

In Active Solids, Connectivity Is as Important as Activity

A robotic metamaterial shows that the odd mechanics of active solids depend on how the active constituents connect across the system.

By Tzer Han Tan

Active materials, composed of microscopic constituents that continuously inject motional energy into the system, can exhibit odd mechanical responses, such as stretching vertically when sheared horizontally. Such properties can be used to make materials that can spontaneously crawl or roll over a difficult terrain [1]. One might naively think that these desirable odd responses could be increased by making the components more active. Jack Binysh of the University of Amsterdam and his colleagues now find that this doesn't always work [2]. The researchers show that in active solids a collective response only emerges when system-spanning connective networks are formed among the individual constituents of the system. Without such networks, the effects of microscopic activity remain confined locally and the macroscopic response

disappears.

An active solid is, fundamentally, an elastic lattice made up of self-driving constituents. Examples include robotic lattices composed of motorized units [1, 2], magnetic colloidal crystals [3], and chiral living embryos [4]. The active solids that Binysh and his colleagues examined are examples of nonreciprocal active solids, meaning that the interactions between elements are directional. Interactions may become directional when individual constituents process information about their neighbors. Such nonreciprocal interactions arise in a wide range of settings. In robotic metamaterials, local control loops impose directional responses on adjacent mechanical units [1]. And in living chiral collectives, hydrodynamic flows allow rotating embryos to exchange momentum with the surrounding media [4]. These interaction asymmetries give rise to unusual physics by allowing the material to violate the usual rules of equilibrium response.

Soft-matter physicists have recently identified nonreciprocity as a key organizing principle in active matter. These asymmetric interactions give rise to new forms of macroscopic mechanical responses to external perturbations [5]. One prominent example is odd elasticity, where stress and strain are coupled through antisymmetric components that violate Maxwell reciprocity [6]. In materials that have odd elasticity, shear deformations can generate transverse instead of coaligned stresses, and cyclic deformations can produce net mechanical work instead of canceling out over a full cycle. These phenomena are particularly relevant in active solids.

Understanding how microscopic nonreciprocal activity translates into macroscopic mechanical properties remains a

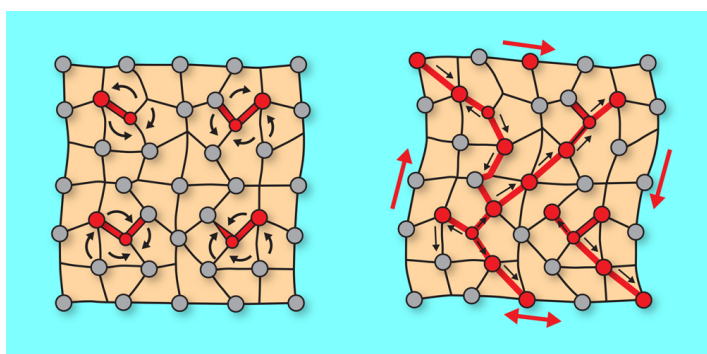


Figure 1: Active (red) and nonactive (gray) building blocks can interact within a solid to yield unexpected macroscopic results. (Left) If the particles' activity remains isolated, its effect remains local. (Right) If, however, the activity percolates, stresses propagate across the material and drive large-scale deformation.

Credit: T. H. Tan/UCSD; APS/Alan Stonebraker

central challenge in the physics of active solids. Binysh and his colleagues now ask a seemingly simple question: If we strengthen the nonequilibrium activity of the microscopic building blocks in active solid, does the nonreciprocal mechanical response necessarily become stronger?

To explore this, the researchers built a robotic metamaterial made of hexagonal cells connected by motorized hinges [1, 2]. These hinges exerted nonreciprocal torques, where pushing the joint in one direction generated a torque that rotated the neighboring elements in a different direction. Classical continuum theory says that increasing the microscopic nonreciprocal torque should monotonically increase the odd elastic modulus: unusual asymmetric components in the material's elastic tensor. Surprisingly, the researchers' observations indicated an opposite behavior: As the active torque is increased, the odd modulus first grew but then saturated and eventually decreased. Their calculations confirmed this behavior and revealed a previously unknown regime where stronger microscopic activity leads to weaker macroscopic response.

To understand this anomalous behavior, the researchers combined experiments with numerical and theoretical models and interpreted the results using ideas from percolation theory. Percolation describes how local connectivity in a disordered system can suddenly produce a system-spanning network. In soft matter, crossing this threshold often signals the emergence of macroscopic properties such as rigidity in gels or electrical conductivity in composites. Binysh and colleagues sought a similar threshold for odd elasticity. By reducing the number of active cells in their lattice and replacing them with nonactive ones, they showed that the odd elasticity only emerged when the active units formed a percolating network capable of transmitting stresses across the material (Fig. 1). When the system became underpercolated, on the other hand, active cells behaved as isolated units. Their stresses canceled locally rather than propagating through the lattice, causing the macroscopic odd response to vanish.

The work therefore offers a new approach for designing active solids: Macroscopic nonreciprocal mechanics don't only

depend on the strength of microscopic activity but also on the presence of a connected network capable of transmitting forces across the system.

This result is significant because it shows that the relationship between microscopic activity and macroscopic mechanical response in active matter is neither monotonic nor purely local. Instead, the emergent behavior depends on the global connectivity of the active elements. The work introduces a new organizing principle for active materials: Macroscopic nonreciprocal mechanics requires the percolation of active stress pathways. By linking odd mechanical responses to ideas from rigidity percolation and disordered networks, the study suggests that the properties of active solids may be governed as much by transitions in connectivity as by the strength of activity itself.

This insight also provides a simple route for tuning nonequilibrium mechanical behavior in engineered solids. By controlling either the level of activity or the spatial arrangement of the active units, materials can be made to switch between regimes that have a strong collective response and regimes where activity remains localized and unnoticeable at large scales. Such control could guide the design of programmable robotic metamaterials and help interpret the mechanics of biological active solids such as tissues or cytoskeletal networks, where both activity and connectivity evolve dynamically.

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REFERENCES

1. J. Veenstra *et al.*, "Adaptive locomotion of active solids," *Nature* **639**, 935 (2025).
2. J. Binysh *et al.*, "More is less in unpercolated active solids," *Phys. Rev. X* **16**, 021012 (2026).
3. E. S. Bililign *et al.*, "Motile dislocations knead odd crystals into whorls," *Nat. Phys.* **18**, 212 (2021).
4. T. H. Tan *et al.*, "Odd dynamics of living chiral crystals," *Nature* **607**, 287 (2022).
5. M. Fruchart *et al.*, "Odd viscosity and odd elasticity," *Annu. Rev. Condens. Matter Phys.* **14**, 471 (2023).
6. C. Scheibner *et al.*, "Odd elasticity," *Nat. Phys.* **16**, 475 (2020).