From the archive

Butterflies take protein snacks to boost their lifespan, and the quest to fully map the Alps.

50 years ago

To the romantic at least it is somehow all too appropriate that animals as exquisitely and delicately beautiful as some adult moths and butterflies should be ephemeral, disdaining to ingest anything but nectar and living only long enough to reproduce their kind. And to the many people for whom the ephemerality of these creatures is part of their beauty, the news that at least some species ingest amino-acids as well as sugars and survive for several months may be positively unwelcome. But that undeniably is the case … [S]ome species of the attractive neotropical genus of butterflies *Heliconius* (Nymphalinae) ingest and assimilate amino-acids extracted from collected pollen … [S]everal *Heliconius* species exhibit a curious behaviour by which they appear to mix the dry mass of pollen with fluid, presumably nectar, exuded from the tip of the proboscis, using the proboscis as a whisk … How do the butterflies assimilate amino-acids from pollen without chewing or ingesting it? They seem to achieve this by exploiting the fact that when pollen is mixed with sucrose solution most of the free amino-acids in the pollen are rapidly leached into solution … [P]ollen … can supply enough amino-acids to support six months of reproductive life.

From *Nature* 14 July 1972

150 years ago

The Alps are not likely to be thoroughly explored for several generations yet to come; and I doubt not that it will be possible … half a century hence to spend … ten or twelve seasons in the Alps, and still to find valleys which have not been described or even visited … The Alps are very imperfectly known … [I]t is in the highest degree unlikely that a complete map of the Alps will be produced within many years. Nevertheless, materials for a complete map are rapidly accumulating; the greater part of the chain has been surveyed with considerable accuracy.

From *Nature* 11 July 1872

Biophysics

Odd living matter defies golden rule of mechanics

Jack Binysh & Anton Souslov

Self-assembling 'crystals' of starfish embryos exhibit a curious behaviour termed odd elasticity, which seemingly violates Newton's laws of classical mechanics. This discovery poses questions for physicists and biologists alike. **See p.287**

The golden rule – do unto others as you would have them do unto you – is cheerfully broken by most social interactions. For instance, citing your colleague's paper does not necessarily mean that they will cite yours in return. By contrast, many physical laws dictate reciprocity. The best example of this is perhaps Isaac Newton's third law of motion, which states that every action has an equal and opposite reaction, a tenet that applies even to atoms in a crystal. But this requires the crystal to be in equilibrium, or close to it. On page 287, Tan *et al.*[1] report the self-assembly of a different type of crystal, one composed of starfish embryos floating on water, which can be thought of as 'atoms' far from thermodynamic equilibrium. The behaviour of this living crystal exhibits a mechanical non-reciprocity called odd elasticity[2], which is prohibited in equilibrium.

What is odd elasticity? In an ordinary crystal at equilibrium (imagine a metal, or even table salt), reciprocal interactions between atoms result in the mechanical properties that we are used to: if you push on a material, it pushes directly back. However, exotic crystals that are out of equilibrium can have non-reciprocal interactions with large-scale mechanical consequences: 'odd' responses to mechanical stimuli occur, which are forbidden by classical mechanics and which break the golden rule of reciprocity. For example, compression and rotation couple non-reciprocally in these odd materials: compressing the material causes rotational stress, but rotation does not cause compressional stress. Despite their name, these odd couplings are not so odd: they are generically expected when the constraints of equilibrium are lifted.

Tan and colleagues' experiments demonstrate these features beautifully. The starfish embryos sit at an air–water interface and spin spontaneously, forming a 2D living crystal, which also undergoes a collective rotation. As the starfish spin, they pull fluid towards them and downwards. This fluid motion causes a reciprocal attractive force between embryos, which affects their potential energy – the stored energy that is determined solely by their relative positions in the crystal, and is similar to the interaction energy of atoms in a crystal at equilibrium (Fig. 1). But the motion of the fluid also generates a second transverse force that cannot be ascribed to potential energy, and constitutes an odd-material behaviour. Such non-reciprocal forces are not specific to starfish embryos[3]. They occur naturally as a direct consequence of the non-equilibrium nature of living matter.

The Polish scientist Stanislaw Ulam once said: "Ask not what physics can do for biology. Ask what biology can do for physics." Indeed, living systems provide intriguing – if messy – platforms for studying the ideas of non-equilibrium physics. Tan and colleagues' experiments continue the fruitful trend of distilling biological systems to their essential components[4–7] to clarify the basic properties that matter possesses when it comes alive[8]. But such experiments also pose questions for biologists. By understanding the essential physics of these purified biomimetic systems, we gain insights into the *in vivo* biological system from which they came.

For an example of this simplification procedure in action, take active nematics[5], a class of material composed of elongated particles that actively pull or push on each other. Passive nematics form the basis of liquid-crystal displays, and the well-established theories describing these systems have been adapted to describe the intriguing behaviours that arise in their active counterparts.

The cytoskeleton – the meshwork of biopolymers that gives a cell its structure – can be described as an active nematic system. Researchers therefore use purified mixtures of these polymers to study the physics of active nematics, with a level of quantitative detail that can't be achieved inside the cell[6]. But insights into the patterns formed have not been restricted to the physics of the purified components. Instead, these ideas are beginning to feed back into the biological context

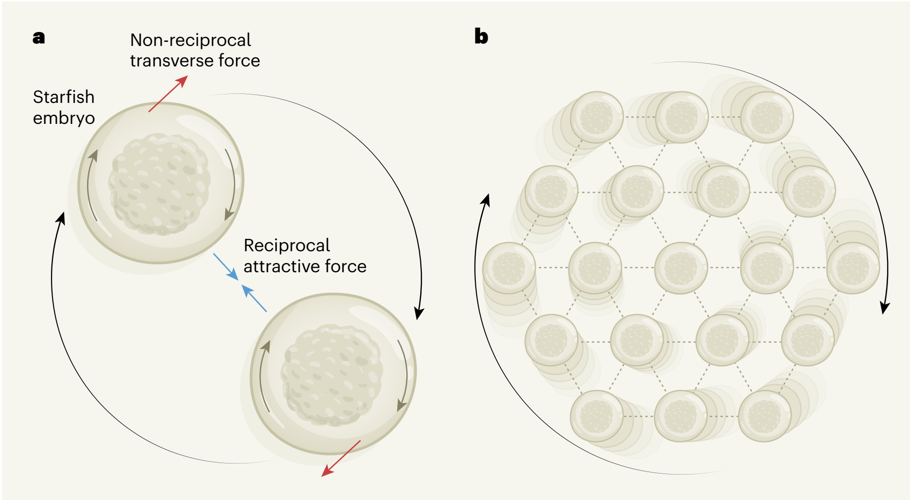

Figure 1 | Non-reciprocal interactions between starfish embryos. a, Tan *et al.*[1] report the formation of a crystal in which the 'atoms' are starfish embryos floating on water, which spin around their own axis. Hydrodynamic interactions between two spinning embryos give rise to a reciprocal attractive force (blue arrows), but also a non-reciprocal transverse force (red arrows), which causes spontaneous rotation of the embryos around one another. **b**, The attractive forces cause many of these embryos to cluster into a crystal. This cluster spins as a whole. The microscopic transverse forces give this crystal an 'odd' elastic response, which is forbidden by classical mechanics.

from which they came. For example, an active nematic framework gave rise to the revelation that defects in nematic ordering can help to coordinate the development of organisms[7].

In the same vein, Tan and colleagues' identification of odd elasticity in a biological system invites two broader questions. First, how widespread are odd behaviours in living matter? Second, do they serve some biological function? The team's experiments demonstrate the fundamental link between oddness and chirality (handedness): odd elasticity necessarily implies that a material can be distinguished as being either right-handed or left-handed. In Tan and co-workers' experiments, chirality dictates the direction of rotation of the starfish embryos. More generally, chirality is found in many biological systems, so the findings hint at the idea that odd behaviour might also be commonplace. Could it imply a role for chirality that hasn't yet been revealed?

Seen instead from a design perspective, the platform that Tan *et al.* have developed is a step along the road to animate matter[9] — materials that are able to sense, compute and respond to an external stimulus. Such materials might mimic animate behaviour by synthetic means[10], as in the realization of odd elasticity in a system of spinning colloids, reported this year[11]. Alternatively, they might directly include biological elements, as is the case in the starfish-embryo crystals. This latter approach has the advantage that an internal energy reservoir is built into the system: the odd elasticity demonstrated by Tan *et al.* lasts for several hours without external input, stopping only when embryo growth breaks the crystal apart.

In what sense is an odd material animate? Tan and colleagues' system generates spontaneous waves of oscillations in the positions of the embryos, and these waves persist throughout the lifetime of the crystal. A theoretical prediction for odd materials is that such waves can be induced in response to external compression — or, more generally, that a system displaying odd behaviour will exhibit oscillatory motion in response to specific stimuli. Such dynamical states could form the basis of mechanical programming and computation in the material itself; for example, by switching between different dynamical states in response to different stimuli.

Tan and co-workers' study sits at the nexus of materials design and fundamental physics: their system gives us a glimpse into how breaking the golden rule of reciprocity leads to intriguing emergent behaviour in active solids. Although odd elasticity is one hallmark of living crystals, there are likely to be many others. We are yet to understand the broader principles of designer materials created using living constituents.

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Virology

Norovirus from the mouths of babes

Elizabeth A. Kennedy & Megan T. Baldridge

The discovery that gut viruses can be transmitted from mouse pups to their mothers in saliva during breastfeeding reveals previously unrecognized sites of viral replication and means of viral transmission. **See p.345**

Gastrointestinal viruses such as norovirus and rotavirus spread with impressive efficiency, causing more than 300 million childhood infections worldwide each year[1]. These viruses can cause a range of unpleasant symptoms, including abdominal pain, diarrhoea and vomiting. They are thought to be spread almost exclusively through the faecal–oral route, in which a person ingests tiny particles of stool or vomit that have either come directly from an infected person or have contaminated food and water. But on page 345, Ghosh *et al.*[2] present intriguing evidence of salivary infection routes for gastrointestinal viruses, indicating that measures to contain viral spread might require enhanced sanitation techniques.

It has been assumed that, once ingested, gastrointestinal viruses replicate mainly in intestinal cells before being shed in the stool, thereby driving the next cycle of transmission[3]. Although viral copies have been detected in the saliva of infected people even in the absence of vomiting, these particles were thought to be a