementary fashion the functioning of a neuron but equally represents an XOR gate, based on two photoreactions in aqueous solution; see figure 6(b) [53].

The two inputs are identical flashes of light, while the output is the absorbance at 434 nm. The two communicating molecular species are $[Co(CN)_6]^{3-}$ and an acidochromic and photochromic chalcone, **11**. With no light applied the chalcone rests in its non-absorbing

*trans*-form. Application of one light flash isomerizes the chalcone, which is then cyclized to give **12** due to an acid-promoted condensation reaction, losing water. Application of a second flash of light liberates a basic cyanide which promotes the reverse reaction regenerating a non-absorbing *trans*-chalcone **11**. In other words, an output (434 nm absorption) can be obtained only when either input 1 (flash 1) or input 2 (flash 2) is used, whereas there is no output under the action of neither or both inputs, i.e. XOR behaviour. Intermolecular communication is facilitated in this case by ions. Gust and Moore's systems also belong here (see section 7), as do Raymo's (see section 6).

## 4. Localization of gates

Many of the current examples operate in homogeneous solution. Different practical molecular devices may require localization of devices in organized arrays and/or deposition on surfaces to facilitate addressing, reset through rinse cycles etc [79]. Localizing a molecular logic/sensing device in a chosen micro/nanoenvironment is challenging [80]. In many cases this compartmentalization may be anticipated to have only a small effect on its functioning when compared to the analogous case in solution. Recently progress has been made in this area as outlined below.

Incorporation of an additional module, a long hydrocarbon chain, to the five existing modules shown in figure 2, gave an AND gate programmed to function in a specific nanodomain [81]. In fact the long hydrocarbon chain, due to hydrophobic interactions, serves as an anchor, to force the localization of the logic gate in the self-assembled tetramethylammonium dodecyl sulfate (TMADS) micelles in aqueous media. The AND operation in the presence of $Na^+$ and $H^+$ works as usual, *vide supra*. The space needed to perform this operation is known to be around 3 nm, thus demonstrating the miniaturization capabilities of molecular computing elements [82]. These charged micelles additionally aid the accumulation of ion inputs, potentially improving the sensitivity of these devices [80, 83]. For other examples of micelle operated molecular switching systems see [84]. Whitesides' recent demonstration of self-assembled aggregates that spontaneously reconfigure their structures in response to their environment may have interesting ramifications on suitably tailored systems of this type [85].

Komura *et al* localized an acid-sensitive, positively charged fluorophore [86] in a polyanionic Nafion® film on an ITO (indium tin oxide) electrode. As well as being addressed by protons, this molecule can equally be operated by an electrochemical (oxidation) process due to the adjacent electrode surface. Leblanc's team [87] prepared monolayers of lipoidal peptides by the Langmuir method and deposited the films by the Langmuir–Blodgett techniques. Fluorophore, receptor and 'fluorophore–spacer–receptor' systems are used, as well as mixed monolayers of fluorophores and receptors.

Appending alkoxysilane side chains onto fluorophores and receptors allows grafting onto silica nanoparticles, as described by Brasola *et al* [88]. Foundational material is available concerning fluorophores anchored on such nanoparticles [89]. Latex particle-based molecular switching devices are also similarly valuable [90]. By varying the fluorophore–receptor ratio the sensitivity can be tuned. This effect is not seen in solution, suggesting that the pseudo-intramolecular arrangement of fluorophore and receptor on the solid is critical. Related systems grafted onto macroscopic quartz surfaces are known [91] as is operation of photochromes in crystals [92] and in a silica monolith [93].

## 5. Biochemical logic gates

In this section diverse biological molecular systems are considered which have been shown to have the capacity to perform logic operations. While prototypical synthetic DNA-based computation, harnessing the massive parallelism which can be achieved with DNA, was

demonstrated over a decade ago [94], logic operation based on biological systems is a somewhat more recent area of interest. Systems of this type may profit from immediate compatibility with a cellular environment (i.e. computation *in vivo* [95]) along with the unparalleled selectivity which cannot currently be achieved in synthetic molecular recognition systems.

Stojanovic and co-workers reported **13** as a DNA-based catalyst [96], analogous to Cech's ribozymes [97], for the hydrolysis of DNA-type oligonucleotide substrate **14** which has a single ribonucleotide (rA) as the cleavage site; see figure 7(a). Due to the presence of complementary binding units on its backbone, **13** folds into a stem–loop configuration as represented in figure 7(a). In the absence of suitable oligonucleotide **15** (input 0), the stem–loop form of **13** uses its terminal sequences to hybridize with substrate **14** which is then hydrolysed. As a result the EET donor and acceptor (fluorescein derivative F and rhodamine derivative R, respectively) are separated. Thus unquenched fluorescence of F is observed (output 1). The catalytic stem–loop configuration of **13** is destroyed upon addition of **15** (input 1) due to hybridization. Substrate **14** therefore remains intact with EET de-exciting F (output 0) non-radiatively. NOT logic is achieved with chemical inputs and outputs. However, fluorescence and photophysical electronic energy transfer processes are still needed for the read-out [98]. Input/output homogeneity has been addressed qualitatively as the oligonucleotide output from one DNA-based catalyst can, in principle, serve as an input for another catalyst. System reset requires slow chemical hydrolysis reactions (minutes to hours); however parallel processing can more than compensate [94, 99]. Other gates demonstrated include AND and XOR gates. Stojanovic and Stefanovic subsequently applied their approach to the development of a deoxyribozyme-based half-adder [100], Boolean control of aptamer binding sites [101] and an undefeatable molecular player of tic-tac-toe (using 23 logic gates), under well-defined conditions [102]. Most recently they extend their deoxyribozyme logic toolbox to include ligases [103].

Other logic systems based on allosteric control using biomolecules include those of Lotan [104] where changing the conformation of a molecular switch (e.g. *cis-/trans*-isomerization of an azobenzene [105]) can block/unblock the active site of an enzyme ($\alpha$-chymotrypsin) whose activity was ascribed a '1' or '0'. When combined with a proflavine inhibitor which could be activated (oxidized) or deactivated (reduced), an AND gate was obtained. A further example of enzymatic computing was described by Conrad [106].

Shorter DNA oligomers than those of Stojanović can also be harnessed in a more direct fashion using chemical inputs, a fluorescence output and excitation light as the power source. Ghadiri and colleagues used this approach to develop, for example, the NAND gate represented in figure 7(b) [107]. This single-stranded 16-mer oligonucleotide (**16**) is decorated at the 3' terminus with a carboxyfluorescein moiety. The two chemical inputs are a complementary 16-mer (**17**) and a DNA intercaland, **18**. Selective excitation of the fluorescein unit gives strong fluorescein emission (output 1) when one or both inputs are absent. When both inputs are applied, **16**–**17** hybridization occurs and **18** intercalates into the resulting duplex at a position sufficiently close to the fluorescein moiety for efficient EET to occur, from the fluorescein unit to **18**. An output 0 results as fluorescein emission is quenched. Equally, **16** displays other logic types including AND and three-input INHIBIT when different inputs are chosen (see reconfigurable gates in section 2.1.3).

This approach of reversibly reconfiguring molecular logic gates by choosing different input sets was recently applied to cytochrome c by Konermann [108]. Cytochrome c has quenched fluorescence (output 0) in its native form due to the close approach of a tryptophan fluorophore to a haem quencher unit. The chemical inputs provoke protein unfolding so tryptophan fluorescence (output 1) is observed as this fluorophore is distanced from the quencher. Application of either $H^+$ or $OH^-$ gives a fluorescence output 1. Upon simultaneous

**a)**



**14**

5'-CATTGGACATAACTT- 3'

**15**



**13**

**b)**



**16**  5'-GCCAGAACCCAGTAGT- 3'

**17**  3'-CGGTCTTGGGTCATCA- 5'

**18**



**c)**



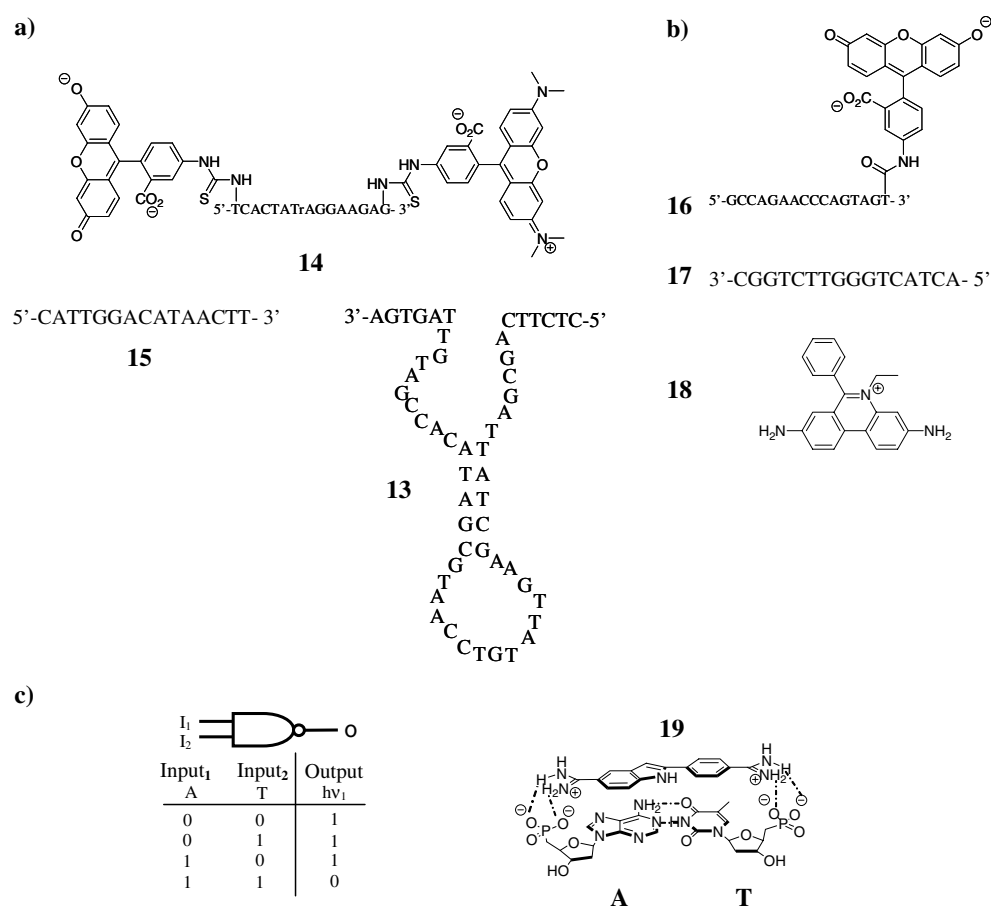| Input₁ | Input₂ | Output |
|--------|--------|--------|
| A | T | hν₁ |
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

**19**



**A**       **T**

**Figure 7.** Different DNA-based approaches to molecular logic in (a) and (b) and Watson–Crick pairing in a small synthetic system (c).

application in stoichiometric amounts, they annihilate one another to give no net effect and the protein remains poorly fluorescent (output 0), i.e. XOR logic. Reconfiguring cytochrome c to demonstrate AND logic was achieved by changing inputs to urea and $H^+$. Both must be present simultaneously in order for denaturing to occur with a resulting fluorescence output of 1. Reset could be achieved upon input removal by dialysis, returning the protein to its native form. For other protein-based examples see [109] and [110] for molecular logic based on synthetic peptides.

The recent photoactive DNA (bearing artificial nucleobases) logic gates of Okamoto and Saito [111] have been deployed to reproduce the unusual functioning of a molecular full adder and is therefore best discussed in section 7. Meanwhile, Willner recognized AND gate behaviour when considering the optical output signalling of telomerization and DNA replication by CdSe–ZnS quantum dots [112].

To conclude this section, we can consider an artificial molecular system which calls upon the principles of DNA Watson–Crick base pairing to implement NAND gate behaviour [113, 114]. NAND gates have high value in electronics since multiple copies of these (as well as NOR gates) can be wired up to emulate all the other logic types [1]. However,

this advantage is only available to molecular logic schemes if full input–output heterogeneity is possible (see section 6). Akkaya and Baytekin used hydrogen bonding interactions along with luminescence for logic design with small molecules. Molecule **19** is known to intercalate into adenine (A)–thymine (T) base pair regions of DNA. In aqueous–organic solvent mixtures they observe binding between the A–T mononucleotide pair and **19**, with the binding being signalled by luminescence spectral changes; see figure 7(c). Careful choice of the emission wavelength (455 nm) leads to significant reduction of luminescence intensity only when both A and T are present, i.e. NAND logic.

## 6. Integration of molecular logic gates

Unlike quantum computing systems, other types of information processing require interconnection of logic gates to lead to a 'fan-out' process. One critical feature, which contributes to the undoubted success of silicon-based microprocessor systems, is input–output signal homogeneity. The same electronic voltage value emerging as the output of one logic gate can be admitted as the input of another, even identical, gate. While molecular logic gates profit from a variety of inputs and outputs (optical, electrical and chemical), often the input and output signal do not belong to the same category. However, this variety may constitute an impediment if molecular logic gates have to be connected in series, that is, if the output of a gate has to drive the input of the following one. In this section we shall outline some approaches to address this integration issue.

Physical integration of simpler gate molecules remains difficult for single-molecule studies. However, functional integration of logic operations was initially achieved through rational design without physical integration of simpler gate molecules [43]. As an example of functional integration, in the framework of Boolean algebra, NOR (NOT OR) logic can be deliberately targeted in a photoionic system as follows. While NOT logic implies chemically induced luminescence quenching, OR logic would require non-selective luminescence enhancement (in a positive logic convention). NOT OR logic would therefore require non-selective luminescence quenching induced by two chemical species. This is illustrated in figure 8(a) with **20**, where the fluorescence of a 1,3-diaryl-$\Delta^2$-pyrazoline is quenched by $H^+$ (when the imine nitrogen lone electron pair interacts with hydrogen centres [115]) or $Hg^{2+}$ (due to population of a non-emissive ligand-to-metal charge transfer state [116]) inputs. Equally, NAND is equivalent to a NOT gate working on an AND output; while an INHIBIT function is equivalent to the output of a NOT gate serving as an input to an AND gate. These and several other basic examples of functional integration can be obtained. Other recent examples of small scale integration include enabled OR, where the output of an OR gate serves as an input for an AND gate [83], and the integration of XOR and OR gates [48]. Three-input systems can also produce truth tables which can be analysed using rules of combinational logic in terms of arrays of simpler two-input AND, two-input OR and one-input NOT gates. Building on the structural and mechanistic operation of the AND gate **2** (see figure 8(b)), Dabestani, Ji and co-workers replaced the simple tertiary amine group with an azacrown ether, which responds to $K^+$ as well as $H^+$. Additionally, a calixarene receptor is used in place of the benzocrown ether to host $Cs^+$ [117]. $Cs^+$ causes fluorescence enhancement of **21** in acid media, while $K^+$ has no effect. On the other hand, $K^+$ causes fluorescence enhancement in basic media, while $Cs^+$ has no effect. This simple elaboration makes possible a four-gate, eight-wire array featuring two two-input AND gates, a two-input OR gate and a one-input NOT gate as illustrated in figure 8(b). An analogous case involving $Na^+$ instead of $Cs^+$ has also been reported [118].

An original molecular logic function obtained by Lee *et al* [20] is a disabled XNOR, which can be described as an XNOR gate (driven by acid and base inputs) feeding into a
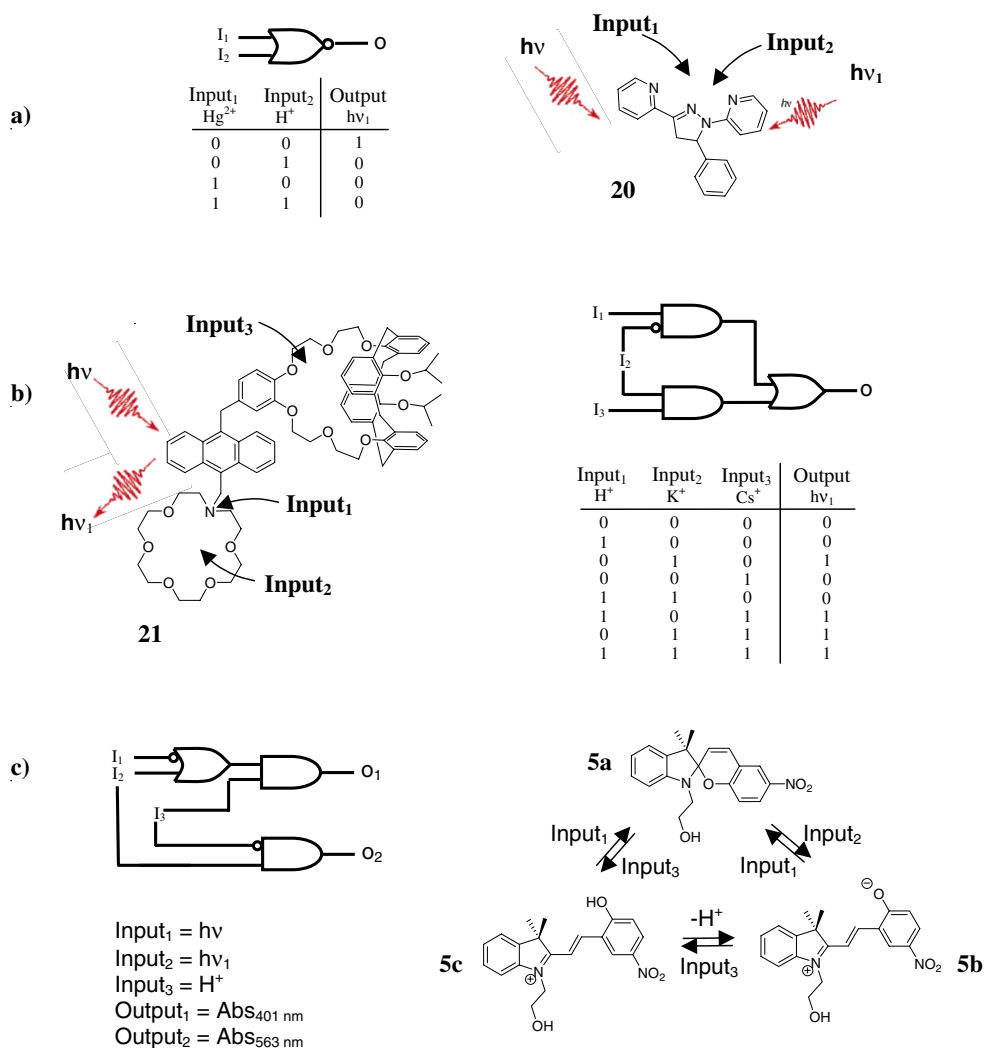
**a)**

| Input₁<br>$Hg^{2+}$ | Input₂<br>$H^+$ | Output<br>$h\nu_1$ |
|:---:|:---:|:---:|
| 0 | 0 | 1 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 0 |

**20**

**b)**

**21**

| Input₁<br>$H^+$ | Input₂<br>$K^+$ | Input₃<br>$Cs^+$ | Output<br>$h\nu_1$ |
|:---:|:---:|:---:|:---:|
| 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 |
| 0 | 0 | 1 | 0 |
| 1 | 1 | 0 | 0 |
| 1 | 0 | 1 | 1 |
| 0 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 |

**c)**

Input₁ = $h\nu$
Input₂ = $h\nu_1$
Input₃ = $H^+$
Output₁ = $Abs_{401\,nm}$
Output₂ = $Abs_{563\,nm}$

**Figure 8.** Functional integration giving rise to combinatorial logic circuits of differing complexity in (a)–(c).

two-input AND gate, the second input being the output of a NOT gate driven by $Pb^{2+}$ input. The disabling input is therefore $Pb^{2+}$. Such disabling lines have only been demonstrated within INH gates [20, 43, 55, 56, 119].

   Utilization of the presence of a receptor integrated within a spiropyran **5** photochrome allowed Raymo and Giordani to develop three-input molecular logic systems exhibiting small-scale integration [64]. Their systems rely on spiropyran photochrome **5**, which as well as open and closed forms shows an additional state in the presence of $H^+$; see figure 8(c). Ultraviolet light changes **5a** to the coloured merocyanine form (**5b**), protonation of which (giving **5c**) changes the colour again. Ultraviolet light, visible light and $H^+$ are the three inputs. Two outputs can be monitored, the absorption of **5a** at 401 nm (output₁) and the absorption of **5b** at 563 nm (output₂). A logic array can thus be generated comprising several simpler logic gates, including two-input AND, two-input OR and one-input NOT, to describe the functions

performed by this simple molecular system. This system demonstrates functional integration as well as wavelength reconfigurability.



**22**

**24**

**10**

**23**
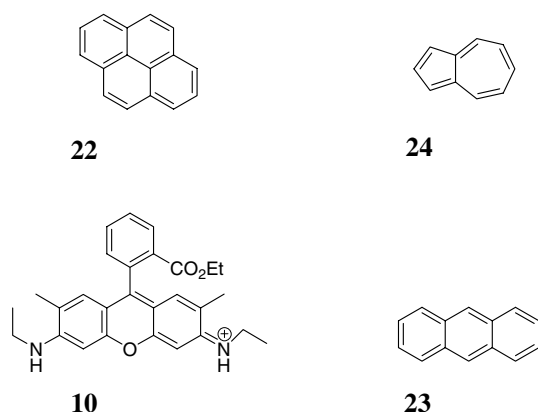
Subsequently, this three-state system was concatenated with an external fluorophore, e.g. **22** or **23** (a PASS 1 logic gate), via its fluorescence output [120]. Fluorophore specific emitted light from the latter was sent through the system **5a/5b/5c**, so that this three-state system effectively serves as a light filter which can be modulated due to its photochromic and acidochromic properties. While the overall wavelength-reconfigurable combinational logic array is rather similar to that seen for the absorbance output of **5a/5b/5c** alone, the wavelengths are defined by an external fluorophore. The simultaneous use of several fluorophores in the same solution [57] can allow progress towards another case of superposed logic [48]. While this EET emission–reabsorption mechanism dominates at large distances of separation between the two species, from 10 nm to astronomical scales, dipole–dipole or Förster energy transfer takes over as the main EET mechanism at molecule-scale distances of about 5 nm (see section 2.1.2). Remacle *et al* [40] also used energy transfer to couple **10** and **24**. Structurally simple **10** and **24** can both be described using equally complex logic arrays of XOR and AND gates, while the result of the concatenation is significantly more complex logically. Since the XOR function can be represented as a set of two two-input AND, one two-input OR and two one-input NOT gates, the final array possesses six two-input AND, two two-input OR and four one-input NOT logic modules—one of the largest scale irreducible integration demonstrated on the molecular scale (*vide infra*).

Chemical species can also serve to link molecular logic units instead of light, for example using a chemical output from one gate as the input of a second gate. This chemical signal transfer is known to control entire cascades of biochemical reactions and is attractive because the number of possible concatenations is not limited energetically, unlike downhill energy-wasting EET. Also the large diversity of chemical species could enable unique links between chosen gate pairs within large sets. Stojanovic and colleagues [96] harness this advantage with various oligonucleotides as the transfer agents. Raymo and Giordani [121, 122] consider $H^+$ as the transfer agent so that variety is lacking but diverse logic integrations are still possible. This type of proton transfer can also be identified in Balzani and Pina's system [53] as well as the fluorescent systems of Guo *et al* [123]. Though not in a logic context, Fabbrizzi describes molecular machines based on controlled intramolecular translocation of transition metal ions between two binding sites [124].

Logic systems driven by up to five inputs are described by Szacilowski and Stasicka [125] based on the equilibrium reaction of thiols with the well-known metal complex $[Fe(CN)_5NO]^{2-}$, though some of these transformations are irreversible. The nitroprusside ion

provides an established colour test for sulfide, so absorbance at a chosen wavelength in the visible region (526 nm) is the output. Szacilowski and Stasicka found that this reaction could be controlled by several variables such as thiol, protons, light, metal and other cations and anions, as well as temperature and pressure. The latter physical properties induce relatively slow, small absorbance changes rather than the sharp sigmoidal changes which are suited to switching action. Nevertheless, this represents use of physical properties in a logical context. All these variables are employed as the inputs to generate rather complex molecular-scale logic integrations with a simple compound. Several examples of reconfigurable logic as well as some analogue computing illustrations were also reported. Szacilowski more recently applied his structurally simple pentacyanoferrate complexes in a series of geometrical patterns leading to three-dimensional logic systems. He was able to identify logic systems comprising up to twenty AND and OR gates and claims his system can process up to 16 bits of input data [126].

## 7. Molecular number processing: molecular half-adders; half-subtractors and full adders

The half-adder represents an interesting target for small combinatorial circuits at the molecular level because this type of system offers an entry into the world of nanometric numeracy. Adders are the logic circuits that perform addition within central processing units of computers, are able to add three bits and can be cascaded to yield serial adders for adding large (multibit) integers. A half-adder is a key building block for a full adder. Comprising logic gates of type XOR and AND, the half-adder is capable of adding two bits (or binary digits) of information where the XOR gate proves the sum digit and the AND gate provides the carry digit.

Implementation of a nanometre-sized half-adder to achieve rudimentary computation can be achieved through the parallel operation of two compatible molecular logic gates. The simplest arithmetic operations which can be achieved with a half-adder correspond to the sums $0 + 0 = 0, 0 + 1 = 1$ (or $1 + 0 = 1$) and $1 + 1 = 2$ (or a binary '10'). Considering the prototype half-adder (see figure 9(a)) [49], compatibility concerns chemical inputs, optical outputs and power supplies, with minimal intergate interference. The output from both types of gate is light, transmitted light for XOR gate **4** (see section 2.1.3) and fluorescence from AND gate **25**, which operates on the same principles as **2** using PET, but uniquely with inputs $Ca^{2+}$ and $H^+$. The fluorescence output from **25** provides the first bit (the carry) of the two-bit number 'output$_1$ output$_2$', which is observed only in the presence of two high inputs. The second bit (the sum) is derived from the transmittance output of **4**. The truth table describing a half-adder, as shown in figure 9(a), is satisfied. Therefore, through operation of two carefully designed molecules in parallel, rudimentary arithmetic involving two binary numbers is performed for the first time with synthetic molecules.

A unimolecular half-adder was subsequently reported by Guo *et al* with **5** [127]. By changing the input conditions of **5** this three-state switch was adapted to a four-state switch and demonstration of the half-adder action was possible when observing the absorbance at two different wavelengths. As well as using $Fe^{3+}$ as an input (which also serves an oxidizing agent) $Na_2S_2O_3$ is required as a reducing agent, along with $2,2'$-bipyridine as a scavenger of $Fe^{3+}$.

Stojanović and Stefanović [100] recently applied their strategy of nucleic acid-based logic gates, with oligonucleotides as inputs and outputs, to the development of a half-adder. Their XOR gate comprises a NOT and an AND gate, such that the ensemble comprises three deoxyribozymes which analyse two common inputs, producing two separate outputs deemed the carry product and the sum product. The two substrates were decorated with fluorophores of different colours (green and red) at the $5'$ ends and with suitable fluorescence quenchers at the $3'$ ends, cleavage of the oligonucleotide strand would therefore restore fluorescence.
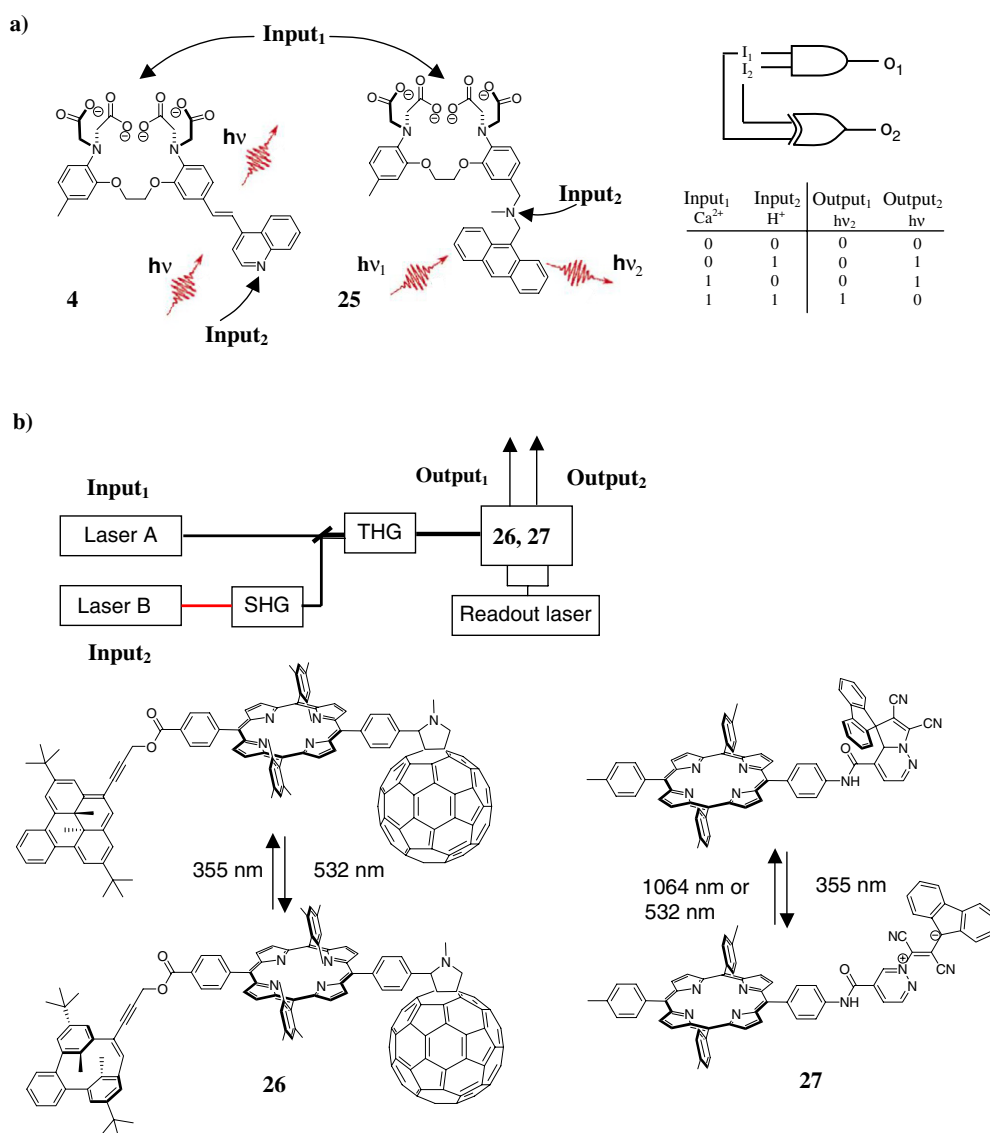
**Figure 9.** AND (left) and XOR gates (right) for photoionic prototype half-adder **4** and **25** (a); all-optical version with **26** and **27** (b) with the experimental set-up and combinatorial logic circuit.

The presence of both oligonucleotides uniquely activated the AND gate, detected through an increase in green fluorescence. The presence of only one input only activated the XOR gate resulting in red fluorescence. With no substrate input present, both gates remained silent. This DNA-based half-adder comprising three deoxyribozymes operating in parallel could add a single bit (defined by oligonucleotide input$_1$) to another single bit (defined by oligonucleotide input$_2$) to produce two output bits (signalled by green and red fluorescence). Addition was achieved in 30 min. The authors point out that 'cross-talk' is apparent in solutions at higher concentrations, suggesting a maximal concentration and hence a limit to the number of potential computing elements in solution.
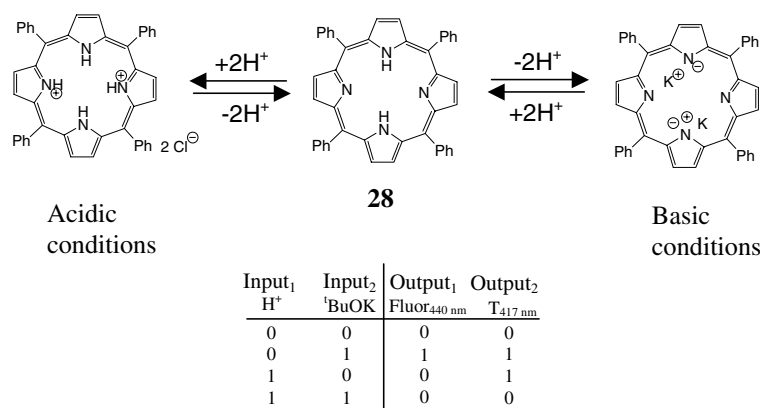
| Input$_1$ | Input$_2$ | Output$_1$ | Output$_2$ |
| H$^+$ | $^t$BuOK | Fluor$_{440\,nm}$ | T$_{417\,nm}$ |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 1 | 1 | 1 |
| 1 | 0 | 0 | 1 |
| 1 | 1 | 0 | 0 |

**Figure 10.** Molecular half-subtractor based on a teraphenyl porphyrin **28** showing three different states, the truth table and the corresponding combinatorial logic circuit.

Gust and Moore approach the half-adder in an all-photonic framework (see figure 9(b)). In a reversal of the prototype example, a fluorescent XOR gate **27** (porphyrin fluorescence output) and a changing absorbance from an AND gate **26** (transient absorption signature of the fullerene radical anion) are considered using molecules acting in parallel [128]. Each of these porphyrin-containing molecules also contains a different photochromic switching unit absorbing at different wavelengths. Exciting the AND gate results in a PET reaction generating the fullerene radical anion. However, the lifetime of the charge separated state is on the microsecond timescale (due to a charge shift reaction) when the dihydropyrene photochrome is closed, compared to the nanosecond timescale where back-electron transfer to the adjacent porphyrin radical ion is rapid when it is open [129]. If the weak fullerene absorption signature is probed after a designated time delay, a '1' will only be obtained if the photochrome is closed and the porphyrin has been excited, i.e. via simultaneous application of two laser pulses of different colours conferred by the laser set-up in figure 9(b). The two-module XOR gate is fluorescent only when the dihydroindolizine photochrome is closed, when open a PET reaction from the excited porphyrin quenches its fluorescence. Irradiation of the XOR gate with the photochrome in the initially open form with either laser A or B closes the photochrome and luminescence is observed (output 1). Application of both lasers results in no net isomerization, the PET process dominates and no fluorescence (output 0) is measured. The two shared laser beams are 1064 nm (input A) and 532 nm (input B). A third-harmonic generator (THG) is also essential with cycle times estimated to be sub-10 $\mu$s. The authors suggest that as the outputs are based on electron transfer reactions, they could in principle be detected electronically if incorporated into electronic circuits.

The porphyrin-based report by Langford and Yann [130] on commercially available **28** represents the first molecular demonstration of the mathematical operation of rudimentary subtraction, which is demonstrated with a single-molecule type (see figure 10). Half-subtractors are built from INHIBIT and XOR logic gates in silicon technology [1]. The numerical function of **28** is revealed using simple UV–visible absorption spectroscopy and fluorescence spectroscopy. The small binary numbers treated by **28** are input in chemical form, as stoichiometric amounts of acid and base which can annihilate each other.

Porphyrin **28** can form either dicationic or dianionic species on addition of acid (H$^+$) or base ($^t$BuO$^-$K$^+$), respectively, in DMF solvent. In its neutral form, **28** absorbs strongly at 417 nm. Addition of acid or base leads to red shifting of the absorption band by about

15 nm. By monitoring transmittance at 417 nm, a 'difference' output (D) can be obtained (i.e. XOR logic). Monitoring fluorescence emission yields INHIBIT logic or the 'borrow' output (B). While neutral **28** displays a weak emission band at 654 nm, deprotonation causes a blue shift to 637 nm and protonation yields no fluorescence at the monitoring wavelength. Monitoring emission at 637 nm thus yields the borrow output and nanometre-scale subtraction is demonstrated.

It is interesting to note that INHIBIT and XOR operations can be achieved within the same molecule **3** discussed above via transmittance and fluorescence channels respectively, when suitable wavelengths are employed [48]. This also constitutes half-subtractor action.

The first implementation of an arithmetic processor (**29**) which is capable of *both* elementary addition and subtraction was reported by Shanzer; see figure 11 [57, 131]. As outlined above, addition requires AND logic for the carry digit and XOR for the sum digit, while subtraction needs INH logic for the borrow digit and XOR for the difference digit. Reconfiguring with several chemical inputs (acetic acid, acetate as base and EDTA as complexant), gives rise to several two-input logic gates. The inputs interact with hydroxamate, carboxylate and phenolate, as well as $Fe^{3+}$ sites. Due to the possibility of reading blue (pyrene) or green (fluorescein) output channels, the variety of logic configurations is magnified further. Amongst these, the four arithmetically significant logic gates mentioned above are identified. Fluorescence quenching by PET and EET is provoked by the open-shell $Fe^{3+}$. The blue fluorescence of pyrene is inhibited as EET to fluorescein results in green fluorescence instead. This EET is inefficient when fluorescein is protonated (acidic media) resulting in a less delocalized $\pi$-system. Additionally, $Fe^{3+}$ loses its usual quenching ability towards fluorescein in basic solution as ligation of the base to $Fe^{3+}$ reduces its ability to participate in a PET reaction. Notably, the XOR logic function results from the summing of two complementary INH functions arising in the blue and green output channels.

The implementation of a molecular full adder, as mentioned above, is a formidable challenge. However, this challenge was undertaken by Remacle, Speiser and Levine [40] using multiphoton spectroscopic techniques and FRET between fluorophores in solution. When certain technical issues are surmounted, **10** and **24**, which can be identified as half-adders in their own right, can potentially perform molecular number operations more complex than those achieved by half-adder systems. The first XOR output, the one-photon fluorescence emission of **10**, can be fed into **24**. Another light input to pump **24** is easily supplied. However, a separate OR gate is required to collect the outputs from the AND outputs of **10** and **24**, creating a full adder. While a definite step forward, further work from these authors on this issue is awaited.

Okamoto and Saito [111] have recently deployed photoactive DNA (bearing artificial nucleobases) logic gates to reproduce the functioning of a biomolecular full adder. Molecular logic gates were described utilizing the hole transporting ability of a short synthetic DNA comprising adenine modified with electron-rich substituents to aid the process of hole transport along the strand. Hole transport efficiency in the logic gate strand was defined by the damage ratio (denoted by a high value) after irradiation. The truth table of the full adder was demonstrated after irradiating two solutions, each comprising five logic gate strands (one being common to both), which give the sum and carry outputs and the addition of three bits of information. Indirect reading of the output slows down the read-out process, with strand scission rather than fluorescence as the output channel. It is notable that larger DNA-type oligonucleotides can also be persuaded to be numerate, even as regards larger numbers [132].

## 8. Outlook

It is interesting to see what chemical and biochemical approaches can bring to the field of logic operations, which is defined by mathematics and so clearly dominated by semiconductor
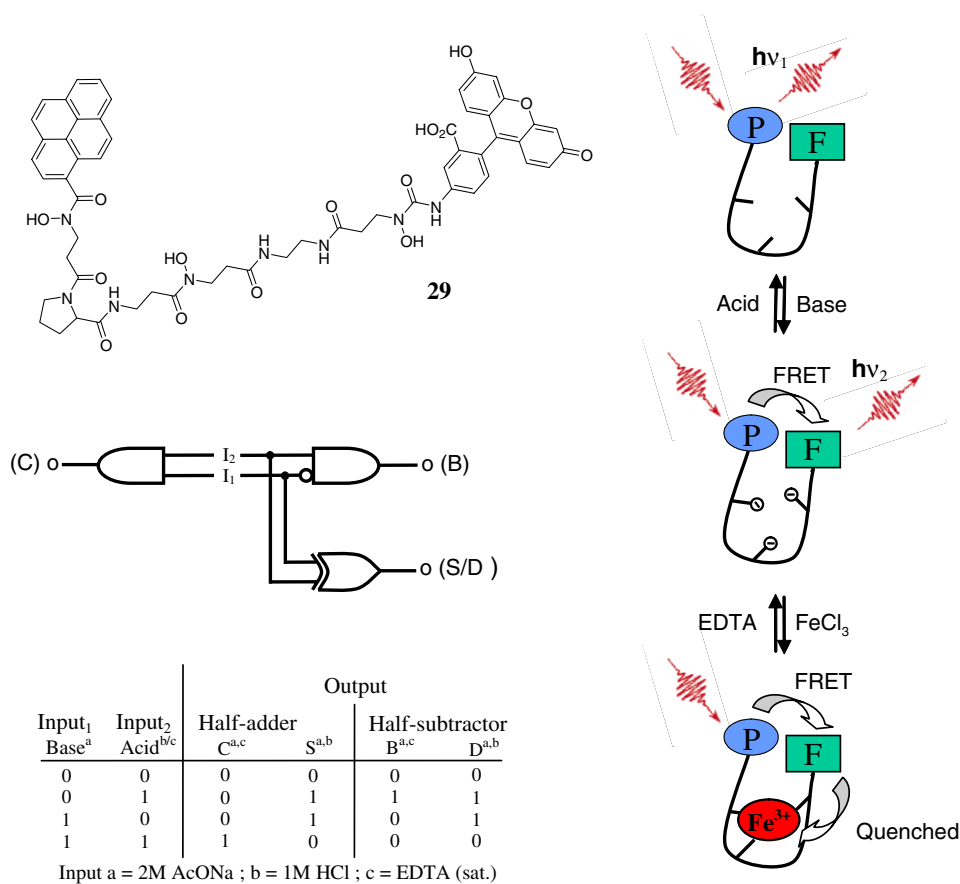
**Figure 11.** Bichromophoric **29** which can be reconfigured as a half-adder or half-subtractor, as shown in the truth table, based on acid/base reactions and metal complexation/decomplexation. P = pyrene; F = fluorescein.

physics. The clearly small size of molecules is an important driver, since computing operations can be envisaged in the small spaces of biology. Even though the logic operations achieved thus far are rather simple, they are the only ones which can enter this vital milieu. The preceding pages show how rather small molecules, somewhat larger polymers and biomolecules can employ the transfer of electrons, energy or electronic charge under photochemical conditions to perform simple computation. Another powerful photochemical phenomenon—photochromism—also offers valuable examples and ideas. The controlled motion of molecular components within supramolecular assemblies, when coupled with photochemical processes, adds further impetus to the field. The demonstrable confinement or immobilization of molecular computing elements provides new avenues for exploration of small spaces. In spite of the short history of the field, the achievement of small scale integration, reconfigurability (simultaneous in some instances) and numeracy augurs well for the future.

## References

[1] Malvino A P and Brown J A 1993 *Digital Computer Electronics* 3rd edn (Lake Forest: Glencoe)
    Mitchell R J 1995 *Microprocessor Systems: An Introduction* (London: Macmillan)

Ben-Ari M 1993 *Mathematical Logic for Computer Science* (Hemel Hempstead: Prentice-Hall)

[2] Intel Press Release; http://www.intel.com/pressroom/archive/releases/20040830net.htm 08/30/2004

[3] Reed M A and Tour J M 2000 *Sci. Am.* **282** 86

Tour J M 2000 *Acc. Chem. Res.* **33** 791

[4] See for example Bard A J 1994 *Integrated Chemical Systems: A Chemical Approach to Nanotechnology* (New York: Wiley)

Graham D J and Schulmerich M V 2004 *J. Chem. Inf. Comput. Sci.* **44** 1612

[5] Feynman R P 1960 *Eng. Sci.* **23** 22

Feynman R P 1960 *Saturday Rev.* **43** 45

[6] Luo Y *et al* 2002 *Chem. Phys. Chem.* **3** 519

Pease A R, Jeppesen J O, Stoddart J F, Luo Y, Collier C P and Heath J R 2001 *Acc. Chem. Res.* **34** 433

Chen J *et al* 2002 *Ann. New York Acad. Sci.* **960** 69

[7] Collier C P, Wong E W, Belohradsky M, Raymo F M, Stoddart J F, Kuekes P J, Williams R and Heath S R 1999 *Science* **285** 391

Collier C P *et al* 2000 *Science* **289** 1172

Derycke V, Martel R, Appenzeller J and Avouris P 2001 *Nano Lett.* **1** 453

[8] de Silva A P, McCaughan B, McKinney B O F and Querol M 2003 *Dalton* p 1902 and references therein

[9] Weiss S 1999 *Science* **283** 1676

Zander C, Enderlein J and Keller R A 2002 *Single Molecule Detection in Solution* (Berlin: Wiley–VCH)

[10] Steinbock O, Kettunen P and Schowalter K 1996 *J. Chem. Phys.* **100** 18970

[11] Kompa K L and Levine R D 2001 *Proc. Natl Acad. Sci. USA* **98** 410

Remacle F, Schlag E W, Selzle H, Kompa K L, Even U and Levine R D 2001 *Proc. Natl Acad. Sci. USA* **98** 2973

[12] Stenitz D, Remacle F and Levine R D 2002 *Chem. Phys. Chem.* **3** 43

[13] Kuciauskas D, Liddell P A, Moore A L, Moore T A and Gust D 1998 *J. Am. Chem. Soc.* **120** 10880

[14] Herges R, Deichmann M, Grunenberg J and Bucher G 2000 *Chem. Phys. Lett.* **327** 149

[15] Hod O, Baer R and Rabani E 2005 *J. Am. Chem. Soc.* **127** 1648

[16] Zhou Y, Zhang D, Zhang Y, Tang Y and Zhu D 2005 *J. Org. Chem.* **70** 6164

[17] Yoshizawa M, Tamura M and Fujita M 2004 *J. Am. Chem. Soc.* **126** 6846

[18] Schneider H-J, Liu T J, Lomadze N and Palm B 2004 *Adv. Mater.* **16** 613

[19] de Silva A P and McClenaghan N D 2004 *Chem. Eur. J.* **10** 574

Balzani V, Credi A and Venturi M 2003 *Chem. Phys. Chem.* **3** 49

Raymo F M 2002 *Adv. Mater.* **14** 401

[20] Bu J H, Zheng Q Y, Chen C F and Huang Z T 2004 *Org. Lett.* **6** 3301

Lee S H, Kim S K, Lee J H and Kim J H 2004 *Tetrahedron* **60** 5171

Cheng P N, Chiang P T and Chiu S H 2005 *Chem. Commun.* 1572

Wang Z, Zheng G and Lu P 2005 *Org. Lett.* **7** 3669

[21] Balzani V 2003 *Electron Transfer in Chemistry* (Weinheim: Wiley–VCH)

Kavarnos G J 1993 *Fundamentals of Photoinduced Electron Transfer* (New York: VCH)

Fox M A and Chanon M 1988 *Photoinduced Electron Transfer* (Amsterdam: Elsevier)

Mattay J (ed) 1990 Photoinduced electron transfer I *Top. Curr. Chem.* **156** 1

Mattay J (ed) 1991 Photoinduced electron transfer II *Top. Curr. Chem.* **158** 1

Mattay J (ed) 1991 Photoinduced electron transfer III *Top. Curr. Chem.* **159** 1

Mattay J (ed) 1992 Photoinduced electron transfer IV *Top. Curr. Chem.* **163** 1

Mattay J (ed) 1993 Photoinduced electron transfer V *Top. Curr. Chem.* **169** 1

[22] Bryan A J, de Silva A P, de Silva S A, Rupasinghe R A D D and Sandanayake K R A S 1989 *Biosensors* **4** 169

Bissell R A, de Silva A P, Gunaratne H Q N, Lynch P L M, Maguire G E M, McCoy C P and Sandanayake K R A S 1993 *Top. Curr. Chem.* **168** 223

[23] Siegermann H and Weinberg N L 1975 *Techniques of Electroorganic Synthesis. Part 2* (New York: Wiley)

[24] Zang L, Liu R, Holman M W, Nguyen K T and Adams D M 2002 *J. Am. Chem. Soc.* **124** 10640

[25] Brasselet S and Moerner W E 2000 *Single Mol.* **1** 17

[26] de Silva A P, Gunaratne H Q N and McCoy C P 1993 *Nature* **364** 42

[27] de Silva A P, Gunaratne H Q N and McCoy C P 1997 *J. Am. Chem. Soc.* **119** 7891

[28] Callan J F, de Silva A P and McClenaghan N D 2004 *Chem. Commun.* 2048

[29] Cooper C R and James T D 2000 *J. Chem. Soc. Perkin Trans.* **2** 963

[30] de Silva A P, McClean G D and Pagliari S 2003 *Chem. Commun.* 2010

[31] Koskela S J M, Fyles T and James T D 2004 *Chem. Commun.* 945

[32] Bag B and Bharadwag P K 2005 *Chem. Commun.* 5133

[33] Uchiyama S, Kawai N, de Silva A P and Iwai K 2004 *J. Am. Chem. Soc.* **126** 3032

[34] Hughes E 1990 *Electrical Technology* 6th edn (Burnt Mill: Longman)

[35] Matsui J, Mitsuishi M, Aoki A and Miyashita T 2003 *Angew. Chem. Int. Edn* **42** 2272

[36] Matsui J, Mitsuishi M, Aoki A and Miyashita T 2004 *J. Am. Chem. Soc.* **126** 3708

[37] Turro N J 1991 *Modern Molecular Photochemistry* (Mill Valley, CA: University Science Books)

[38] Speiser S 2003 *J. Lumin.* **102/103** 267

[39] Yeow E K L and Steer R P 2003 *Chem. Phys. Lett.* **377** 391

[40] Remacle F, Speiser S and Levine R D 2001 *J. Phys. Chem.* B **105** 5589

[41] Indelli M T, Ghirotti M, Prodi A, Chiorboli C, Scandola F, McClenaghan N D, Puntoriero F and
     Campagna S 2003 *Inorg. Chem.* **42** 5489

[42] Gunnlaugsson T, MacDónail D A and Parker A D 2000 *Chem. Commun.* 93

[43] de Silva A P, Dixon I M, Gunaratne H Q N, Gunnlaugsson T, Maxwell P R S and Rice T E 1999 *J. Am. Chem.
     Soc.* **121** 1393

[44] Bissell R A, de Silva A P, Gunaratne H Q N, Lynch P L M, Maguire G E M and Sandanayake K R A S 1992
     *Chem. Soc. Rev.* **21** 187

[45] Valeur B 2002 *Molecular Fluorescence* (Weinheim: Wiley–VCH)

[46] Martin M M, Plaza P, Meyer Y H, Badaoui F, Bourson J, Lefebvre J P and Valeur B 1996 *J. Phys. Chem.*
     **100** 6879

     Létard J F, Lapouyade R and Rettig W 1993 *Pure Appl. Chem.* **65** 1705

[47] Moerner W E and Basche T 1993 *Angew. Chem.* **105** 537

     Moerner W E and Basche T 1993 *Angew. Chem. Int. Edn Engl.* **32** 457

[48] de Silva A P and McClenaghan N D 2002 *Chem. Eur. J.* **8** 4935

[49] de Silva A P and McClenaghan N D 2000 *J. Am. Chem. Soc.* **122** 3965

[50] Cox G S, Turro N J, Yang N C and Chen M J 1984 *J. Am. Chem. Soc.* **106** 422

     Bouas-Laurent H, Castellan A, Daney M, Desvergne J-P, Guinard G, Marsau P and Riffaud M N 1986 *J. Am.
     Chem. Soc.* **108** 315

[51] Deng G, Sakaki T and Shinkai S 1993 *J. Polym. Sci.* A **31** 1915

     Ballardini R, Balzani V, Credi A, Gandolfi M T, Kotzyba-Hibert F, Lehn J-M and Prodi L 1994 *J. Am. Chem.
     Soc.* **116** 5741

[52] Jiménez D, Martínez-Mánez R, Sancenón F, Ros-Lis J V, Soto J, Benito A and García-Breijo E 2005 *Eur. J.
     Inorg. Chem.* 2393

[53] Pina F, Melo M J, Maestri M, Passaniti P and Balzani V 2000 *J. Am. Chem. Soc.* **122** 4496

[54] Credi A, Balzani V, Langford S J and Stoddart J F 1997 *J. Am. Chem. Soc.* **119** 2679

[55] Montenegro J M, Perez-Inestrosa E, Collado D, Vida Y and Suau R 2004 *Org. Lett.* **6** 2353

[56] Gunnlaugsson T, MacDónaill D A and Parker D 2001 *J. Am. Chem. Soc.* **123** 12866

[57] Margulies D, Melman G, Felder C E, Arad-Yellin R and Shanzer A 2004 *J. Am. Chem. Soc.* **126** 15400

     Raymo F M and Giordani S 2002 *J. Am. Chem. Soc.* **124** 2004

     Alves S, Pina F, Albelda M T, Garcia-Espana E, Soriano C and Luis S V 2001 *Eur. J. Inorg. Chem.* 405

[58] Dürr H and Bouas-Laurent H 1990 *Photochromism. Molecules and Systems* (Amsterdam: Elsevier)

     Irie M (ed) 2000 *Chem. Rev.* **100** 1683

[59] Hirshberg Y 1956 *J. Am. Chem. Soc.* **78** 2304

[60] Tomasulo M, Sortino S and Raymo F M 2005 *Org. Lett.* **7** 1109

[61] Irie M 2001 *Molecular Switches* ed B L Feringa (New York: Wiley–VCH) p 37

[62] Tamaki T and Ichimura K 1989 *J. Chem. Soc., Chem. Commun.* 1477

[63] Wojtyk J T C, Kazmaier P M and Buncel E 1998 *Chem. Commun.* 1703

[64] Raymo F M and Giordani S 2001 *J. Am. Chem. Soc.* **123** 4651

[65] Inouye M, Akamatsu K and Nakazumi H 1997 *J. Am. Chem. Soc.* **119** 9160

[66] Gobbi L, Seiler P and Diederich F 1999 *Angew. Chem. Int. Edn* **38** 674

[67] Tian H, Qin B, Yao R X, Zhao X L and Yang S J 2003 *Adv. Mater.* **15** 2104

[68] Endtner J M, Effenberger F, Hartshuh A and Port H 2000 *J. Am. Chem. Soc.* **122** 3037

[69] Irie M, Fukaminato T, Sasaki T, Tamai N and Kawai T 2002 *Nature* **420** 759

[70] Guo X, Zhang D and Zhu D 2004 *Adv. Mater.* **16** 125

[71] Guo X, Zhang D, Zhou Y and Zhu D 2003 *J. Org. Chem.* **68** 5681

     Guo X, Zhang D, Tao H and Zhu D 2004 *Org. Lett.* **6** 2491

[72] Straight S D, Andréasson J, Kodis G, Bandyopadhyay S, Mitchell R H, Moore T A, Moore A L and Gust D 2005
     *J. Am. Chem. Soc.* **127** 9403

[73] Asakawa M, Ashton P R, Balzani V, Credi A, Mattersteig G, Matthews O A, Montalti M, Spencer N,
     Stoddart J F and Venturi M 1997 *Chem. Eur. J.* **3** 1992

[74] Leigh D A *et al* 2005 *Angew. Chem. Int. Edn* **44** 3062

[75] Birge R R, Crandall B C and Lewis B C 1992 *In Nanotechnology; Research and Perspectives* (Cambridge, MA: MIT Press) p 156

[76] Aviram A and Ratner M A 1974 *Chem. Phys. Lett.* **29** 277
Hopfield J J, Onuchic J N and Beratan D N 1988 *Science* **241** 817

[77] Lukas A S, Bushard P J and Wasielewski M R 2001 *J. Am. Chem. Soc.* **123** 2440
Andersson M, Sinks L E, Hayes R T, Zhao T and Wasielewski M R 2003 *Angew. Chem. Int. Edn* **42** 3139

[78] Zhang T H, Zhang C P, Fu G H, Li Y D, Gu L Q, Zhang G Y, Song Q W, Parsons B and Birge R R 2000 *Opt. Eng.* **39** 527

[79] He H, Mortellaro M, Leiner M J P, Young S T, Fraatz R J and Tusa J 2003 *Anal. Chem.* **75** 549
He H, Mortellaro M, Leiner M J P, Fraatz R and Tusa J 2003 *J. Am. Chem. Soc.* **125** 1468

[80] Bissell R A, Bryan A J, de Silva A P, Gunaratne H Q N and McCoy C P 1994 *J. Chem. Soc., Chem. Commun.* 405
Fernandez M S and Fromherz P 1977 *J. Phys. Chem.* **81** 1755

[81] Uchiyama S, McClean G D, Iwai K and de Silva A P 2005 *J. Am. Chem. Soc.* **127** 8920

[82] Sumaru K, Matsuoka H, Yamaoka H and Wignall G D 1996 *Phys. Rev.* E **53** 1744

[83] For similar amplifying effects see Fernández M S and Fromherz P 1977 *J. Phys. Chem.* **81** 1755
Roque A, Pina F, Alves S, Ballardini R, Maestri M and Balzani V 1999 *J. Mater. Chem.* **9** 2265

[84] Grandini P, Mancin F, Tecilla P, Scrimin P and Tonellato U 1999 *Angew. Chem. Int. Edn* **38** 3061
Díaz-Fernández Y, Pérez-Gramatges A, Amendola V, Foti F, Mangano C, Pallavacini P and Patroni S 2004 *Chem. Commun.* 1650
Díaz-Fernández Y, Pérez-Gramatges A, Rodríguez-Calvo S, Mangano C and Pallavacini P 2004 *Chem. Phys. Lett.* **398** 245
Russell J C, Costa S B, Seiders R P and Whitten D G 1980 *J. Am. Chem. Soc.* **102** 5678
Nakahara Y, Kida T, Nakatsuji Y and Akashi M 2004 *Chem. Commun.* 224
Bhattacharya S and Gulyani A 2003 *Chem. Commun.* 1158

[85] Mao C, Thalladi V R, Wolfe D B, Whitesides S and Whitesides G M 2002 *J. Am. Chem. Soc.* **124** 14508

[86] Komura T, Niu G Y, Yamaguchi T and Asano M 2003 *Electrochim. Acta* **48** 631

[87] Zheng Y, Orbulescu J, Ji X, Andreopoulos F M, Pham S M and Leblanc R M 2003 *J. Am. Chem. Soc.* **125** 2680

[88] Brasola E, Mancin F, Rampazzo E and Tonellato U 2003 *Chem. Commun.* 3026

[89] Prodi L, Montalti M, Zaccheroni N and Falini G 2002 *J. Am. Chem. Soc.* **124** 13540

[90] Meallet-Renault R, Pansu R, Amigoni-Gerbier S and Larpent C 2004 *Chem. Commun.* 2344

[91] Crego-Calama M and Reinhoudt D N 2001 *Adv. Mater.* **13** 1171

[92] Morimoto M, Kobatake S and Irie M 2003 *Photochem. Photobiol. Sci.* **2** 1088

[93] Giordani S and Raymo F M 2003 *Org. Lett.* **5** 3559

[94] Adleman L M 1994 *Science* **266** 1021

[95] Guet C C, Elowitz M B, Hsing W and Leibling S 2002 *Science* **296** 1466

[96] Stojanovic M N, Mitchell T E and Stefanovic D 2002 *J. Am. Chem. Soc.* **124** 3555

[97] Cech T R 1990 *Angew. Chem. Int. Edn Engl.* **29** 759

[98] de Silva A P, Gunaratne H Q N, Gunnlaugsson T, Huxley A J M, McCoy C P, Rademacher J T and Rice T E 1997 *Chem. Rev.* **97** 1515
Lakowicz J R 1999 *Principles of Fluorescence Spectroscopy* 2nd edn (New York: Plenum)

[99] Mao C D, La Bean T H, Reif J H and Seeman N C 2000 *Nature* **407** 493
Liu Q, Wang L, Frutos A G, Condon A E, Corn R M and Smith L M 2000 *Nature* **403** 175

[100] Stojanović M N and Stefanović D 2003 *J. Am. Chem. Soc.* **125** 6673

[101] Kolpashchikov D M and Stojanovic M N 2005 *J. Am. Chem. Soc.* **127** 11348

[102] Stojanovic M N and Stefanovic D 2003 *Nat. Biotech.* **21** 1069

[103] Stojanović M N, Semova S, Kolpashchikov D, Macdonald J, Morgan C and Stefanović D 2005 *J. Am. Chem. Soc.* **127** 6914

[104] Ashkenazi G, Ripoli D R, Lotan N and Scheraga H A 1997 *Biosensors Bioelectron.* **12** 85

[105] Sivan S, Tuchman S and Lotan N 2003 *Biosystems* **70** 21

[106] Zauner K P and Conrad M 2001 *Biotechnol. Prog.* **17** 553

[107] Saghatelian A, Völcker N H, Guckian K M, Lin V S Y and Ghadiri M R 2003 *J. Am. Chem. Soc.* **125** 346

[108] Deonarine A S, Clark S M and Konermann L 2003 *Future Generation Comput. Syst.* **19** 87

[109] Lotan N, Ashkenazi G, Tuchman S, Nehamkin S and Sideman S 1993 *Mol. Cryst. Liq. Cryst.* **236** 95
Preboda K E, Scott J E, Mullins R D and Lim W A 2000 *Science* **290** 801

[110] Ashkenasy G and Ghadiri M R 2004 *J. Am. Chem. Soc.* **126** 11140

[111] Okamoto A, Tanaka K and Saito I 2004 *J. Am. Chem. Soc.* **126** 9458

[112] Patolsky F, Gill R, Weizmann Y, Mokari T, Banin U and Willner I 2003 *J. Am. Chem. Soc.* **125** 13918
[113] Iwata S and Tanaka K 1995 *J. Chem. Soc., Chem. Commun* 1491
      Parker D and Williams J A G 1998 *Chem. Commun.* 245
[114] Baytekin H T and Akkaya E U 2000 *Org. Lett.* **2** 1725
[115] de Costa M D P, de Silva A P and Pathirana S T 1987 *Can. J. Chem.* **65** 1416
[116] Sabbatini N, Guardigli M and Lehn J-M 1993 *Coord. Chem. Rev.* **123** 201
[117] Ji H F, Dabestani R and Brown G M 2000 *J. Am. Chem. Soc.* **122** 9306
[118] Xu H, Xu X, Dabestani R, Brown G M, Fan L, Patton S and Ji H F 2002 *J. Chem. Soc. Perkin Trans.* 2 636
[119] De Sousa M, Kluciar M, Abad S, Miranda M A, de Castro B and Pishel U 2004 *Photochem. Photobiol. Sci.*
      **3** 639
[120] Raymo F M and Giordani S 2001 *Org. Lett.* **3** 1833
[121] Raymo F M and Giordani S 2001 *Org. Lett.* **3** 3475
[122] Raymo F M, Alvarado R J, Giordani S and Cejas M A 2003 *J. Am. Chem. Soc.* **125** 2361
[123] Guo X, Zhang D, Zhou Y and Zhu D 2003 *Chem. Phys. Lett.* **375** 484
[124] Fabbrizzi L, Foti F, Patroni S, Pallavicini P and Taglietti A 2004 *Angew. Chem. Int. Edn* **43** 5073
      Amendola V, Fabbrizzi L, Mangano C, Miller H, Pallavicini P, Perotti A and Taglietti A 2002 *Angew. Chem.
      Int. Edn* **41** 2553
[125] Szacilowski K and Stasicka Z 2002 *Coord. Chem. Rev.* **229** 17
[126] Szacilowski K 2004 *Chem. Eur. J.* **10** 2520
[127] Guo X, Zhang D, Zhang G and Zhu D 2004 *J. Phys. Chem.* B **108** 11942
[128] Andréasson J, Kodis G, Terazono Y, Liddell P A, Bandyopadhyay S, Mitchell R H, Moore T A, Moore A L and
      Gust D 2004 *J. Am. Chem. Soc.* **126** 15926
[129] Liddell P A, Kodis G, Andréasson J, de la Garza L, Bandyopadhyay S, Mitchell R H, Moore T A,
      Moore A L and Gust D 2004 *J. Am. Chem. Soc.* **126** 4803
[130] Langford S J and Yann T 2003 *J. Am. Chem. Soc.* **125** 14951
      Langford S J and Yann T 2003 *J. Am. Chem. Soc.* **125** 11198
[131] de Silva A P 2005 *Nat. Mater.* **4** 15
[132] Yurke B, Mills A P and Cheng S L 1999 *BioSystems* **52** 165
      Guarnieri F, Fliss M and Bancroft C 1996 *Science* **273** 220