News & views

Engineering

Programmable capillary action controls fluid flows

Tammi L. van Neel & Ashleigh B. Theberge

A technological platform has been developed in which millimetre-scale cubes are assembled into 3D structures that control capillary action — enabling programmable fluid flows and modelling of a range of fluidic processes. **See p.58**

Scientists often draw inspiration from the world around them. On page 58, inspired by nature's ability to efficiently perform processes involving multiple phases of matter, Dudukovic *et al.*[1] present cellular fluidics: a technological platform in which many cubic building blocks with complex internal structures are assembled to guide fluid flow using capillary action. The authors use this platform to construct a variety of fluidic structures, and demonstrate that it can model important multiphase processes such as transpiration — by which trees absorb water through their roots and transport it to leaves at the tips of their branches, where it evaporates. Cellular fluidics also enables the fabrication of patterned multi-material structures, including objects that contain alternating electrically conducting and insulating regions.

Capillary action drives many processes, such as the wetting of hairs on a paint brush and eyes tearing up. It enables the flow of liquid in small spaces — in the gaps between fibres in a paper towel, for example, or in capillary tubes used to collect blood — without the need for external forces such as pumps. For this reason, it has found use in the field of microfluidics, which studies the movement of small volumes of fluid through spaces of submillimetre dimensions. Capillary action underpins many microfluidic technologies, such as at-home pregnancy tests and portable glucose monitors. By combining engineering, chemistry and physics, miniature 'lab-on-a-chip' devices such as these have been developed for use in many fields[2].

Conventional microfluidic systems are closed (the fluid is completely confined within channels), require external pumps to push the fluid and are accessible only through sealed-off ports. The field of open microfluidics was therefore conceived to make microfluidic systems more accessible, for example to pipettes[3–5]. In open microfluidics, at least one boundary of the flowing fluid is exposed to the air, creating an air–liquid interface.

Dudukovic *et al.* have drawn on the growing body of open-microfluidics theory to come up with a refined concept for this field: a unit cell from which complex 3D architectures can be built. Unit cells are usually thought of in the context of crystal lattices — they are the smallest repeating unit of a lattice. The unit cells in Dudukovic and colleagues' fluidics system are similarly used as the smallest building blocks of their fluidics platform. Each of these unit cells is a millimetre-scale cube with internal empty spaces that are open to the surrounding atmosphere (Fig. 1a).

The spaces are delineated by struts, which partly act as supports to prevent the unit cells from collapsing. By tuning the shape and size of the struts, the authors can control capillary action in the cells. Moreover, when the cells are coupled together, the combined capillary action of each cell produces a controllable path through which the fluid flows. Impressively, by building a tree-like structure (tens of millimetres in height) from the unit cells, they demonstrate that the combined capillary action of the cells enables a multi-phase process similar to transpiration (Fig. 1b). If an analogous tree-like structure were made from similarly sized, hollow unit cells lacking internal struts, the water from the roots would not make it very far through the tree (see Extended Data Fig. 6 of the paper[1]).

The flow of liquid in natural structures, such as tree leaves or soil, depends on the arrangement of the components in those structures[3]. Cellular fluidics is therefore the perfect tool with which to mimic such liquid flow, because the unit cells can be arranged in the same way as can the building blocks of the natural structures.

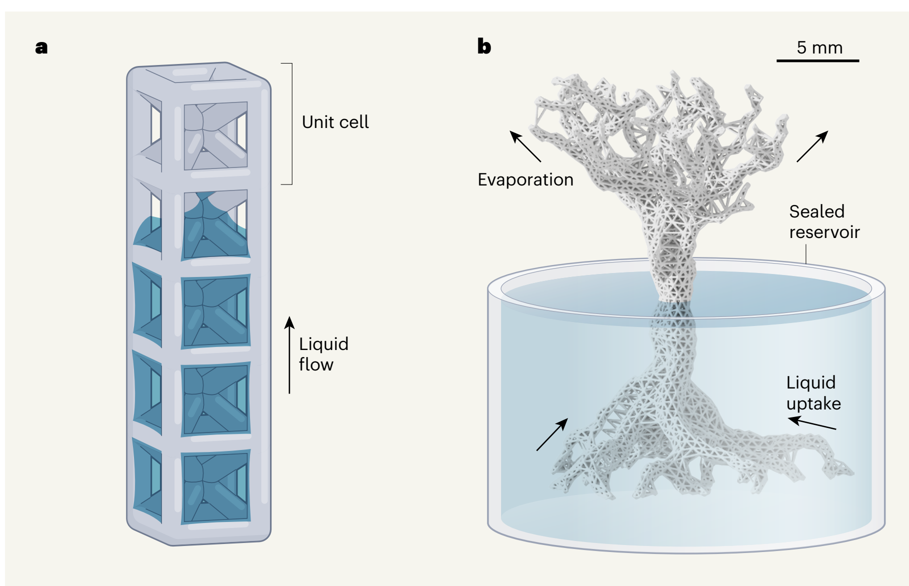

Figure 1 | Capillary flow and a transpiration-like process in cellular fluidic systems. Dudukovic *et al.*[1] report a technological platform called cellular fluidics. **a**, In this platform, millimetre-scale cubes known as unit cells have internal architectures that draw up fluids through capillary action. The combined capillary action of stacked unit cells produces a vertical flow of fluid. **b**, The authors report that a tree-like structure built from the unit cells continuously delivers liquid from a reservoir to the tips of the branches, where the liquid evaporates — a process that mimics transpiration in natural trees. (Tree image adapted from Fig. 4a of ref. 1.)

Capillary action occurs when the cohesive forces that hold molecules together in a fluid work together with the adhesive forces that cause the fluid to cling to a solid surface (such as the wall of a tube), thereby pulling the liquid in a given direction. Gravitational forces act against capillary action when fluid rises vertically. Capillary flow in simple systems, such as tubes, can be described mathematically by considering the interplay between these various forces. The capillary rise in Dudukovic and colleagues' unit cells is more complex than that in tubes, and so the authors derived a theoretical model that describes how strut diameter and the number of cells coupled together influence the overall capillary action of a cellular fluidics system.

The fabrication of open structures, such as Dudukovic and co-workers' unit cells, can be difficult to achieve using many of the methods typically used in microfluidics. The authors therefore used 3D printing to build up their unit cells layer by layer. This is an attractive option because one can think of a design in the morning, then draw a model using computer-aided design programs, upload the file to a 3D printer and simply press 'start'. A working prototype can be ready by the end of the day. 3D printing is also appealing because of the range of materials that can be printed, from hard resins for prototypes of diagnostic devices to biocompatible gels for tissue engineering. However, in many applications it is necessary to produce structures that are fabricated from multiple materials.

Cellular fluidics provides a solution to this problem. Dudukovic *et al.* show that, by adjusting the size, shape and density of the unit cells in a 3D structure, fluid flow can be controlled and guided along a chosen path (Fig. 2). This provides a way to coat specific unit cells in a structure with metal: when solutions of appropriate catalysts and reagents were channelled along a particular pathway, only the cells in that pathway were metallized when the whole structure was subsequently immersed in a plating solution. The authors used this approach to coat selected regions of a cylinder-shaped structure with metal, producing concentric rings that alternated between being electrically conductive and non-conductive (see Fig. 6e of the paper[1]). The researchers also suggest that the ability to channel fluids to specific areas of a structure could be used to deliver fluids within artificial organs.

Fluidic systems based on unit cells have been developed previously[6,7], and a limitation of Dudukovic and colleagues' work is that it largely reports known physical phenomena. However, a key advance of the present study is that it considerably increases our understanding of fluid flow in coupled unit-cell structures. We look forward to future applications in which cellular fluidics is used to investigate unknown physical principles or to fabricate novel multi-material structures. This technological platform opens up many exciting opportunities for research and is a valuable addition to the open-microfluidics toolkit.

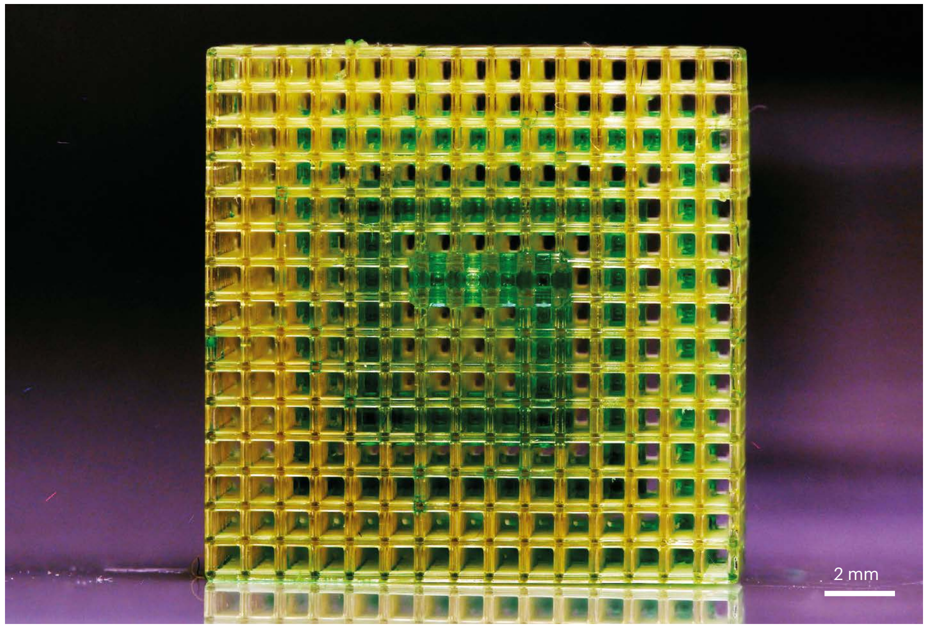

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Figure 2 | Selective fluid flow in 3D structures. Dudukovic *et al.*[1] demonstrate that the flow path of a fluid through 3D cellular fluidics structures can be precisely controlled by altering the size, shape and density of unit cells. Here, a green fluid passes along a spiral path.

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Microbiology

Designer fibre meals sway human gut microbes

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Understanding how diet affects gut microbes and thereby influences human health might lead to targeted dietary strategies. A clinical trial now provides some steps on the path towards this goal. **See p.91**

There is growing evidence that our normal resident gut microorganisms, termed commensal microbes, can affect human health. Promoting beneficial commensal microbes through a type of nutritional supplement called a prebiotic is an area of intensive scientific and medical research. However, trying to harness a diet with the desired effect is challenging because the gut microbial community (also known as the microbiome) is highly complex, and because dietary responses are modulated by multiple hereditary and non-hereditary factors. On page 91, Delannoy-Bruno *et al.*[1] fill an essential gap in our mechanistic understanding of diet–microbiome interactions by focusing on dietary fibre, a family of substances of pronounced physiological virtues that are predominantly metabolized by commensal