Almost action at a distance

Drive your car past a large truck on the highway and you'll experience a hydrodynamic force — one mediated between two objects by an intervening fluid. The truck, while moving, diverts air flows that first push, then pull on your car as you pass. Bicycle riders in the recent Tour de France exploited similar hydrodynamic forces by 'drafting', saving energy — as much as 30% — by riding in the turbulent wake of lead riders.

These forces usually play a marginal role for people, but they become far more important in the micro-world. For bacteria and other microbes, water is as viscous as honey, and any motion in the surrounding fluid dominates their own. So too for the movement of proteins and other macromolecules within cells, which is usually through pores, membranes or channels. These structures, research is beginning to show, often act to control the nature of hydrodynamic forces between molecules through geometry. In some cases, they enable molecules to interact over very long distances, seemingly in defiance of ordinary physics.

Imagine two tiny particles in a liquid, separated by a short distance. Now move one particle sharply. This movement will generate a pattern of flow in the fluid that propagates outward, influencing the fluid in the vicinity of the second particle. In three-dimensional space, studies find that the resulting hydrodynamic force falls off, in general, as $1/R$, with R being the distance between particles.

This result is well supported experimentally, and accords with basic considerations of conservation of momentum. The brief particle motion imparts a small momentum to the fluid, and the momentum flux at radius R away should decay in proportion to $1/R^2$ if momentum is to be conserved. This leads to the expectation that the force on the second particle — linked to the velocity of fluid flow at its position — should go in proportion to $1/R$ (Haim Diamant, preprint at http://arxiv.org/abs/0812.4971; 2009).

If particles are geometrically confined by structures, things change. After all, the liquid no longer conserves momentum, as boundaries can absorb it. The force falls off more quickly — as $1/R^2$ — in a liquid confined to two dimensions. And, according to basic theory, it should decay even more quickly, in exponential

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fashion, in systems in one dimension. This has been found with particles held in narrow channels too, at least for small separations.

Yet this simple story of weakening interactions with decreasing dimension falls apart for very narrow channels, where interaction forces often do not seem to fall off at all. This possibility was suggested by Derek Frydel and Haim Diamant on theoretical grounds a few years ago (preprint at http://arxiv.org/abs/1001.1898; 2010), and it finds clear support in new experiments by Karolis Misiunas and colleagues (preprint at http://arxiv.org/abs/1503.06048; 2015), who experimented with pairs of small colloidal particles held in microfluidic channels. They find strikingly different behaviour depending on the boundary conditions at the channel ends.

First, consider two particles separated by a distance d in a channel of length L, with one side of the channel open to a reservoir and the other closed. Each particle, naturally, will undergo Brownian motion in one dimension as it receives small molecular kicks. The authors monitored these movements, looking for a correlation between them, as this would reveal a force acting between the particles. The results show a strong correlation with the particles close together — separated by only a single particle diameter — and then a rapid decay at further distances.

Now consider a different case: open the channel's closed end, so that fluid can now pass to or from reservoirs on either side. This simple difference is consequential, as a closed end blocks the movement of fluid away from a particle. If a particle moves, the flow it generates only circulates around that particle. In contrast, in the channel with both ends open, fluid movement can easily propagate over large distances. In the limit of a particle of exactly the same size as the channel, you can imagine that the liquid between the particles would act as a rigid link. The movement of one particle could immediately cause identical movement of the second.

As Misiunas and colleagues show, much the same story also holds for particles that only partially block a channel. In their experiments, they used particles with a diameter approximately 60% of the channel width and found that the Brownian movement of the two particles remained correlated no matter how far they were separated. The effective force acting between them decays with increasing separation, but only to a finite value that turns out to be inversely proportional to the channel length, L. An open channel, therefore, enables particles to exert significant hydrodynamic forces over very long distances.

These somewhat surprising results, the authors show, follow from simple theory. Imagine that one particle moves, stirring up a fluid flow. Some of the fluid will flow back past the particle, moving around its sides. Poiseuille's law implies that the increase in pressure on the particle should be proportional to the channel length, and inversely proportional to the fourth power of its width. Another relation among these quantities comes from mass conservation around the moving sphere, and a third from elementary lubrication theory, which predicts the flow of a viscous liquid at a given pressure given a minimum gap width. Putting these relations together, the authors derive a formula for the mean flow in the channel, as it depends on channel width R and length L. Significantly, the simple $1/L$ dependence of the flow — and hence on the force between two particles, independent of the distance between them — drops out, in perfect agreement with the experiments.

Misiunas and colleagues speculate that biology probably already exploits this effect in enhancing biochemical control over the extended distances of whole cells. For example, myriad processes within cells require molecular diffusive transport through narrow channels. Such diffusion, they argue, occurs about 40% faster than it otherwise would as a result of the long-distance flows. It's surprising that such a simple effect could have gone undetected for so long. We typically think of geometric confinement as a restriction, yet, paradoxically, it can also be a resource. ❐

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