the thermodynamic sense that the energy dissipated per bit loaded or unloaded tends to zero in the limit of zero speed.

To transport his bistable systems, Landauer invokes the technology of a modern ski-lift, which accelerates its passengers smoothly from a standing start at the boarding point, then drops them off equally smoothly at their destination. Such a system, also reversible in principle, could transport molecules or other bistable systems without risking inelastic effects that might be caused by a sudden change of velocity.

Once it has been brought up to speed, the molecule has kinetic energy and internal excitation energy above the ground state (which is a symmetric superposition of the two chiral states). Both are reusable, but in any case they can be made negligible compared with kT by moving the molecule slowly and by choosing one with a sufficiently large potential-energy barrier.

Ordinarily, one thinks of matter as an available building material, but if one had to manufacture a material information carrier out of nothing, the energy investment needed would be the carrier's rest energy, $E=mc^2$. Although far larger than kT for any molecule stable at temperature T, rest energy is almost perfectly re-usable, because spontaneous processes that would dissipate it (proton decay or cold fusion, for example) are rare even on cosmological timescales. By re-using the carrier more than mc^2/kT times, the rest energy per bit transmitted can be made less than kT.

Although molecules are quite stable against proton decay and cold fusion, they are less stable against loss of their stored data via tunnelling through or hopping over the energy barrier. That sets a limit on how slowly the molecular channel can be operated, which in turn sets a minimum (typically much less than kT, but still greater than zero) on the dissipative losses from chemical reactions, which approach zero only in the limit of zero speed. Fortunately, one can make the energy barrier higher and broader by using larger molecules, increasing the half-life of stored information roughly exponentially with molecule size. Meanwhile, the chemical reaction times also increase, but much more slowly. That suggests that there is no limit to the energy efficiency of matter-based communications channels other than those set by the stability of matter itself.

In the 35 years since Landauer's early paper[3] on irreversibility and heat generation in the computing process, the thermodynamics of information processing has become well understood[4]. General-purpose computation, communication, and even measurement can be performed in a thermodynamically reversible fashion, so long as information is not thrown away; in other words, so long as there is a 1:1 mapping between the initial and final states of the information-processing apparatus. If information *is* thrown away, the energy cost is $kT\ln 2$ per bit discarded.

In the past few years there has been a belated realization that the laws of quantum mechanics give rise to a larger and more complete theory of communication and computation, encompassing the transmission and manipulation of intact quantum states as well as classical bits (see refs 5 and 6, and reprints in the Los Alamos archive[7]). This larger theory explains and predicts such novelties as quantum cryptography, quantum data compression, the massive speed-up of certain computations by quantum parallelism, and, most recently, quantum error-correcting codes and fault-tolerant quantum gate arrays, which raise the hope of achieving quantum computation in practice.

Landauer's main contribution to this explosion of interest in quantum computation has been to offer constructive criticisms and warn against excessive optimism, but his molecular ski-lift, perhaps inadvertently, makes use of some of the new theory's most fashionable features. Via the so-called quantum watchdog effect, even extremely weak interactions between the lactic-acid molecule and its environment serve to stabilize the molecule's left- and right-handed states, while greatly accelerating the decay of any coherent superposition, such as the isolated molecule's true ground state. These interactions, in other words, make the lactic-acid molecule a better carrier of classical information, but useless as a carrier of quantum information. Isolating the molecule from the interactions (very difficult in practice), or using a quantum error-correcting code to hide a one-bit quantum message in a redundantly entangled state of five molecules, would allow the channel to be used for both kinds of information. □

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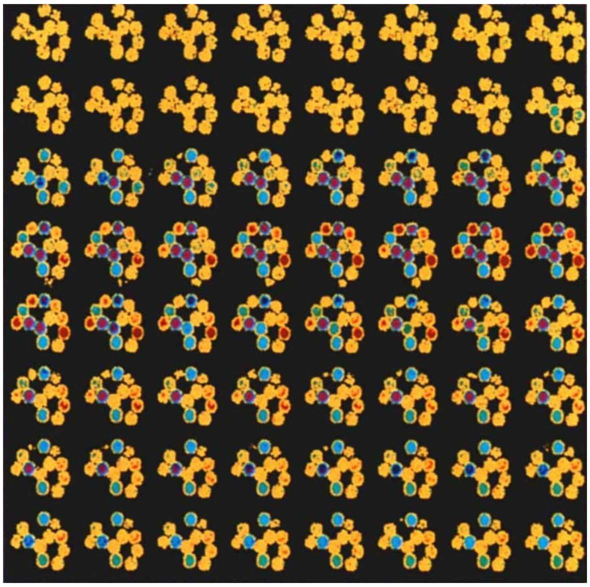
SENSORS

A triumph for common scents



THE smell of benzene is a familiar one to organic chemists, yet it has never appeared like this before. This time-series of images of fluorescent intensity from the tips of a bundle of optical fibres encodes a spatiotemporal 'fingerprint' of the organic compound. In the artificial nose described by Walt and co-workers on page 697, a neural network has been trained to recognize this fingerprint. Each fibre tip is coated with a dye and one of several different polymers; the colours represent the fluorescent response of each dye/polymer combination to a pulse of benzene gas (yellow is the resting state, and green, purple and red indicate increasing intensity; blue indicates decreased fluorescence). Images of the response (here taken at intervals of 133 milliseconds) together provide a unique time-varying signal for many different odorant molecules. An artificial nose of this sort mimics the operation of the olfactory system, in which an array of cross-reactive odour receptors or sensors provides a complex signature of each odorant, which is then decoded in a higher-level processing operation than the detection events themselves. A system of this sort, which sniffs out low concentrations of chemical species with high selectivity, might find valuable uses in environmental and medical monitoring.

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