MICROFLUIDICS

Tuned-in flow control

Analogues of the resistors, capacitors and diodes of an electronic circuit could eliminate the need for bulky external pumps to control the flow of liquids in a microfluidic circuit.

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The field of microfluidics promises eventually to integrate all of the functions of a conventional chemistry laboratory into a single, disposable chip[1]. Although there has been steady progress in the development of the micrometre-scale valves, mixers and other components needed to achieve this goal[2], multiple large external pumps and associated regulating hardware are needed to control the injection of fluids into a microfluidic circuit. This threatens to prevent or severely limit the use of 'lab-on-chip' systems in contexts where they might otherwise do the most good — that is, outside the laboratory, for such applications as the monitoring of pollutants in the environment, and medical analyses in community clinics. On page 231 of this issue, Leslie and colleagues[3] show that by designing different parts of a microfluidic circuit to respond in different ways to an oscillating fluid pressure they can selectively control the flow of multiple different fluids through the system. By reducing the amount of equipment needed to operate microfluidic systems, this approach could greatly improve their portability and widen the range of applications.

To build circuits whose fluid-carrying characteristics are frequency-dependent, Leslie *et al.* take advantage of the elastic response of certain soft materials. The creative use of soft materials for flow control is not new to microfluidics: various types of valves and other components have been designed that function by changing shape in response to a pressure[4,5]. Individually, however, there is no distinctive frequency dependence of these components. The new element introduced by Leslie *et al.* is to use multiple components in series to provide a specific frequency response that is easily controlled.

The inspiration for this approach comes from elementary electrical circuit theory. For example, the response of (ideal) linear electronic components such as resistors does not depend on the frequency of an applied voltage. But if a resistance R is joined in series with a capacitance C their combined response becomes frequency-dependent, with a characteristic frequency given by $1/RC$. Thus, a circuit with two different RC elements in parallel can establish two different downstream potentials for the same input potential. Combining these ideas with a third nonlinear element, a diode, provides a d.c. component to an a.c. forcing. This behaviour is regularly used to control the flow of current in an electrical circuit, and provides the guiding principle behind frequency-selective microfluidic control introduced by Leslie and co-workers. But doing so requires microfluidic structures that behave as analogues of the resistors, capacitors and diodes of conventional electronics.

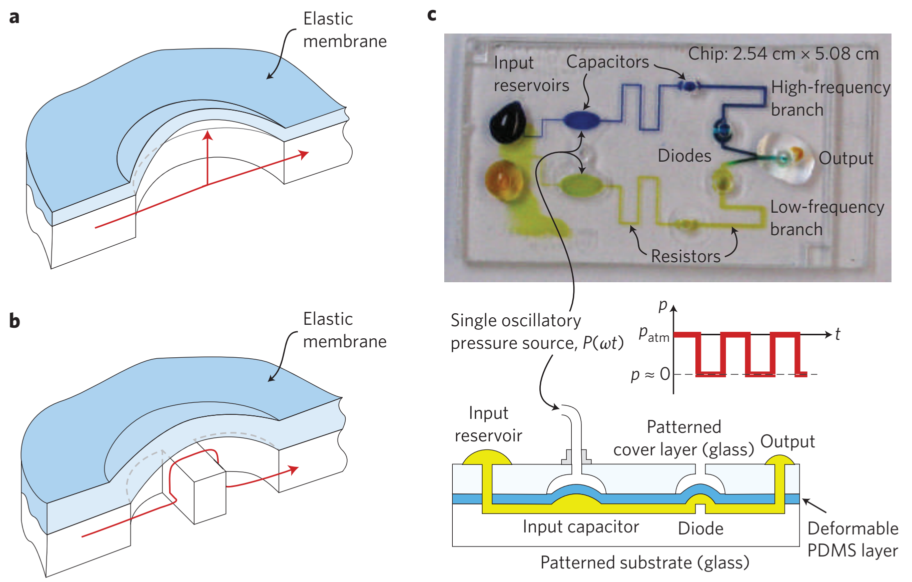

Figure 1 | Building a resonant microfluidic circuit. **a**, A simple cavity covered with an elastic membrane forms a reservoir that behaves as the microfluidic equivalent of an electronic capacitor. The red arrows indicate fluid flow. **b**, A microfluidic valve, behaving as the analogue of an electronic diode, consists of a membrane-covered cavity structure similar to a microfluidic capacitor but with a barrier running across to hinder the flow of liquid at low pressures. Increasing the pressure lifts the membrane away from the barrier, thus allowing current to flow more freely. **c**, Leslie *et al.*[3] demonstrate their approach by integrating two channels with two sets of microfluidic resistors, capacitors and valves, driven by a single oscillatory source and feeding into a single output channel. Changing the frequency of the source switches the flow of liquid to the output from one channel to another. Figure reprinted from ref. 3.

As has already been mentioned, the elasticity of materials used for microfluidics is central to the design of such components. In most ordinary circumstances we treat liquid and gas flows as occurring at constant density. For such incompressible flows, the microfluidic analogues of voltage and current are fluid pressure, p, and flow rate, q, respectively. The flow of liquid in any channel experiences viscous resistance, depending on the length and cross-sectional area of the channel and on the viscosity of the fluid, and so provides a direct equivalent of electrical resistance. Also, elastic reservoirs that expand and contract to hold varying amounts of liquid, like a water balloon (see Fig. 1a), provide the fluid equivalent of electrical capacitors. Using detailed knowledge of the elastic behaviour of the materials and geometry of their components, Leslie *et al.* are able to systematically design a circuit with a microfluidic resistance R, capacitance C and characteristic frequency $1/RC$.

But, of course, resistors and capacitors are not enough. Although they allow effective control over a purely oscillating flow (the equivalent of an a.c. electrical current), practical microfluidics invariably require the ability to generate and control a steady flow (the equivalent of a d.c. electrical current). For this, Leslie *et al.* introduce the microfluidic equivalent of a diode, a pressure-sensitive valve (see Fig. 1b). At low liquid pressures, such a valve strongly limits the flow of liquid. But as the pressure is increased, the valve opens up, allowing the liquid to flow more freely. The importance of this element is evident when you consider the response of a resistor, capacitor and pressure-sensitive valve connected in series. The frequency-dependent resistor and capacitor establish a narrow range of frequencies with large enough pressures to maintain the valve open and generate a net flow.

Leslie *et al.* demonstrate this approach by constructing two different channels, built with two sets of resistors, capacitors and diodes; the two branches have different characteristic frequencies, are filled with two different coloured liquids and are fed into a single output channel (see Fig. 1c). Driving the two channels with a single oscillatory pressure source, they show that as the driving frequency ω is varied, the liquid flowing to the output channel changes from one predominant colour to another, which demonstrates that the flow has switched from one input channel to the other.

Although it is certainly a promising development, there is still much to be done. The switching from one channel to another is not perfect, which is probably because of the relatively large bandwidth of each channel's resonant response. The authors note that this is one of the first issues that they hope to address in future research. Looking forward, it is interesting to imagine how this concept will scale up to manipulate the flow through many more channels or perhaps in three-dimensional networks[6]. Alternatively, the integration of CMOS technologies with microfluidic networks[7] allows ready manipulation of materials using electric and magnetic fields without extensive hardware. It might then be possible to use embedded magnets in elastic materials to actively manipulate the resonant characteristics of different parts of a microfluidic circuit and thus allow even greater control over the properties and behaviour of the system as a whole. ❐

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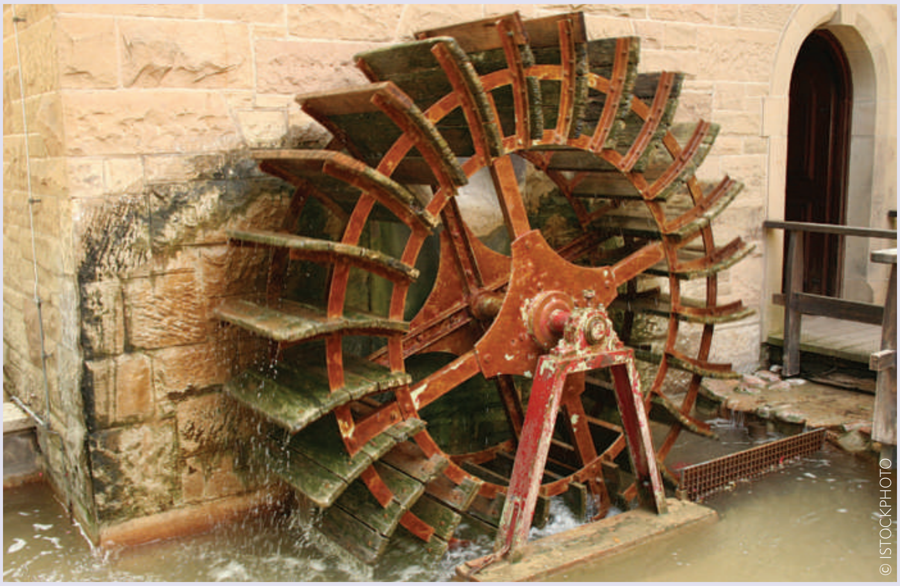
NANOTECHNOLOGY

Atomic waterwheels set in motion



Waterwheels have been used for centuries to harness the energy of flowing water. Simulations reported in *Nature Nanotechnology* show that the same idea could be transferred to the atomic scale — a 'waterwheel' made of just a few atoms that is driven by a stream of electrons.

Advances in computational techniques have made it possible to investigate the ways in which a current affects individual atoms in a conductor. This power has provided a better understanding of the damage that can be done to electrical interconnects by the current-induced forces that act on atoms, a consideration that becomes increasingly important as circuitry gets smaller and smaller.

Daniel Dundas and his colleagues wondered, however, whether these forces could be put to a more productive use (*Nature Nanotech*. **4,** 99–102; 2009). To phrase it more technically, is the energy conserved by the current-induced forces or is there some spare that can be put to work? It is a question that has been considered before but no clear answer had been found — until now.

The system that Dundas *et al.* investigated is a simple one, comprising a line of atoms — an atomic wire — with an electrode attached at each end to enable a voltage to be applied. The wire is given a sharp bend in the middle, at an atom that is of a different type from the others. In the simulations, this atom is allowed to move and its trajectory is calculated when a bias is applied.

When the wire is bent by 70° and 1 volt is applied, the central atom eventually settles into an orbital trajectory, the radius of which slowly increases. This demonstrates that net work is being done during each revolution: that is, the current-induced forces are non-conservative.

This current-driven atomic motor is, of course, overly simple. However, it represents a formal solution to an important question. And if nanotechnology continues to advance at the rate at which it has over the past decade or so, it may not be that long before devices based on this initial concept are realized in practice.

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