Interestingly, the formula derived in the paper shows that the position of the negative-slope region can be controlled so that it occurs at a desired frequency and wavenumber. The principal tuning knob is the order of the non-local springs. For example, Fig. 1b,c illustrates the cases of third-order and fourth-order nearest-neighbour couplings, in blue and green, respectively. As seen in Fig. 1d, by engineering longer-range interactions within the lattice, more slope inversion can be brought into the first Brillouin zone. This scheme leads to multiple rotons on a single band, which has no known quantum equivalent.

But could one create classical rotons in the real world? In their work, Chen et al. performed full-wave finite-element simulations that demonstrated that rotons could be experimentally observed in a specially designed three-dimensional acoustic metamaterial. The design proposed in the paper seems very simple, but its future experimental demonstration may require a careful decoupling between nearest-neighbour and beyond-nearest-neighbour connections, which remains a serious experimental challenge — even in the metamaterial field.

Artificial wave media, such as metamaterials, phononic crystals or photonic crystals, are ideal platforms to explore concepts originating from condensed-matter physics with simple tabletop experiments in which symmetries, coupling interactions and resonances can be readily controlled. Acoustic crystals based on three-dimensional printing, for example, bring about an almost unlimited level of freedom in designing very complex band structures. This in turn allows the exploration of involved systems that may never be achievable in condensed matter, such as the exploration of new insulating and semi-metallic topological phases. In this regard, Chen et al. also went considerably beyond what is traditionally possible in superfluids by creating multiple classical rotons on the same band. ❐

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Competing interests

The author declares no competing interests.

THREE-DIMENSIONAL FLUID LATTICES

Endless forms fabricated

The patterning dynamics of confined immiscible fluids has inspired an elegant and versatile approach to building periodic three-dimensional multi-material architectures. The technique extends to triphasic composites, three-dimensional droplet networks and even biological tissues.

Séverine Le Gac

At first glance, the wings of a butterfly have little in common with coral in the ocean — and perhaps even less to do with a human organ. But these objects all share the same characteristics of periodic three-dimensional (3D) organization, although the scales and materials differ. Nature excels at building such structures, and yet the task is far from trivial for engineers, especially when multiple materials are involved. Now, writing in *Nature Physics*[1], Hiroki Yasuga and colleagues report that they have come up with an innovative two-step approach to creating 3D multi-material periodic structures — offering a platform that is at once simple and extremely powerful.

The team have dubbed their technique FLUID3EAMS, referring to their revelation that fluid–fluid interfacial energy drives 3D structure emergence in a micropillar scaffold. This is the core principle behind the method: namely, that two immiscible fluids in a micromachined solid scaffold organize spontaneously as discrete particles in a continuous phase, to yield a well-defined 3D multiphasic structure (Fig. 1). This fluid-patterning process is specifically driven by the fluid–fluid surface tension, and the overall 3D multi-material architecture is governed by the geometry of the scaffold. For this self-organization process to be successful, two conditions must be fulfilled: the geometry of the solid scaffold needs to comprise fluid traps corresponding to the discrete fluid particles, and the fluid–fluid interfacial energy must dominate the fluid–solid interfacial energy.

The beauty of this process comes from the fact that it is straightforward, spontaneous and scalable, provided the fabrication of the initial 3D solid scaffold is possible. It is also amenable to the production of large 3D arrays. FLUID3EAMS additionally offers control of the geometry and size of the fluid particles, with less than 10% dispersity. Another unique feature of this process is that it forms an enormous fluid–fluid surface area, spanning several square metres per cubic centimetre, which presents exciting opportunities in the fields of materials science and heterogeneous catalysis, among others.

The concept of discrete fluid particles in a continuous fluid phase is arguably reminiscent of droplet microfluidics[2]. Yet, FLUID3EAMS goes well beyond droplet microfluidics because it is 3D in nature, and the presence of a scaffold not only governs the organization of the two immiscible fluids but also stabilizes the resulting architecture. Furthermore, this process is less demanding on the fluids employed as continuous and discrete phases. Finally, in contrast to conventional droplet microfluidics, FLUID3EAMS does not require a complex set-up with advanced microfluidic devices and expensive pumping systems. And yet it does so without compromising the fluid particle production throughput.

Using a combination of experiments and simulations, Yasuga et al. first validated

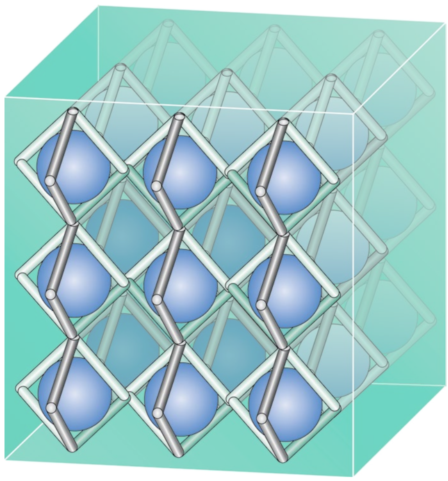

Fig. 1 | A schematic of FLUID3EAMS. A 3D solid scaffold (in light grey), produced using stereolithography or 3D printing, is filled with two immiscible fluids, which spontaneously self-organize as discrete particles (in blue) in a continuous phase (in green) to yield a 3D tri-material periodic structure. Figure adapted with permission from ref. [1], Springer Nature Ltd.

the FLUID3EAMS concept and established its working range, using a solid scaffold exhibiting a tetragonal lattice. By simply altering the filling conditions, the geometry of the fluid particles could easily be varied from spherical to diamond-like in such scaffolds.

To illustrate the versatility of the process, they successfully generated a variety of continuous and discrete phases, such as gas, liquids and solids — the latter made possible by in situ polymerization of a liquid on the scaffold. Smart architectures were also realized by incorporating materials that could be actuated. The team demonstrated this by using a thermosensitive polymer as the continuous phase to yield a 'breathing' material with on-demand opening of well-defined pores.

The first application of FLUID3EAMS showcased the fabrication of a soft tissue-like architecture. Yasuga et al. achieved this by layering, in a continuous oil phase, 2D arrays of aqueous compartments resembling cells. Communication between these well-organized compartments in the resulting 3D architecture was measured by recording the conductance of α-haemolysin ion channel proteins, which spontaneously inserted themselves into model cell membranes at the intercompartment interfaces.

Real biological cells were also encapsulated in homogeneously sized hydrogel particles, with an unprecedented density of ten million cells per millilitre. This is approximately one order of magnitude higher than that achievable using alternative technologies. After their easy removal from the scaffold, these cell-laden beads could be made available for in vivo implantation.

One limitation of FLUID3EAMS is the need for a solid scaffold, which may be an obstacle in the production of submicrometric architectures. There are also constraints on the geometry of the scaffold, so the concept cannot be applied to any given architecture. Returning to the analogy with droplet microfluidics, the absence of surfactants could also be a limitation, as surfactants not only stabilize droplets but also act as a barrier for molecular communication between them[3]. Finally, for many applications, in particular in the fields of biophysics, biology and tissue engineering, imaging of such 3D multi-material constructs is highly challenging.

Still, with the examples provided by Yasuga et al., the FLUID3EAMS story is just beginning, and there remain countless exciting possibilities to be explored using this elegant principle. One promising application is the production of a synthetic alternative to paper, which may be useful for diagnostic assays[4]. Another is in the field of heterogeneous catalysis, which is currently seeking materials that present an infinite surface area to maximize interactions with reactants in solution together with a tunable and homogeneous porosity. Similar features in a solid support also make analytical chemists dream of realizing perfectly ordered stationary phases for separating molecules with limited dispersion and minimal flow resistance[5].

And finally, vascularization of engineered tissues remains a major challenge in regenerative medicine, but it is crucial for proper delivery of oxygen and nutrients in large-scale 3D cell constructs. FLUID3EAMS may well provide new opportunities to create a 3D vasculature around cell-laden capsules, either by dissolving the solid scaffold or by replacing the continuous fluid to create structures in which endothelial cells could be seeded. Only time will tell how many of these applications FLUID3EAMS can achieve. ❐

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