News & views

Fluid physics

Active flows solve sudoku-like problems

Mathieu Le Verge-Serandour & Karen Alim

Networks filled with self-propelled fluids display meandering patterns that have been shown to follow rules similar to those of sudoku puzzles — offering design principles for microfluidic devices, and the possibility of 'active fluid' logic.

Have you ever wondered how blood flows through the intricate vascular network that spans your entire body? Conservation of fluid volume ensures that the sum of flows into each node of this network is equal to the outgoing flows. So an increase in flow at one node can affect the whole network, setting up complex relationships between flows at different points in the vasculature[1]. For a normal fluid (even a complex one, such as blood), these relationships result in the emergence of patterns. So, what happens in the case of a self-propelled — or 'active' — fluid? Writing in *Nature Physics*, Jorge *et al.*[2] analysed active fluids flowing through large-scale networks and found a set of rules that fully predict the patterns they observed.

A normal viscous fluid can be set in motion only by a difference in pressure: squeeze one end of a straw and the fluid inside will move instantly to a lower-pressure region. This means that the flow through a fluid network is determined entirely by the conservation of the fluid volume, the friction exerted by the channels (which, in turn, depends on their geometry) and the connections between the channels (that is, the network architecture). The flow in each channel can therefore be calculated directly from the applied pressure difference across the network, although the calculation can be cumbersome.

Conversely, active fluids move spontaneously at fixed velocity without requiring a pressure difference; instead, they are propelled internally by their components. This property might sound unusual, but it's actually very common: it emerges in, for example, suspensions of bacteria[3], biological filaments propelled by molecular motors[4] and synthetic soft materials[5]. Despite moving at fixed velocity, active fluids still fulfil conservation of fluid volume if there are equal numbers of incoming and outgoing flows across a node. However, this balance is impossible for an active fluid at a network node with an odd number of connecting channels[6].

The simplest example is a node connecting three channels (Fig. 1a). In this case, the net flow through one channel must be zero to enable the remaining two channels to conserve fluid volume. An active fluid achieves zero net flow by forming circular patterns in a channel instead of moving along it. Physicists describe the zero-flow channel as being geometrically 'frustrated' by its neighbouring channels[6]. This frustration takes on new meaning when the single node becomes many, as is the case for a honeycomb network, which comprises an array of three-way nodes. Theory predicts that the patterns formed by active flows on a honeycomb network can be determined by playing a game that is similar to sudoku[7], in which the object is to place the three numbers +1, 0 and −1 at every network node using the

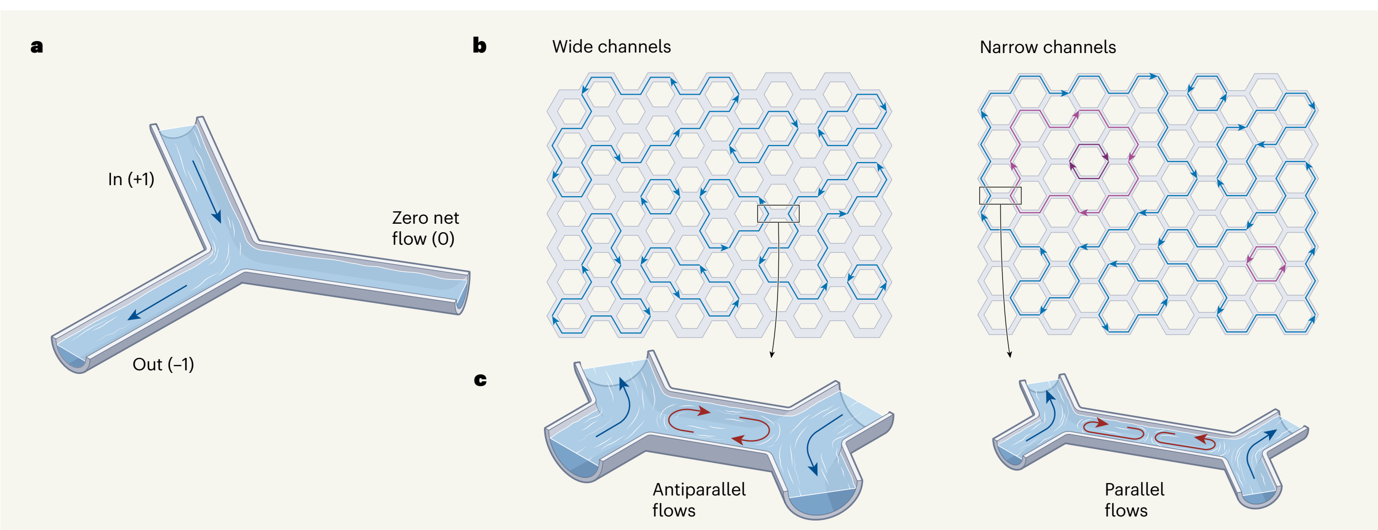

Figure 1 | Active fluids through networks. **a**, Unlike normal fluids, when active (self-propelled) fluids move through a node connecting three channels, the net flow through one channel must be zero to conserve fluid volume across the node. Predicting active flows through a network is therefore similar to playing a game in which each node is assigned either +1, 0 or −1. **b**, In the case of a honeycomb network, which is an array of three-way nodes, Jorge *et al.*[2] found that active-flow patterns depend on the channel's aspect ratio. Loops in networks of wide channels tend to be segregated, whereas those in narrow-channel networks are more often nested. **c**, The authors determined that these patterns are related to channel geometry: in wide channels with no net flow, the fluid forms a single vortex, so flows through neighbouring channels at either end are antiparallel; by contrast, narrow channels permit two vortices, making the flows at either end parallel.

fewest zeros possible[8,9].

Jorge *et al.* investigated this idea by studying the patterns of motorized synthetic particles, called Quincke rollers, as they moved through a large honeycomb network of channels. The authors observed the formation of steady flow patterns consisting of an intricate mix of self-avoiding loops that circled clockwise or anticlockwise. But unlike the deterministic flow patterns that form in normal fluids, Jorge and colleagues' flows displayed a different, disordered flow pattern each time the authors repeated an identical experiment. Even more intriguingly, they found that solving the sudoku-like optimization problem did not account for the flow-field statistics in their experiments. Instead, the authors observed that varying the channel's aspect ratio had an impact on the emerging flow fields: wide channels gave rise to segregated loops, whereas loops were more often nested in networks of narrow channels (Fig. 1b).

The authors determined that the reason for this lies in how an active fluid circulates in a channel that is constrained geometrically to have zero net flow. Wide channels can have only one circulating vortex, whereas narrow channels have two vortices circulating in opposite directions. In both cases, the circulating flow meets neighbouring directed flows at the nodes on either end of the zero-flow channel and dictates the direction of these flows through a gear-like mechanism (Fig. 1c). For a single vortex, directed flows that are separated by a zero-flow channel are antiparallel; for two vortices, the flows are parallel, and this triggers nested flow loops. Together with network topology and channel geometry, these interactions at nodes determine the whole flow pattern.

Research on active fluids in networks is dominated largely by theory and numerical simulations, so Jorge and co-workers' experiments are an exciting addition to the field. Their results show that the active nature of self-propelled fluids induces interactions between neighbouring flows in networks. Such interactions are expected for networks of regular fluids, in which flows split at every network node[1], but the interactions for active fluids reported by the authors were not anticipated. And these interactions are non-local, in that they correlate flows through channels that don't actually meet — a property that is essential for the emergent complexity that Jorge *et al.* observed.

It is always surprising — and gratifying — when an out-of-equilibrium process, such as an active fluid moving through a network, can be explained by the physics of systems in equilibrium. It also makes technological applications easier to design: Jorge and co-workers' quantitative description of active-flow patterns could enable the development of microfluidic devices that can transport self-propelled particles (for drug delivery, for example) in a controlled manner. The authors' rules could even be used to build active analogues of fluid-logic circuits[9] (devices that use fluids to perform computer-logic operations) for biocompatible computing. Jorge and colleagues' mechanistic insight into how non-local interactions emerge in active systems might also guide research into the motility of living cells and organisms in complex environments.

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1. Alim, K., Parsa, S., Weitz, D. A. & Brenner, M. P. *Phys. Rev. Lett.* **119**, 144501 (2017).
2. Jorge, C., Chardac, A., Poncet, A. & Bartolo, D. *Nature Phys.* **20**, 303–309 (2024).
3. Wioland, H., Lushi, E. & Goldstein, R. E. *N. J. Phys.* **18**, 075002 (2016).
4. Wu, K.-T. *et al. Science* **355**, eaal1979 (2017).
5. Morin, A. & Bartolo, D. *Phys. Rev. X* **8**, 021037 (2018).
6. Ortiz-Ambriz, A., Nisoli, C., Reichhardt, C., Reichhardt, C. J. O. & Tierno P. *Rev. Mod. Phys.* **91**, 041003 (2019).
7. Baxter, R. J. *J. Math. Phys.* **11**, 784–789 (1970).
8. Woodhouse, F. G., Forrow, A., Fawcett, J. B. & Dunkel J. *Proc. Natl Acad. Sci. USA* **113**, 8200–8205 (2016).
9. Woodhouse, F. G. & Dunkel, J. *Nature Commun.* **8**, 15169 (2017).

The authors declare no competing interests.
This article was published online on 6 February 2024.

Animal behaviour

An innovative way for whales to sing

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Mammals make sounds when air flow causes paired tissue folds in their voice box to oscillate. However, such air flow in the baleen group of whales takes an unusual path, enabling them to make sounds in a previously unknown way. **See p.123**

Baleen whales — a group that includes blue whales (*Balaenoptera musculus*) and humpback whales (*Megaptera novaeangliae*) — are known for their ability to sing under water. Songs are produced by an organ located in the animal's throat called the larynx, or voice box. However, the anatomical basis of the mechanism that generates sound is not fully understood. On page 123, Elemans *et al.*[1] report the discovery of a previously unknown method of sound production that originates from an unusual site for vibrations. This research is a game-changer for understanding how biological sounds are generated.

Until now, whales were thought to produce sound only by pushing air between paired folds of tissue, causing them to vibrate. But Elemans and colleagues reveal a unique airflow pathway in the larynx of baleen whales, in which air is squeezed between a fold of tissue and a cushion of fatty material above it, causing the fold to vibrate and generate sound.

Society has long been fascinated by baleen whale songs. Early sailors documented hearing eerie sounds below deck that reverberated through the ship's hull. These haunting melodies were attributed to ghosts, mythical sea creatures or simply the imagination of drunken sailors. The sea was otherwise considered to be a silent world.

It wasn't until the invention of in-water microphones, called hydrophones, that underwater sounds could finally be documented. The first hydrophones were used to locate icebergs as a safety check after the ocean liner *Titanic* sank in 1912. Hydrophones were modified during the First World War to detect submarines. During the Second World War and the cold war, arrays of these devices were used to track submarine movements on the basis of engine or propeller noise, but these recordings also included a variety of natural underwater sounds. The soundtracks were military secrets until marine biologists were given access and found that many of the sounds were produced by whales[2,3].

Scientists have searched for decades to discover the method that whales use to produce sound. Publications before the 1960s describe the anatomy of whales using specimens dissected after the animals had become stranded on a beach or examined at commercial whaling stations. These studies included depictions of the whale larynx, but they did not associate it with sound production or identify its internal structures as vocal cords. This is because whales were considered not to have the ability to make sounds, and several papers[4] suggested that whales lacked vocal cords (or in more-scientific terminology, vocal folds).

But anatomical studies have now established that a U-shaped structure in the whale's larynx