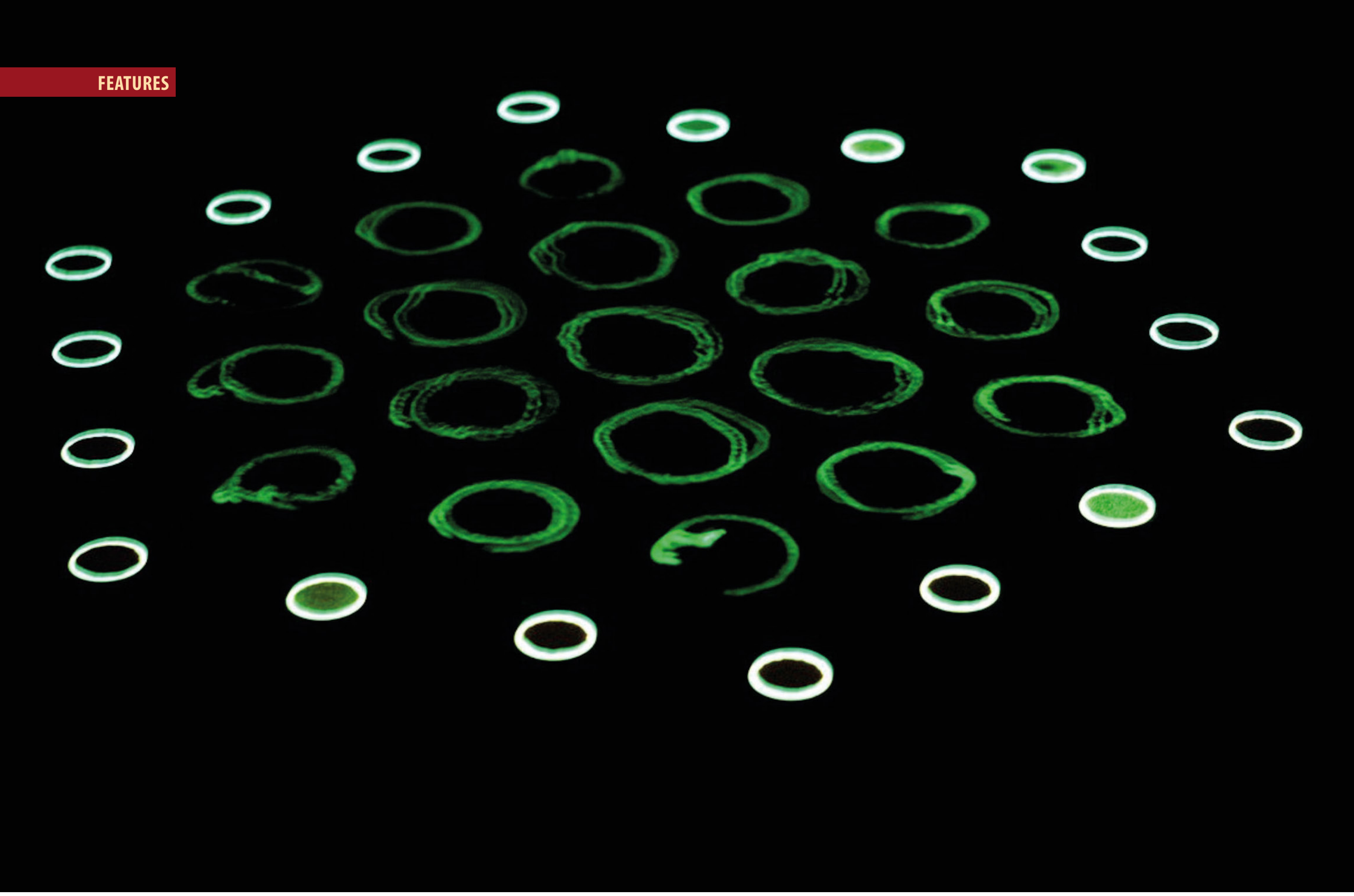

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COLLECTIVE DYNAMICS IN ACTIVE SOLIDS

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After 25 years of research activity, the physics of collective motions -- flights of starlings, shoals of fish, micro-swimmers or artificial walkers -- is well understood. Here, we describe a new form of self-organization, emerging from the coupling between elasticity and activity: collective actuation, the solid counterpart of collective movements.

Active matter is made up of out of equilibrium constituents, which convert a local source of energy into work, for example in the form of directed motion [1]. It is the seat of rich collective phenomena including new forms of transition between dynamic phases that do not exist at equilibrium. Collective motion within large animal groups is the most spectacular manifestation of this.

In their search for model experimental systems, physicists have developed a vast arsenal of artificial active systems, from colloidal suspensions to granular materials, emulsions, and liquid crystals [2]. Quantitative experiments, against which a wealth of theoretical proposals have been confronted, has led to remarkable and well-established results. For example, a system of active particles, whose interactions are purely repulsive, nevertheless exhibits liquid-gas phase separation [3]. Collective motions result from a first-order transition between a disordered gas phase and a moving liquid, with a coexistence regime made of propagative structures [4]. The nematic phase of active liquid crystals is unstable and spontaneously forms topological defects, giving rise to chaotic flows [5].

However, there are circumstances in which the analogy of these systems with liquids is not necessarily appropriate. Cohesive cells, bridges built by army ants, or nests of wild bees have undeniable elastic properties and call for a description in term of active elastic solids.

We focus on two model active solids: an active crystal, obtained by confining active discs, which are propelled by mechanical vibration, and an active elastic network in each node of which is trapped a Hexbug©, a centimeter-sized toy propelled by a motor. We highlight two new phenomena: the presence of permanent flows within a crystalline phase and the spontaneous collective actuation of an elastic structure.

Artificial Walkers

Except for crabs, walkers in the living world usually progress with their head pointed forward while their left-right symmetry with respect to the axis of their body ensures straight motion. Artificial walkers, whether sophisticated robots or simpler systems, generally strive to respect these properties.

The first type of artificial walker, created in the laboratory around twenty years ago [6], is a small metal disc, a few millimeters in diameter, supported by two different contacts with the ground (Fig. 1a). Contact is made at the front by a metal spike and at the rear by a large rubber pad. Placed on a vertically vibrating plate, this disc is animated by a persistent motion (Fig.1b). The second type of walker, a Hexbug© can be purchased commercially (Fig.1c). Equipped with an internal vibrator powered by a battery, this centimeter-sized toy is set in motion by the inclined shape of its legs.

The reader probably had occasion to collide with another pedestrian. If so, they may have noticed that they will tend to realign their body in the direction of the displacement resulting from the collision. This process also takes place in artificial walkers. When a displacement is not aligned with the axis of the body, the distribution of frictional forces opposing the direction of motion is no longer symmetrical with respect to the axis of the body. A resulting torque reorients the body (Fig. 1d). This self-aligning torque is the key ingredient for collective motion in liquids of active hard discs (Fig. 1e); it is also central to the collective dynamics described below.

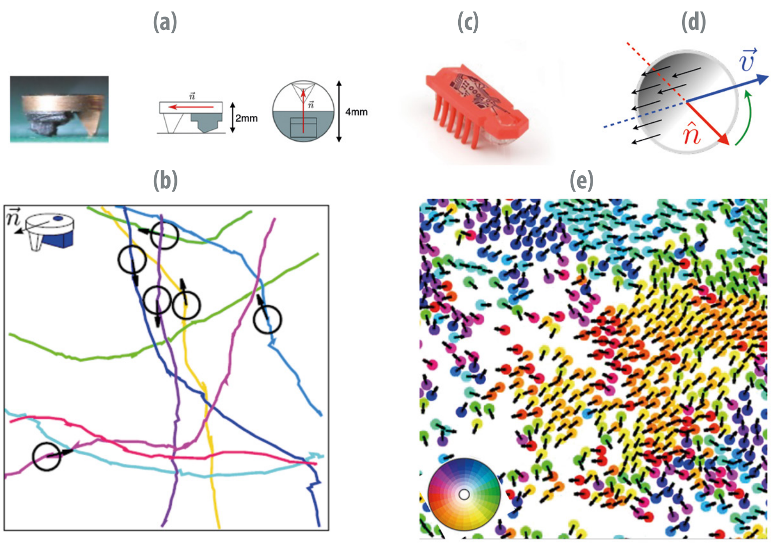
Permanent flow in Crystal

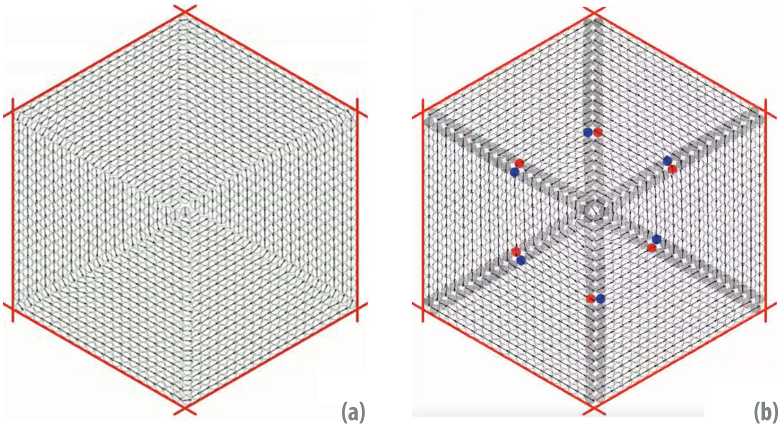
The high-density confinement of an assembly of disks, all the same diameter, leads to the formation of a crystalline structure on a triangular lattice. The crystallization of hard disks at thermodynamic equilibrium is very specific and was the subject of important work in the 1970s [7], which earned the 2016 Nobel Prize in Physics to its authors, David J. Thouless. F. Duncan M. Haldane and J. Michael Kosterlitz "for theoretical discoveries of topological phase transitions and topological phases of matter". In the case of walking disks, the scenario is very different and is still the subject of intense research [8]. It is anyhow possible to prepare a crystalline assembly of walking discs, whose orientations are initially randomly distributed. Since the crystalline phases of matter are assumed to be solid, it is expected that, in such a configuration, no collective motion can take place.

Nothing of the sort! After a while, the multiple collisions between the discs promote the alignment of their orientations and the onset of large-scale flows [9]. The large-scale organization of this alignment inherits the symmetries of the crystal. In each 60° sector, the discs orient parallel to the side of the enclosure adjacent to them (Fig. 2a). The resulting collective displacements within each sector produce localized shear at the junctions between the sectors, which in turn induces plastic deformations and allow for the crystal to flow (Fig. 2b). These plastic deformations are manifested by dislocations that propagate from the corners of the hexagonal enclosure towards the center of the crystalline packing (1). This necessitates only a local expansion of the structure. As a result, flow can take place at the highest densities allowed by the geometry. Numerical simulations of stochastic dynamics (Newton's equations enriched with noise of mechanical origin) describing the system, confirm the experimental observations, and establish their robustness for increasing system sizes.

The persistent motion of the discs, coupled with the self-aligning mechanism, gives rise to a new phase of active matter, spatially ordered but animated by permanent currents of matter.

▾ FIG. 1: Artificial walkers: (a) a 4 mm diameter metal disc with two distinct contacts with the vibrating plate on which it is placed: a metal tip at the front and a large rubber pad at the rear; (b) examples of persistent trajectories obtained when these discs are subjected to low amplitude vertical vibration; (c) Hexbug©, a centimeter toy with an internal vibrator and battery; (d) schematic diagram of the self-alignment mechanism: in red, the axis of the walker's body; in blue, a movement not aligned with this axis; in black, the friction induced by the movement is asymmetrical with respect to the direction of movement, and induces a self-aligning torque, in green, from the orientation of the walker towards its movement; (e) collective motion observed in a liquid of walking discs (the color of the discs indicates their direction, according to the chromatic circle).





▲ **FIG. 2:** Flow within an active crystal: (a) the discs are all aligned parallel to the walls of the hexagonal confinement enclosure; (b) the generation and propagation of dislocations from the vertices towards the center of the hexagon allows the crystal to flow (the discs in blue, respectively in red, have 5, respectively 7 neighbors).

Collective actuation of an elastic network

High-density confinement therefore does not guarantee the existence of a reference configuration around which the elementary entities of the active material would vibrate, like the atoms of a crystal in equilibrium. Can this reference configuration be imposed, and if so, what happens?

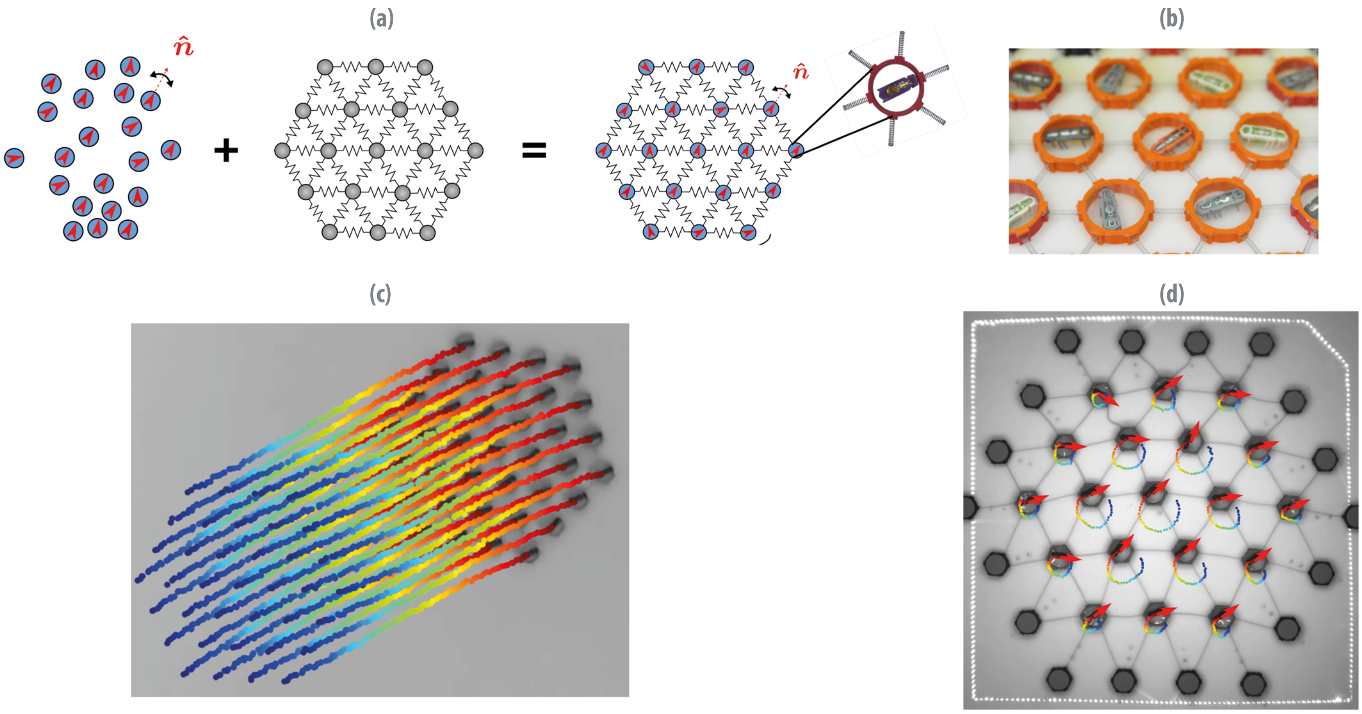
To answer this question, we now turn to our second model system, a hybridization between the physics of elastic solids and that of active liquids (Fig.3-a). It consists in trapping mobile entities within an elastic structure, while leaving them free to reorient [10]. In practice, Hexbugs© are trapped inside cylindrical rings attached to each other by springs (Fig.3-b). They can reorient but are constrained to move in the vicinity of the reference configuration of the elastic network.

The first surprise is that if we are not careful to attach the system to the laboratory reference frame, the particles within the lattice align with each other, the lattice acquires a translational motion and the experimental system escapes from the laboratory (Fig. 3-c)! The translational modes of the lattice have no restoring force - they are known as zero modes: the energy injected into the system concentrates in these zero modes and sets the system in motion, revealing a new mechanism for collective motion in solids.

Let's now consider the system whose peripheral elements are fixed. The active forces induced by each of the Hexbugs induce deformations within the network. Beyond a critical deformation, the resulting displacements reorient the neighboring Hexbugs, by virtue of the self-alignment property. One then observes a collective actuation of the network, which takes the form of a synchronous oscillation around the reference configuration (Fig. 3-d). This remarkable dynamic also has the property of exciting only a few modes of the elastic structure, according to a non-linear selection principle.

Collective actuation will certainly play a central role in the development of metamaterials whose active elementary cells will enable local and autonomous actuation. The applications in robotics, and more generally in the design of functional materials, are potentially countless.

▼ **FIG. 3:** Active elastic network: (a) schematic diagram of the hybridization of an active liquid and an elastic network; (b) experimental implementation using Hexbugs trapped in rings attached by springs; (c) global translational movement of the structure when it is not fixed to the laboratory reference frame; (d) collective actuation in the form of synchronous oscillations for a structure whose peripheral nodes are fixed.



Conclusion and perspectives

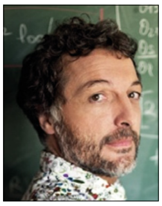
Summarizing our observations with a brief aphorism: there's no rest in active matter! Whether under confinement or at the heart of an elastic structure, collective dynamics impose themselves and reveal new horizons.

The physics of active solids opens new research directions. The study of the mechanical response of active solid is still in its infancy. It will play a decisive role in understanding morphological processes in living organisms as well as in the development of artificial active materials.

From an experimental point of view, the ever-increasing mastery of DNA, enzymes and proteins together with the ever-increasing capacity for mechanical miniaturization, let us anticipate a hybridization between artificial active materials and living active materials, towards a bionic, active and programmable material with undreamt-of possibilities.

Finally, in more general terms, the study of active matter has shed new, transdisciplinary light on collective dynamics that are not constrained by the laws of thermodynamic equilibrium. This applies not only to animal dynamics, but also to population dynamics, swarm robotics, cognitive dynamics, sociological dynamics, *etc.* The development of experimental model systems, inspired by swarm robotics, will certainly help to lift the veil on the mysteries, hidden in these complex systems. ■

About the Author



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References

[1] T. Vicsek and A. Zafeiris, *Physics reports* **517.3-4**, 71 (2012).

[2] C. Bechinger, R. Di Leonardo, H. Löwen, C. Reichhardt and G. Volpe, *Rev. Mod. Phys.* **88**, 1 (2016).

[3] M.E Cates, *and J. Tailleur. Annu. Rev. Condens. Matter Phys.* **6.1**, 219 (2015).

[4] A. Bricard, J.B. Caussin, N. Desreumaux, O. Dauchot and D. Bartolo, *Nature* **7474**, 95 (2013).

[5] J.M Yeomans, *Europhysics News* **48/2**, 21 (2017)

[6] J. Deseigne, O. Dauchot, and H. Chaté., *Phys. Rev. Lett.* **105.9**, 098001 (2010).

[7] J.M. Kosterlitz and D. J. Thouless. "Ordering, metastability and phase transitions in two-dimensional systems." Basic Notions Of Condensed Matter Physics. CRC Press, 493 (2018).

[8] G. Briand and O. Dauchot. *Phys. Rev. Lett.* **117.9**, 098004 (2016).

[9] G. Briand, M. Schindler and O. Dauchot, *Phys. Rev. Lett.* **120(20)**, 208001 (2018).

[10] P. Baconnier, D. Shohat, C. H. López, C. Coulais, V. Démery, G. Düring and O. Dauchot, *Nature Physics* **18** (10), 12341239.