said to have been demonstrated before. A molecule that fluoresces only when well supplied with protons acts, in effect, as a 'YES' gate; conversely, if protons inhibit the fluorescence, we have a 'NOT' gate. The new molecule is more complex. It contains two recognition sites, corresponding to two input channels: the first site binds hydrogen ions, and the second (crown ether) site binds sodium ions. Variation in fluorescence — the output — depends on whether the molecule is provided with hydrogen ions, sodium ions or both. The properties of the dual input/single output arrangement in this system correspond to an AND gate, as strong fluorescence is seen only when both types of ion are present.

Although potentially useful as they stand for ion monitoring, these single-molecule systems provide only rudimentary models for future logic devices, for they operate in solution. Solid-state devices would be far more convenient, although one of the problems then is how to communicate with the device from the outside world; in other words, how to feed in the input and read the output. Some type of circuitry will be necessary, perhaps in the form of conducting molecules to act as molecular 'wires'. It might be possible to communicate with particular devices by applying a magnetic or electric field, or by monitoring the change in absorption or transmission of light. Communication remains one of the chief challenges associated with this field.

One approach is illustrated by the molecular system proposed by Aviram². In developing a blueprint for a molecular switch, Aviram based his designs on the 'spiro' molecule, incorporating two orthogonally oriented thiophene strings (see figure). The thiophene chains are associated with extensive π -electron delocalization and become conductors on oxidation (that is, on electron removal). The chains are linked by a 'bridge' of two pentagonal carbon rings (σ -bonded) at right angles to each other. Overall, the molecule amounts to a π - σ - π arrangement with the saturated spiro bridge corresponding to the σ component. In the normal course of events the σ bridge might be expected to serve as an insulator, but under certain conditions it can permit conduction, allowing transfer of an electron from one polythiophene chain to the other.

In the oxidized form, one of the thiophene chains contains one more electron than the other (in the figure, the latter chain bears the positive charge). This arrangement is equivalent to the electron being in a box with the shape of a double-well potential. The electron might normally be expected to oscillate between the two wells by quantum-mechanical tunnelling. But the incorporation of the spiral moiety makes the two possible states orthogonal and theory indicates

that this will inhibit tunnelling. Molecular orbital calculations predict that applying an electric field (directed along the axis that passes through the central spiro carbon and the two thiophene rings adjacent to the bridge) will alter the relative energies of the two states; if the field is strong enough, electron transfer or 'switching' from one chain to the other may occur³.

Already there is progress towards the practical synthesis of suitable spiro-bridged polythiophene molecules⁴, and modern developments in nanolithography now make it possible to fabricate patterns with line dimensions down to about 15 nanometres, to act as the required connectors and accompanying circuit.

Difficulties still remain. The construction of a successful device of this type requires the thiophene chains to assemble, or be assembled, across the appropriate gaps in the 'wiring' such that their ends make electrical contact with the wiring. It is likely that suitable reactive chemical groups at the terminus of each chain will be needed to make such connections. For gold wiring, thiol groups may prove suitable; their affinity for binding to gold surfaces has been well established⁵.

The above examples are just some of the many approaches being tried to overcome the formidable difficulties in producing practical molecular electronic and optoelectronic components. Uncertainties abound. Two-dimensional arrays are not necessarily the ideal for future devices. Three-dimensional ordered arrays of molecules, with, for example, 'tunable' intermolecular orbital overlaps in different directions (which could be used to control electron movement in each direction), may also prove important, especially if the system is able to self-assemble. It is not even clear that the fast speeds associated with optical and/or electron processes will necessarily dominate, as the use of parallel processing may enable slower processes (such as ion movement or molecular conformational change) to be useful.

Despite these uncertainties, engineering and scientific advances in critical areas continue across a wide front. There seems little doubt that useful molecular-scale devices will be made in the foreseeable future. □

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Bars to entry

DREADCO has a company cat: a friendly tabby, which enters the premises through its own cat-flap. To stop its friends coming in as well, Daedalus has fitted the cat-flap with a supermarket bar-code reader. It reads every cat approaching the flap, and lets it in only if it shows the correct pattern of stripes.

Daedalus now wants to use this scheme on the company's human employees as well. Current card and key-based security systems are awkward, annoying and often go wrong. But a bar-code reader operates automatically, works at a distance, and can read a code presented at any speed, in either direction, and at a wide range of angles. Properly sited, it could scan and identify everyone who enters or leaves the building.

Even Daedalus hesitates to brand or tattoo bar-codes on his work-force. But many traditional garments, from prisoners' uniforms to pin-striped trousers, have a strong striped motif already. So DREADCO tailors are devising a machine-readable company dress code. If it works, they plan to licence it to other organizations as well. They are developing machine-readable striped trousers for the British civil service, digitally striped shirts for the City, and coded variants of striped and barred rank-insignia for the military.

Scottish organizations could exploit the bar-code compatibility of the tartan, which after all was invented to distinguish one clan from another. Its vertical and horizontal stripes have a further advantage: an inebriated wearer could crawl horizontally into the premises and still be recognized.

The final system will classify the employees as well as identifying them. Among civil servants, for example, permanent secretaries would need a different pattern of pin-stripe from administrative trainees. Differentially coded patterned tights could be designed for female bureaucrats. A security tailoring company might have to change the patterns regularly, to frustrate intruders who try to sneak into the hallowed halls of authority in forged tights or trousers.

As a simplistic first step, however, Daedalus is scanning his motley work-force with a bar-code reader anyway. Anybody walking past it will generate some code number, simply by his pattern of light and shade. With luck this code will be quite characteristic. Once all the permitted staff have been coded in this way, the system may spot nearly all intruders. They couldn't even disguise themselves as legitimate employees: they wouldn't know what features to imitate.

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