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RPPR Final Report

as of 12-Sep-2023

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Final Report for Period Beginning 01-May-2019 and Ending 01-Nov-2022

Title: Odd Elasticity in Chiral Active Solids

Begin Performance Period: 01-May-2019

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STEM Participants: 4

Major Goals: Odd elasticity

The goal of our research is to derive and study a generalization of elasticity theory appropriate for solids whose microscopic constituents are active (i.e., can consume energy).

The conceptual starting place for our research is as follows. Active materials are composed of interacting constituents—ranging from synthetic components to living organism—that are individually capable of converting internal energy into work or self-sustained motion. When the active components are held together by interactions in a solid structure, the resulting medium displays emergent mechanical properties at the interface between continuum mechanics and dynamical systems. Our objective is to investigate the modifications of the elastic properties of such solids.

The theory of elasticity is the universal language for describing the mechanical deformations of continuous media at sufficiently large length scales. At its essence, elasticity is the study of the relationship between strain (i.e. deformations) and stresses (currents of momentum that cause motion). For long wavelength deformations, this relationship is well described by the linear relationship:

$$\tau_{ij} = K_{ijmn} u_{mn},$$

where τ_{ij} is the stress, u_{ij} is the strain, and K_{ijmn} is an object known as the elastic modulus tensor (or stiffness tensor). In its usual formulation for passive media, the stress-strain relationship prescribed by elasticity rests on a basic assumption: the existence of an elastic potential energy. This imposes the fundamental symmetry constraint on the elastic modulus tensor: $K_{ijmn} = K_{mnij}$. However, for active media, the existence of an elastic potential energy is not ensured and therefore the symmetry $K_{ijmn} = K_{mnij}$ is generically not valid. Hence, for active solids, the elasticity requires the inclusion of an additional term:

$$K_{ijmn}^o = -K_{mnij}^o$$

which, unlike the standard elastic modulus tensor, is antisymmetric under the exchange of indices. We refer to the class of active solids in which this antisymmetric contribution to the elasticity as odd elastic media. The central aims of our research is to understand the microscopic physical origins of such a term and its implications for the design and phenomena associated with odd elastic media when viewed as (1) a material (2) a distributed machine and (3) a dynamical system.

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Specifically, our project has three main objectives:

- Extend the standard formalism of continuum mechanics to describe active solids and elucidate the design of active elastic engines.

- Provide explicit coarse-graining procedure of suitable microscopic models that can test the validity of these continuum approaches in conjunction with simulations.

- Predict and test in simulations the emergent mechanical properties.

Achieving these major goals is organized into four main thrusts with subobjectives:

- Build a theoretical blueprint to design and operate active elastic engines.

- 1.1 Provide a design and realization of active elastic engines.

- 1.2 Characterize the efficiency of active elastic engines

- 1.3 Study the modes of actuation of active elastic engines

- Construct explicit microscopic models that give rise to continuous media exhibiting odd elasticity.

- Identify concrete experimental realizations

- Derive the equations of odd elasticity from coarse graining

- Numerically test the validity of the continuum description

- Numerically explore non-linear and short wavelength regimes

- Perform a rigorous symmetry analysis that classifies all allowed terms in odd elastic theories.

- Study the effects of anisotropy

- Study the effects of rotations and Cosserat theory

- Characterize the effects of non-affine microscopic deformations

- Systematically study the peculiar mechanical properties of odd elastic media.

- Determine the spectrum and properties of odd elastic waves

- Investigate the static response of odd elastic solids to applied stresses and deformations

- Explore the instabilities of odd elastic materials, especially in extreme geometries.

Proposed timeline:

The initial proposed timeline for the three-year award is organized as follows. The first year and a half focus on thrusts 1 and 2 (active cycles and microscopic models). Thrust 3 (symmetry analysis) is targeted for the beginning of year two and intended to take approximately one and a half years. Thrust 4 (mechanical properties) is allotted two and a half years beginning midway through the first year. The general organization of this timeline is intended to proceed from areas with partial or preliminary results and gradually shift to more open-ended goals.

Dualities for metamaterial design

In addition to the goals stated in the original proposal, the grant extension ("Dualities for metamaterial design") focuses on the systematic development of mechanical dualities as a design principle to engineer structures capable of mechanical spintronics and related generalizations.

This extension is inspired by the following preliminary results. The first is that the vibrational properties of mechanical systems (in particular phononic crystals) can exhibit the notion of a duality. Here, by duality, we refer to a generalized notion of a symmetry. To understand this notion, we observe that a given design for a material often depends on several parameters, for example the choice of stiffnesses of mechanical components or a specific geometric realization of a reconfigurable parts. A symmetry is a nontrivial action of a system that maps the system back onto itself with the same parameters. A duality is a nontrivial action that maps the system onto itself with a different, but predictable or prescribed, choice of parameters. By introducing this concept of a duality, we can identify special points in the design space in which the duality becomes a symmetry, i.e. the mapping between different parameters happens to be the identity map and the structure is self-dual.

The significance of the self-dual points becomes apparent in light of a concept known as a holonomy. In wave physics (or more generally gauge theories) a holonomy is a phase factor introduced when the system at hand transverses an abstract manifold of parameters (such as position or momentum of the wave). These holonomies take the form of operators, which can either be commutative or non-commutative. In the non-commutative case, the algebra of the holonomy operators endows the system with the possibility of nontrivial computation. Preliminary results show that self-dual points provide platforms for introducing non-commutative holonomies into classical systems.

Generalizing the preliminary results is organized along three specific objectives:

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Extend previously demonstrated momentum-space holonomies to non-Abelian gauge fields in real space.
Systematically constructing duality-covariant families of systems
Generalize preliminary results to other lattices, three-dimensional systems, and other response functions.

Accomplishments: Major activity 1: Slender geometries, plastic deformation, topological defects in odd elastic media.

Results 1.1 (Modified defect interactions and activity induced motility) In [1], we investigate topological defects in active solids with odd elasticity. The odd moduli modify the interaction between dislocations and even reverse the stability of otherwise bound pairs. Moreover, isolated dislocations can also become motile due to microscopic work cycles active at dislocation cores that compete with conventional Peach-Koehler forces caused, for example, by ambient torque densities. We provide a novel computation approach to capture this effect which lies beyond continuum theory. We perform molecular dynamics simulations isolating active plastic processes and discuss their experimental relevance to solids composed of spinning particles and robotic metamaterials. Topological defects such as dislocations are the building blocks of complex phenomena such as plastic deformation and melting and our work generalizes their mechanics to active and driven systems.

Results 1.2 (Odd elasticity of active surfaces) In [2], we study the odd elasticity and non-Hermitian wave dynamics of active surfaces, specifically plates of moderate thickness. We find that a free-standing moderately thick, isotropic plate can exhibit two odd-elastic moduli, both of which are related to shear deformations of the plate. These odd moduli can endow the vibrational modes of the plate with a nonzero topological invariant known as the first Chern number. Within continuum elastic theory, we show that the Chern number is related to the presence of unidirectional shearing waves that are hosted at the plate's boundary. We show that the existence of these chiral edge waves hinges on a distinctive two-step mechanism: the finite thickness of the sample gaps the shear modes and the odd elasticity endows them with chirality.

Major activity 2: Experimental realizations of odd elasticity.

Results 2.1. (Self-sensing metamaterials) In [3], we realize a freestanding active metabeam with piezoelectric elements and electronic feed-forward control that gives rise to an odd micropolar elasticity absent in energy-conserving media. The non-reciprocal odd modulus enables bending and shearing cycles that convert electrical energy into mechanical work, and vice versa. The sign of this elastic modulus is linked to a non-Hermitian topological index that determines the localization of vibrational modes to sample boundaries. At finite frequency, we can also tune the phase angle of the active modulus to produce a direction-dependent bending modulus and control non-Hermitian vibrational properties. Our continuum approach, built on symmetries and conservation laws, could be exploited to design others systems such as synthetic biofilaments and membranes with feed-forward control loops.

Results 2.2 (Active impact and locomotion in robotic media with nonlinear work cycles) In [4], we build and characterize theoretically a class of flexible robotic materials that strategically utilize internal nonconservative forces giving rise to self-sustained work cycles. We harness these inherently nonlinear cycles to power and shed new light on otherwise familiar processes including impact deflection and locomotion. Beyond distributed robotics, our work suggests how these nonlinear work cycles and associated functionalities can emerge as solutions of the non-conservative dynamics of active and biological materials.

Results 2.3 (Machine learning continuum theories in living active solids) In [5], we develop a data-driven biophysical modeling approach to learn the mechanical behavior of adherent cells. We first train neural networks to predict forces generated by adherent cells from images of cytoskeletal proteins. Strikingly, experimental images of a single focal adhesion protein, such as zyxin, are sufficient to predict forces and generalize to unseen biological regimes. This protein field alone contains enough information to yield accurate predictions even if forces themselves are generated by many interacting proteins. We next develop two approaches - one explicitly constrained by physics, the other more agnostic - that help construct data-driven continuum models of cellular forces using this single focal adhesion field. Both strategies consistently reveal that cellular forces are encoded by two different length scales in adhesion protein distributions. Beyond adherent cell mechanics, our work serves as a case study for how to integrate neural networks in the construction of predictive phenomenological models in cell biology, even when little knowledge of the underlying microscopic mechanisms exist.

Major activity 3: Non-reciprocal phase transitions.

Results 3.1 (Bifurcation theory in many-body physics and exceptional points) In [6], we show that non-reciprocity leads to time-dependent phases in which spontaneously broken continuous symmetries are dynamically restored. We illustrate this mechanism with simple robotic demonstrations. The resulting phase transitions are controlled by spectral singularities called exceptional points. We describe the emergence of these phases using insights from bifurcation theory and non-Hermitian quantum mechanics. Our approach captures non-reciprocal generalizations of three archetypal classes of self-organization out of equilibrium: synchronization, flocking and pattern formation.

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Collective phenomena in these systems range from active time-(quasi)crystals to exceptional-point-enforced pattern formation and hysteresis. Our work lays the foundation for a general theory of critical phenomena in systems whose dynamics is not governed by an optimization principle.

Results 3.2 (Informational active matter) Many biomolecular systems can be viewed as ratchets that rectify environmental noise through measurements and information processing. As miniaturized robots cross the scale of unicellular organisms, on-board sensing and feedback open new possibilities for propulsion strategies that exploit fluctuations rather than fight them. In [7], we study extended media in which many constituents display a feedback control loop between measurement of their microstates and the capability to bias their noise-induced transitions. We dub such many body systems informational active matter, and we show how information theoretic arguments and kinetic theory derivations yield their macroscopic properties starting from microscopic agent strategies. These include the ability to self-propel without applying work and to print patterns whose resolution improves as noise increases. We support our analytical results with extensive simulations of a fluid of 'thinker' type particles that can selectively change their diameters to bias scattering transitions. This minimal model can be regarded as a non-equilibrium analogue of entropic elasticity that exemplifies the key property of this class of systems: self-propulsive forces grow ever stronger as environmental noise increases thanks to measurements and control actions undertaken by the microscopic constituents. We envision applications of our ideas ranging from noise induced patterning performed by collections of microrobots to reinforcement learning aided identification of migration strategies for collections of organisms that exploit turbulent flows or fluctuating chemotactic fields.

Major activity 4: Non-reciprocal response in fluids.

Results 4.1 (Sedimentation and point responses) In [8], we explore the consequence of parity-violating and non-dissipative (i.e. odd) viscosities on Stokes flows. These viscosities can occur in systems ranging from synthetic and biological active fluids to magnetised and rotating fluids, in which parity (i.e. mirror reflection) symmetry is broken. We first systematically enumerate all possible parity-violating viscosities compatible with cylindrical symmetry, highlighting their connection to potential microscopic realizations. Then, using

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Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

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Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Vincenzo Vitelli

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Jonathan Colen

Person Months Worked: 5.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Colin Scheibner

Person Months Worked: 1.00

Project Contribution:

Funding Support:

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National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Matthew Schmitt

Person Months Worked: 1.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Howard Timlin

Person Months Worked: 3.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Michel Fruchart

Person Months Worked: 1.00

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National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Nitin Upadhyaya

Person Months Worked: 6.00

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Article Title: Odd Elasticity

Authors: Scheibner, Colin, Souslov, Anton, Banerjee, Debarghya, Irvine, William T. M., Vitelli, Vincenzo

Keywords: Active elasticity, active cycles, Non-Hermitian mechanics, distributed engines, active moduli

Abstract: A passive solid cannot do work on its surroundings through any quasistatic cycle of deformations. In this Article, we show that static elastic moduli altogether absent in passive elasticity can arise from active, nonconservative microscopic interactions. These active moduli enter the antisymmetric (or odd) part of the static elastic modulus tensor and quantify the amount of work extracted along quasistatic strain cycles. In 2D isotropic media, two chiral odd-elastic moduli emerge in addition to the bulk and shear moduli. We discuss microscopic realizations that include networks of Hookean springs augmented with active transverse forces and nonreciprocal active hinges.

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Journal: Physical Review Letters

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Publication Identifier: 10.1103/physrevlett.125.118001

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Date Submitted: 8/31/21 12:00AM

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Publication Location:

Article Title: Non-Hermitian band topology and skin modes in active elastic media

Authors: Colin Scheibne, William T. M. Irvine, Vincenzo Vitelli

Keywords: PT symmetry, skin modes, Non-Hermitian mechanics, active elasticity

Abstract: Solids built out of active components can exhibit non-reciprocal elastic coefficients that give rise to non-Hermitian wave phenomena. Here, we investigate non-Hermitian effects present at the boundary of two-dimensional active elastic media obeying two general assumptions: their microscopic forces conserve linear momentum and arise only from static deformations. Using continuum equations, we demonstrate the existence of the non-Hermitian skin effect in which the boundary hosts an extensive number of localized modes. Furthermore, lattice models reveal non-Hermitian topological transitions mediated by exceptional rings driven by the activity level of individual bonds.

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Article Title: Machine learning active-nematic hydrodynamics

Authors: Jonathan Colen, Ming Han, Rui Zhang, Steven A. Redford, Linnea M. Lemma, Link Morgan, Paul V. Ruj

Keywords: Neural networks, active elasticity, architectures, autoencoders, hybrid biomaterials

Abstract: Hydrodynamic theories effectively describe many-body systems out of equilibrium in terms of a few macroscopic parameters. However, such parameters are difficult to determine from microscopic information. Seldom is this challenge more apparent than in active matter, where the hydrodynamic parameters are in fact fields that encode the distribution of energy-injecting microscopic components. Here, we use active nematics to demonstrate that neural networks can map out the spatiotemporal variation of multiple hydrodynamic parameters and forecast the chaotic dynamics of these systems. We analyze biofilament/molecular-motor experiments with microtubule/kinesin and actin/myosin complexes as computer vision problems. Our algorithms can determine how activity and elastic moduli change as a function of space and time, as well as adenosine triphosphate (ATP) or motor concentration. The only input needed is the orientation of the biofilaments and not the coupled velocity field which is harder to ac

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Article Title: Dualities and non-Abelian mechanics

Authors: Michel Fruchart, Yujie Zhou, Vincenzo Vitelli

Keywords: dualities, non abelian mechanics, adiabatic holonomic computation, mechanical spins

Abstract: Dualities are mathematical mappings that reveal links between apparently unrelated systems in virtually every branch of physics. Systems mapped onto themselves by a duality transformation are called self-dual and exhibit remarkable properties, as exemplified by the scale invariance of an Ising magnet at the critical point. Here we show how dualities can enhance the symmetries of a dynamical matrix (or Hamiltonian), enabling the design of metamaterials with emergent properties that escape a standard group theory analysis. As an illustration, we consider twisted kagome lattices, reconfigurable mechanical structures that change shape by means of a collapse mechanism. We observe that pairs of distinct configurations along the mechanism exhibit the same vibrational spectrum and related elastic moduli. We show that these puzzling properties arise from a duality between pairs of configurations on either side of a mechanical critical point.

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Volume: **Issue:** **First Page #:**
Date Submitted: 8/31/20 12:00AM **Date Published:** 6/15/20 5:00AM
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Article Title: Symmetries and Dualities in the Theory of Elasticity

Authors: Michel Fruchart and Vincenzo Vitelli

Keywords: dualities, active elasticity, symmetries, active elastic moduli

Abstract: Microscopic symmetries impose strong constraints on the elasticity of a crystalline solid. In addition to the usual spatial symmetries captured by the tensorial character of the elastic tensor, hidden nonspatial symmetries can occur microscopically in special classes of mechanical structures. Examples of such nonspatial symmetries occur in families of mechanical metamaterials where a duality transformation relates pairs of different configurations. We show on general grounds how the existence of nonspatial symmetries further constrains the elastic tensor, reducing the number of independent moduli. In systems exhibiting a duality transformation, the resulting constraints on the number of moduli are particularly stringent at the self-dual point but persist even away from it, in a way reminiscent of critical phenomena.

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Article Title: Nuts and bolts of supersymmetry

Authors: Nitin Upadhyaya, Bryan G. Chen, Vincenzo Vitelli

Keywords: isospectral problems, supersymmetry, solitons, topological mechanics

Abstract: Mechanical metamaterials are artificial structures with unusual properties, such as negative Poisson ratio, bistability or tunable vibrational properties, that originate in the geometry of their unit cell. At the heart of such unusual behaviour is often a soft mode: a motion that does not significantly stretch or compress the links between constituent elements. When activated by motors or external fields, soft modes become the building blocks of robots and smart materials. Here, we demonstrate the existence of topological soft modes that can be positioned at desired locations in a metamaterial while being robust against a wide range of structural deformations or changes in material parameters. These protected modes, localized at dislocations, are the mechanical analogue of topological states bound to defects in electronic systems. We create physical realizations of the topological modes in prototypes of kagome lattices built out of rigid triangular plates. We show mathematically that

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Article Title: Topological defects in non-reciprocal active solids with odd elasticity

Authors: Lara Braverman, Colin Scheibner, Bryan VanSaders, Vincenzo Vitelli

Keywords: Topological defects, non-reciprocity, odd elasticity

Abstract: We investigate topological defects in active solids whose microscopic interactions violate Maxwell-Betti reciprocity (MBR). Broken MBR is a ubiquitous property of active and driven matter: it occurs whenever the linear response between microscopic displacements and (non-conservative) forces is asymmetrical. In the continuum, broken MBR yields an asymmetric (or odd) elastic modulus tensor. The odd moduli modify the interaction between dislocations and even reverse the stability of otherwise bound pairs. Isolated dislocations can also become motile due to microscopic work cycles active at dislocation cores that compete with conventional Peach-Koehler forces caused, for example, by ambient torque densities. We provide a novel computation approach to capture this effect which lies beyond continuum theory. We perform molecular dynamics simulations isolating active plastic processes and discuss their experimental relevance to solids composed of spinning particles and robotic metamaterials.

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Article Title: Active impact and locomotion in robotic matter with nonlinear work cycles

Authors: Martin Brandenbourger, Colin Scheibner, Jonas Veenstra, J, Vincenzo Vitelli, Corentin Coulais

Keywords: Active impact, non-reciprocity, odd elasticity, robotic matter

Abstract: Robotic matter describes non-equilibrium systems that exhibit adaptable, autonomous and self-taught behavior that bridges the gap between materials, machines and living organisms. A central challenge is to understand how robust responses at large scales emerge from programmed active components. In this paper, we build and characterize theoretically a class of flexible robotic materials that strategically utilize internal nonconservative forces giving rise to self-sustained work cycles. We harness these inherently nonlinear cycles to power and shed new light on otherwise familiar processes including impact deflection and locomotion. Beyond distributed robotics, our work suggests how these nonlinear work cycles and associated functionalities can emerge as solutions of the non-conservative dynamics of active and biological materials.

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Article Title: Non-reciprocal phase transitions

Authors: Michel Fruchart, Ryo Hana, Peter Littlewood, Vincenzo Vitelli

Keywords: active matter, odd-elasticity, phase transitions, non-reciprocity

Abstract: Out of equilibrium, a lack of reciprocity is the rule rather than the exception. Non-reciprocity occurs, for instance, in active matter, non-equilibrium systems, networks of neurons, social groups with conformist and contrarian members, directional interface growth phenomena and metamaterials. Although wave propagation in non-reciprocal media has recently been closely studied, less is known about the consequences of non-reciprocity on the collective behaviour of many-body systems. In this paper, we show that non-reciprocity leads to time-dependent phases in which spontaneously broken continuous symmetries are dynamically restored. The resulting phase transitions are controlled by spectral singularities called exceptional points. We describe the emergence of these phases using insights from bifurcation theory and non-Hermitian quantum mechanics. Our approach captures non-reciprocal generalizations of three archetypal classes of self-organization out of equilibrium: synchronization, floc

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Article Title: Realization of active metamaterials with odd micropolar elasticity

Authors: Yangyang Chen, YXiaopeng Li, Colin Scheibner, Vincenzo Vitelli, Guoliang Huang

Keywords: active metamaterials, odd-elasticity, micropolar

Abstract: Materials made from active, living, or robotic components can display emergent properties arising from local sensing and computation. Here, we realize a freestanding active metabeam with piezoelectric elements and electronic feed-forward control that gives rise to an odd micropolar elasticity absent in energy-conserving media. The non-reciprocal odd modulus enables bending and shearing cycles that convert electrical energy into mechanical work, and vice versa. The sign of this elastic modulus is linked to a non-Hermitian topological index that determines the localization of vibrational modes to sample boundaries. At finite frequency, we can also tune the phase angle of the active modulus to produce a direction-dependent bending modulus and control non-Hermitian vibrational properties. Our continuum approach, built on symmetries and conservation laws, could be exploited to design others systems such as synthetic biofilaments and membranes with feed-forward control loops.

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Article Title: Statistical mechanics of a chiral active fluid

Authors: Ming Han, Michel Fruchart, Colin Scheibner, Suriyanarayanan Vaikuntanathan, William Irvine, Juan de F

Keywords: Statistical mechanics of chiral active fluids

Abstract: Active materials are characterized by continuous injection of energy at the microscopic level and typically cannot be adequately described by equilibrium thermodynamics. Here we study a class of active fluids in which equilibrium-like properties emerge when fluctuating and activated degrees of freedom are statistically decoupled, such that their mutual information is negligible. We analyse three paradigmatic systems: chiral active fluids composed of spinning frictional particles that are free to translate, oscillating granular gases and active Brownian rollers. In all of these systems, a single effective temperature generated by activity parameterizes both the equation of state and the emergent Boltzmann statistics. The same effective temperature, renormalized by velocity correlations, relates viscosities to steady-state stress fluctuations via a Green–Kubo relation. To rationalize these observations, we develop a theory for the fluctuating hydrodynamics of these non-equilibrium fluids

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Article Title: Stokes flows in three-dimensional fluids with odd and parity-violating viscosities

Authors: Tali Khain, Colin Scheibner, Michel Fruchart, Vincenzo Vitelli

Keywords: active fluids, odd-viscosity, chirality

Abstract: The Stokes equation describes the motion of fluids when inertial forces are negligible compared with viscous forces. In this article, we explore the consequence of parity-violating and non-dissipative (i.e. odd) viscosities on Stokes flows in three dimensions. Parity-violating viscosities are coefficients of the viscosity tensor that are not invariant under mirror reflections of space, while odd viscosities are those which do not contribute to dissipation of mechanical energy. These viscosities can occur in systems ranging from synthetic and biological active fluids to magnetized and rotating fluids. We first systematically enumerate all possible parity-violating viscosities compatible with cylindrical symmetry, highlighting their connection to potential microscopic realizations. Then, using a combination of analytical and numerical methods, we analyse the effects of parity-violating viscosities on the Stokeslet solution, on the flow past a sphere or a bubble and on many-particle sedimentation

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Date Published: 1/26/21 12:00PM

Publication Location:

Article Title: Liquid-crystal-based topological photonics

Authors: Hamed Abbaszadeh, Michel Fruchart, Wim van Saarloos, W., Vincenzo Vitelli

Keywords: nematic, topology, optical metamaterials

Abstract: Liquid crystals are complex fluids that combine a unique ability to manipulate light with the reconfigurability of soft materials. They are at the core of modern display technology. In this paper, we suggest that nematic liquid crystals can also be used as building blocks of topological materials key to realize protected unidirectional waveguides, sensors, and lasers. Building on recent advances in liquid-crystal technology, we propose that suitable spatial modulations of the nematic director field are sufficient to assemble topological photonic materials. These ideas pave the way for fully reconfigurable photonic devices based on topologically protected states.

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Date Submitted: 7/27/23 12:00AM

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Publication Location:

Article Title: Odd elasticity and topological waves in active surfaces

Authors: Michele Fossati, Colin Scheibner, Michel Fruchart, Vincenzo Vitelli

Keywords: Odd elasticity, topological waves, topology, active surfaces

Abstract: Odd elasticity encompasses active elastic systems whose stress-strain relationship is not compatible with a potential energy. As the requirement of energy conservation is lifted from linear elasticity, new anti-symmetric (odd) components appear in the elastic tensor. In this work, we study the odd elasticity and non-Hermitian wave dynamics of active surfaces, specifically plates of moderate thickness. We find that a free-standing moderately thick, isotropic plate can exhibit two odd-elastic moduli, both of which are related to shear deformations of the plate. These odd moduli can endow the vibrational modes of the plate with a nonzero topological invariant known as the first Chern number. Within continuum elastic theory, we show that the Chern number is related to the presence of unidirectional shearing waves that are hosted at the plate's boundary. We show that the existence of these chiral edge waves hinges on a distinctive two-step mechanism: the finite thickness of the sample gaps

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Volume: 12 **Issue:** 1 **First Page #:**
Date Submitted: 7/27/23 12:00AM **Date Published:** 10/1/21 5:00AM
Publication Location:

Article Title: Realization of active metamaterials with odd micropolar elasticity

Authors: Yangyang Chen, Xiaopeng Li, Colin Scheibner, Vincenzo Vitelli, Guoliang Huang

Keywords: odd elasticity, non-reciprocal, active metamaterial, micropolar

Abstract: Materials made from active, living, or robotic components can display emergent properties arising from local sensing and computation. Here, we realize a freestanding active metabeam with piezoelectric elements and electronic feed-forward control that gives rise to an odd micropolar elasticity absent in energy-conserving media. The non-reciprocal odd modulus enables bending and shearing cycles that convert electrical energy into mechanical work, and vice versa. The sign of this elastic modulus is linked to a non-Hermitian topological index that determines the localization of vibrational modes to sample boundaries. At finite frequency, we can also tune the phase angle of the active modulus to produce a direction-dependent bending modulus and control non-Hermitian vibrational properties. Our continuum approach, built on symmetries and conservation laws, could be exploited to design others systems such as synthetic biofilaments and membranes with feed-forward control loops.

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Journal: under review
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Volume: **Issue:** **First Page #:**
Date Submitted: 7/27/23 12:00AM **Date Published:**
Publication Location:

Article Title: Limit cycles turn active matter into robots

Authors: Martin Brandenbourger, Colin Scheibner, Jonas Veenstra, Vincenzo Vitelli, Corentin Coulais

Keywords: robotics, active matter, odd elasticity

Abstract: Active matter composed of energy-generating microscopic constituents is a promising platform to create autonomous functional materials. However, the very presence of these microscopic energy sources is what makes active matter prone to dynamical instabilities and hence hard to control. Here, we show that these instabilities can be coaxed into work-generating limit cycles that turn active matter into robots. We illustrate this general principle in odd active media, model systems whose interaction forces are as simple as textbook molecular bonds yet not constrained to be the gradient of a potential. These emergent robotic functionalities are demonstrated by revisiting what is arguably the oldest of inventions: the wheel. Unlike common wheels that are driven by external torques, an odd wheel undergoes work-generating limit cycles that allow it to roll autonomously uphill by virtue of its own deformation, as demonstrated by our prototypes. Similarly, familiar scattering phenomena, like a b

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Publication Location:

Article Title: Zyxin is all you need: machine learning adherent cell mechanics

Authors: Matthew S. Schmitt, Jonathan Colen, Stefano Sala, John Devany, Shailaja Seetharaman, Margaret L. G

Keywords: machine learning, cell mechanics, biomechanics, neural networks, data

Abstract: Cellular form and function emerge from complex mechanochemical systems within the cytoplasm. No systematic strategy currently exists to infer large-scale physical properties of a cell from its many molecular components. This is a significant obstacle to understanding biophysical processes such as cell adhesion and migration. Here, we develop a data-driven biophysical modeling approach to learn the mechanical behavior of adherent cells. We first train neural networks to predict forces generated by adherent cells from images of cytoskeletal proteins. Strikingly, experimental images of a single focal adhesion protein, such as zyxin, are sufficient to predict forces and generalize to unseen biological regimes. This protein field alone contains enough information to yield accurate predictions even if forces themselves are generated by many interacting proteins. We next develop two approaches - one explicitly constrained by physics, the other more agnostic - that help construct data-driven c

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Journal: under review

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Date Submitted: 7/27/23 12:00AM

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Publication Location:

Article Title: Informational active matter

Authors: Bryan VanSaders, Vincenzo Vitelli

Keywords: information theory, active matter, reinforcement learning

Abstract: Many biomolecular systems can be viewed as ratchets that rectify environmental noise through measurements and information processing. As miniaturized robots cross the scale of unicellular organisms, on-board sensing and feedback open new possibilities for propulsion strategies that exploit fluctuations rather than fight them. Here, we study extended media in which many constituents display a feedback control loop between measurement of their microstates and the capability to bias their noise-induced transitions. We dub such many body systems informational active matter and show how information theoretic arguments and kinetic theory derivations yield their macroscopic properties starting from microscopic agent strategies. These include the ability to self-propel without applying work and to print patterns whose resolution improves as noise increases. We support our analytical results with extensive simulations of a fluid of 'thinker' type particles that can selectively change their diam

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Publication Location:

Article Title: The odd ideal gas: Hall viscosity and thermal conductivity from non-Hermitian kinetic theory

Authors: Michel Fruchart, Ming Han, Colin Scheibner, Vincenzo Vitelli

Keywords: odd ideal gas, hall viscosity, non-Hermitian, kinetic theory

Abstract: The flow of momentum and energy in a fluid is typically associated with dissipative transport coefficients: viscosity and thermal conductivity. Fluids that break certain symmetries such as mirror symmetry and time-reversal invariance can display non-dissipative transport coefficients called odd (or Hall) viscosities and thermal conductivities. The goal of this paper is to elucidate the microscopic origin of these dissipationless transport coefficients using kinetic theory. We show that odd viscosity and odd thermal conductivity arise when the linearized collision operator is not Hermitian. This symmetry breaking occurs when collisions are chiral, i.e. not mirror symmetric. To capture this feature in a minimalistic way, we introduce a modified relaxation time approximation in which the distribution function is rotated by an angle characterizing the average chirality of the collisions. In the limit of an infinitesimal rotation, the effect of the parity-violating collisions can be described

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Article Title: Hydrodynamic correlation functions of chiral active fluids

Authors: Debarghya Banerjee, Anton Souslov, Vincenzo Vitelli,

Keywords: Fluid Flow and Transfer Processes

Abstract:

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Article Title: Observation of topological action potentials in engineered tissues

Authors: Hillel Ori, Marc Duque, Rebecca Frank Hayward, Colin Scheibner, He Tian, Gloria Ortiz, Vincenzo Vitelli

Keywords: General Physics and Astronomy

Abstract:

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Article Title: Active Viscoelasticity of Odd Materials
Authors: Debarghya Banerjee, Vincenzo Vitelli, Frank Jülicher, Piotr Surówka,
Keywords: General Physics and Astronomy
Abstract:
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Article Title: Topological structure and dynamics of three-dimensional active nematics
Authors: Guillaume Duclos, Raymond Adkins, Debarghya Banerjee, Matthew S. E. Peterson, Minu Varghese, Itai
Keywords: Multidisciplinary
Abstract:
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Article Title: Fluctuating hydrodynamics of chiral active fluids
Authors: Ming Han, Michel Fruchart, Colin Scheibner, Suriyanarayanan Vaikuntanathan, Juan J. de Pablo, Vince
Keywords: General Physics and Astronomy
Abstract:
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Publication Location:
Article Title: A mechanism for anomalous transport in chiral active liquids
Authors: Zhenghan Liao, Ming Han, Michel Fruchart, Vincenzo Vitelli, Suriyanarayanan Vaikuntanathan,
Keywords: Physical and Theoretical Chemistry
Abstract:
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Article Title: Topological Defects in Solids with Odd Elasticity
Authors: Lara Braverman, Colin Scheibner, Bryan VanSaders, Vincenzo Vitelli,
Keywords: General Physics and Astronomy
Abstract:
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Volume: 5 **Issue:** 2 **First Page #:**
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Article Title: Systematic generation of Hamiltonian families with dualities
Authors: Michel Fruchart, Claudia Yao, Vincenzo Vitelli,
Keywords: General Physics and Astronomy
Abstract:
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I certify that the information in the report is complete and accurate:

Signature: Vincenzo Vitelli

Signature Date: 7/28/23 12:02PM

Interim Progress Report – Aug 01, 2020 to July 31, 2021

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2. Major Goals: A Description of the major goals of the project. These are determined by the agreement between the researcher and the sponsor. **8000 character limit.**

- a. Hint: List the major goals of the project as stated in the approved application or as approved by the agency. If the application lists milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion.
- b. Hint continued: Generally, the goals will not change from one reporting period to the next. However, if the awarding agency approved changes to the goals during the reporting period, list the revised goals and objectives. Also explain any significant changes in approach or methods from the agency approved application or plan.
- c. **ENTER RESPONSE HERE:**

Odd elasticity

The goal of our research is to derive and study a generalization of elasticity theory appropriate for solids whose microscopic constituents are active (i.e., can consume energy).

The conceptual starting place for our research is as follows. Active materials are composed of interacting constituents—ranging from synthetic components to living organism—that are individually capable of converting internal energy into work or self-sustained motion. When the active components are held together by interactions in a solid structure, the resulting medium displays emergent mechanical properties at the interface between continuum mechanics and dynamical systems. Our objective is to investigate the modifications of the elastic properties of such solids.

The theory of elasticity is the universal language for describing the mechanical deformations of continuous media at sufficiently large length scales. At its essence, elasticity is the study of the relationship between strain (i.e. deformations) and stresses (currents of momentum that cause motion). For long wavelength deformations, this relationship is well described by the linear relationship:

$$\sigma_{ij} = K_{ijmn} u_{mn},$$

where σ_{ij} is the stress, u_{ij} is the strain, and K_{ijmn} is an object known as the elastic modulus tensor (or stiffness tensor). In its usual formulation for passive media, the stress-strain relationship prescribed by elasticity rests on a basic assumption: the existence of an elastic

potential energy. This imposes the fundamental symmetry constraint on the elastic modulus tensor: $K_{ijmn} = K_{mnij}$. However, for active media, the existence of an elastic potential energy is not ensured and therefore the symmetry $K_{ijmn} = K_{mnij}$ is generically not valid. Hence, for active solids, the elasticity requires the inclusion of an additional term:

$$K_{ijmn}^o = -K_{mnij}^o$$

which, unlike the standard elastic modulus tensor, is antisymmetric under the exchange of indices. We refer to the class of active solids in which this antisymmetric contribution to the elasticity as *odd elastic* media. The central aims of our research is to understand the microscopic physical origins of such a term and its implications for the design and phenomena associated with odd elastic media when viewed as (1) a material (2) a distributed machine and (3) a dynamical system.

Specifically, our project has three main objectives:

- Extend the standard formalism of continuum mechanics to describe active solids and elucidate the design of active elastic engines.
- Provide explicit coarse-graining procedure of suitable microscopic models that can test the validity of these continuum approaches in conjunction with simulations.
- Predict and test in simulations the emergent mechanical properties.

Achieving these major goals is organized into four main thrusts with subobjectives:

1. Build a theoretical blueprint to design and operate **active elastic engines**.
 - 1.1 Provide a design and realization of active elastic engines.
 - 1.2 Characterize the efficiency of active elastic engines
 - 1.3 Study the modes of actuation of active elastic engines
2. Construct explicit **microscopic models** that give rise to continuous media exhibiting odd elasticity.
 - 2.1 Identify concrete experimental realizations
 - 2.2 Derive the equations of odd elasticity from coarse graining
 - 2.3 Numerically test the validity of the continuum description
 - 2.4 Numerically explore non-linear and short wavelength regimes
3. Perform a **rigorous symmetry analysis** that classifies all allowed terms in odd elastic theories.
 - 3.1 Study the effects of anisotropy
 - 3.2 Study the effects of rotations and Cosserat theory
 - 3.3 Characterize the effects of non-affine microscopic deformations
4. Systematically study the peculiar **mechanical properties** of odd elastic media.
 - 4.1 Determine the spectrum and properties of odd elastic waves
 - 4.2 Investigate the static response of odd elastic solids to applied stresses and deformations
 - 4.3 Explore the instabilities of odd elastic materials, especially in extreme geometries.

Proposed timeline:

The initial proposed timeline for the three-year award is organized as follows. The first year and a half focus on thrusts 1 and 2 (active cycles and microscopic models). Thrust 3 (symmetry analysis) is targeted for the beginning of year two and intended to take approximately one and a half years. Thrust 4 (mechanical properties) is allotted two and a half years beginning midway through the first year. The general organization of this timeline is intended to proceed from areas with partial or preliminary results and gradually shift to more open-ended goals.

Dualities for metamaterial design

In addition to the goals stated in the original proposal, the grant extension (“Dualities for metamaterial design”) focuses on the systematic development of mechanical dualities as a design principle to engineer structures capable of mechanical spintronics and related generalizations.

This extension is inspired by the following preliminary results. The first is that the vibrational properties of mechanical systems (in particular phononic crystals) can exhibit the notion of a *duality*. Here, by duality, we refer to a generalized notion of a symmetry. To understand this notion, we observe that a given design for a material often depends on several parameters, for example the choice of stiffnesses of mechanical components or a specific geometric realization of a reconfigurable parts. A symmetry is a nontrivial action of a system that maps the system back onto itself with the same parameters. A duality is a nontrivial action that maps the system onto itself with a *different*, but predictable or prescribed, choice of parameters. By introducing this concept of a duality, we can identify special points in the design space in which the duality becomes a symmetry, i.e. the mapping between different parameters happens to be the identity map and the structure is self-dual.

The significance of the self-dual points becomes apparent in light of a concept known as a holonomy. In wave physics (or more generally gauge theories) a holonomy is a phase factor introduced when the system at hand transverses an abstract manifold of parameters (such as position or momentum of the wave). These holonomies take the form of operators, which can either be commutative or non-commutative. In the non-commutative case, the algebra of the holonomy operators endows the system with the possibility of nontrivial computation. Preliminary results show that self-dual points provide platforms for introducing non-commutative holonomies into classical systems.

Generalizing the preliminary results is organized along three specific objectives:

- Extend previously demonstrated momentum-space holonomies to non-Abelian gauge fields in real space.
- Systematically constructing duality-covariant families of systems

Generalize preliminary results to other lattices, three-dimensional systems, and other response functions.

3. Accomplished Under Goals: A description of what was accomplished under the goals during the reporting period. Text only. **8000 character limit.**

- d. Hint: For this reporting period describe 1) major activities; 2) specific objectives; 3) significant results, including major findings, developments, or conclusions (both positive

and negative); and 4) key outcomes or other achievements. Include a discussion of stated goals not met. As the project progresses, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.

e. **ENTER RESPONSE HERE:**

Major activity 1: Slender geometries, plastic deformation, topological defects in odd elastic media.

Results 1.1 (*Modified defect interactions and activity induced motility*) In [1], we investigate topological defects in active solids with odd elasticity. The odd moduli modify the interaction between dislocations and even reverse the stability of otherwise bound pairs. Moreover, isolated dislocations can also become motile due to microscopic work cycles active at dislocation cores that compete with conventional Peach-Koehler forces caused, for example, by ambient torque densities. We provide a novel computation approach to capture this effect which lies beyond continuum theory. We perform molecular dynamics simulations isolating active plastic processes and discuss their experimental relevance to solids composed of spinning particles and robotic metamaterials. Topological defects such as dislocations are the building blocks of complex phenomena such as plastic deformation and melting and our work generalizes their mechanics to active and driven systems.

Results 1.2 (*Odd elasticity of active surfaces*) In [2], we study the odd elasticity and non-Hermitian wave dynamics of active surfaces, specifically plates of moderate thickness. We find that a free-standing moderately thick, isotropic plate can exhibit two odd-elastic moduli, both of which are related to shear deformations of the plate. These odd moduli can endow the vibrational modes of the plate with a nonzero topological invariant known as the first Chern number. Within continuum elastic theory, we show that the Chern number is related to the presence of unidirectional shearing waves that are hosted at the plate's boundary. We show that the existence of these chiral edge waves hinges on a distinctive two-step mechanism: the finite thickness of the sample gaps the shear modes and the odd elasticity endows them with chirality.

Major activity 2: Experimental realizations of odd elasticity.

Results 2.1. (*Self-sensing metamaterials*) In [3], we realize a freestanding active metabeam with piezoelectric elements and electronic feed-forward control that gives rise to an odd micropolar elasticity absent in energy-conserving media. The non-reciprocal odd modulus enables bending and shearing cycles that convert electrical energy into mechanical work, and vice versa. The sign of this elastic modulus is linked to a non-Hermitian topological index that determines the localization of vibrational modes to sample boundaries. At finite frequency, we can also tune the phase angle of the active modulus to produce a direction-dependent bending modulus and control non-Hermitian vibrational properties. Our continuum approach, built on symmetries and conservation laws, could be exploited to design others systems such as synthetic biofilaments and membranes with feed-forward control loops.

Results 2.2 (*Active impact and locomotion in robotic media with nonlinear work cycles*) In [4], we build and characterize theoretically a class of flexible robotic materials that strategically utilize internal nonconservative forces giving rise to self-sustained work cycles. We harness these inherently nonlinear cycles to power and shed new light on otherwise familiar processes including impact deflection and locomotion. Beyond distributed robotics, our work suggests how these nonlinear work cycles and associated functionalities can emerge as solutions of the non-conservative dynamics of active and biological materials.

Results 2.3 (*Machine learning continuum theories in living active solids*) In [5], we develop a data-driven biophysical modeling approach to learn the mechanical behavior of adherent cells. We first train neural networks to predict forces generated by adherent cells from images of cytoskeletal proteins. Strikingly, experimental images of a single focal adhesion protein, such as zyxin, are sufficient to predict forces and generalize to unseen biological regimes. This protein field alone contains enough information to yield accurate predictions even if forces themselves are generated by many interacting proteins. We next develop two approaches - one explicitly constrained by physics, the other more agnostic - that help construct data-driven continuum models of cellular forces using this single focal adhesion field. Both strategies consistently reveal that cellular forces are encoded by two different length scales in adhesion protein distributions. Beyond adherent cell mechanics, our work serves as a case study for how to integrate neural networks in the construction of predictive phenomenological models in cell biology, even when little knowledge of the underlying microscopic mechanisms exist.

Major activity 3: Non-reciprocal phase transitions.

Results 3.1 (*Bifurcation theory in many-body physics and exceptional points*) In [6], we show that non-reciprocity leads to time-dependent phases in which spontaneously broken continuous symmetries are dynamically restored. We illustrate this mechanism with simple robotic demonstrations. The resulting phase transitions are controlled by spectral singularities called exceptional points. We describe the emergence of these phases using insights from bifurcation theory and non-Hermitian quantum mechanics. Our approach captures non-reciprocal generalizations of three archetypal classes of self-organization out of equilibrium: synchronization, flocking and pattern formation. Collective phenomena in these systems range from active time-(quasi)crystals to exceptional-point-enforced pattern formation and hysteresis. Our work lays the foundation for a general theory of critical phenomena in systems whose dynamics is not governed by an optimization principle.

Results 3.2 (*Informational active matter*) Many biomolecular systems can be viewed as ratchets that rectify environmental noise through measurements and information processing. As miniaturized robots cross the scale of unicellular organisms, on-board sensing and feedback open new possibilities for propulsion strategies that exploit fluctuations rather than fight them. In [7], we study extended media in which many constituents display a feedback control loop between measurement of their microstates and the capability to bias their noise-induced transitions. We dub such many body systems informational active matter, and we show how information theoretic arguments and kinetic theory derivations yield their macroscopic properties starting from microscopic agent strategies. These include the ability to self-propel without applying work and to print patterns whose resolution improves as noise increases. We support our analytical results with extensive simulations of a fluid of 'thinker' type particles that can selectively change their diameters to bias scattering transitions. This minimal model can be regarded as a non-equilibrium analogue of entropic elasticity that exemplifies the key property of this class of systems: self-propulsive forces grow ever stronger as environmental noise increases thanks to measurements and control actions undertaken by the microscopic constituents. We envision applications of our ideas ranging from noise induced patterning performed by collections of microrobots to reinforcement learning aided identification of migration strategies for collections of organisms that exploit turbulent flows or fluctuating chemotactic fields.

Major activity 4: Non-reciprocal response in fluids.

Results 4.1 (*Sedimentation and point responses*) In [8], we explore the consequence of parity-violating and non-dissipative (i.e. odd) viscosities on Stokes flows. These viscosities can occur in systems ranging

from synthetic and biological active fluids to magnetised and rotating fluids, in which parity (i.e. mirror reflection) symmetry is broken. We first systematically enumerate all possible parity-violating viscosities compatible with cylindrical symmetry, highlighting their connection to potential microscopic realizations. Then, using a combination of analytical and numerical methods, we analyze the effects of the parity violating viscosities on the Stokeslet solution, flow past a sphere or a bubble, and many-particle sedimentation. In all the cases we analyze parity violating viscosities give rise to an azimuthal flow even when the driving force is along the axis of cylindrical symmetry. The presence of azimuthal flows in cylindrically symmetric systems (sphere, bubble, cloud of particles) can serve as a probe for parity-violating viscosities in experimental systems.

Results 4.2 (*Fluctuating hydrodynamics of active fluids*) In [9], we study a class of active fluids in which equilibrium-like properties emerge when fluctuating and activated degrees of freedom are statistically decoupled, such that their mutual information is negligible. We analyze three paradigmatic systems: chiral active fluids composed of spinning frictional particles that are free to translate, oscillating granular gases, and active Brownian rollers. In all of these systems, a single effective temperature generated by activity parameterizes both the equation of state and the emergent Boltzmann statistics. The same effective temperature, renormalized by velocity correlations, relates viscosities to steady-state stress fluctuations via a Green-Kubo relation. To rationalize these observations, we develop a theory for the fluctuating hydrodynamics of these non-equilibrium fluids and we validate it through large-scale molecular dynamics simulations. These findings shed light on the microscopic origin of odd viscosities and stress fluctuations characteristic of parity-violating fluids, in which mirror symmetry and detailed balance are broken.

Results 4.3 (*Non-Hermitian kinetic theory for odd response coefficients*) The flow of momentum and energy in a fluid is typically associated with dissipative transport coefficients: viscosity and thermal conductivity. Fluids that break certain symmetries such as mirror symmetry and time-reversal invariance can display non-dissipative transport coefficients called odd (or Hall) viscosities and thermal conductivities. In [10], we elucidate the microscopic origin of these dissipationless transport coefficients using kinetic theory. We show that odd viscosity and odd thermal conductivity arise when the linearized collision operator is not Hermitian. This symmetry breaking occurs when collisions are chiral, i.e. not mirror symmetric. To capture this feature in a minimalistic way, we introduce a modified relaxation time approximation in which the distribution function is rotated by an angle characterizing the average chirality of the collisions. In the limit of an infinitesimal rotation, the effect of the parity-violating collisions can be described as an emergent effective magnetic field.

Results 4.4 (*Pattern formation and turbulence in chiral active media*) Fully developed turbulence is a universal and scale-invariant chaotic state characterized by an energy cascade from large to small scales where the cascade is eventually arrested by dissipation. In [11], we show how to harness these seemingly structureless turbulent cascades to generate patterns. Conceptually, pattern or structure formation entails a process of wavelength selection: patterns typically arise from the linear instability of a homogeneous state. By contrast, the mechanism we propose here is fully non-linear and triggered by a non-dissipative arrest of turbulent cascades. Instead of being dissipated, energy piles up at intermediate scales. Using a combination of theory and large-scale simulations, we show that the tunable wavelength of these cascade-induced patterns is set by a non-dissipative transport coefficient called odd or gyro viscosity. This non-dissipative viscosity is ubiquitous in chiral systems ranging from plasmas, bio-active media and quantum fluids. Beyond chiral fluids, cascade-induced pattern formation could occur in natural systems including oceanic and atmospheric flows, planetary and stellar plasma such as the solar

wind, as well as in industrial processes such as the pulverization of objects into debris or in chemistry and biology where the coagulation of droplets can be interrupted at a tunable scale.

Major activities 5: Dualities for metamaterial design

Results 5.1 (*Mechanical dualities*) Dualities are mathematical mappings that reveal unexpected links between apparently unrelated systems or quantities in virtually every branch of physics. Systems that are mapped onto themselves by a duality transformation are called self-dual and they often exhibit remarkable properties, as exemplified by an Ising magnet at the critical point. In [12], we unveil the role of dualities in mechanics by considering a family of so-called twisted Kagome lattices. These are reconfigurable structures that can change shape thanks to a collapse mechanism easily illustrated using LEGO. Surprisingly, pairs of distinct configurations along the mechanism exhibit the same spectrum of vibrational modes. We show that this puzzling property arises from the existence of a duality transformation between pairs of configurations on either side of a mechanical critical point. This critical point corresponds to a self-dual structure whose vibrational spectrum is two-fold degenerate over the entire Brillouin zone. The two-fold degeneracy originates from a general version of Kramers theorem that applies to classical waves in addition to quantum systems with fermionic time-reversal invariance. We show that the vibrational modes of the self-dual mechanical systems exhibit non-Abelian geometric phases that affect the semi-classical propagation of wave packets. Our results apply to linear systems beyond mechanics and illustrate how dualities can be harnessed to design metamaterials with anomalous symmetries and non-commuting responses.

Results 5.2 (*Dualities in elasticity*) Microscopic symmetries impose strong constraints on the elasticity of a crystalline solid. In addition to the usual spatial symmetries captured by the tensorial character of the elastic tensor, hidden non-spatial symmetries can occur microscopically in special classes of mechanical structures. Examples of such non-spatial symmetries occur in families of mechanical metamaterials where a duality transformation relates pairs of different configurations. In [13], we show on general grounds how the existence of non-spatial symmetries further constrains the elastic tensor, reducing the number of independent moduli. In systems exhibiting a duality transformation, the resulting constraints on the number of moduli are particularly stringent at the self-dual point but persist even away from it, in a way reminiscent of critical phenomena.

Results 5.3 (*Systematic generations of dualities*) Dualities are hidden symmetries that map seemingly unrelated physical systems onto each other. In [14], we systematically construct families of Hamiltonians endowed with a given duality and to provide a universal description of Hamiltonians families near self-dual points. We focus on tight-binding models (also known as coupled-mode theories), which provide an effective description of systems composed of coupled harmonic oscillators across physical domains. We start by considering the general case in which group-theoretical arguments suffice to construct families of Hamiltonians with dualities by combining irreducible representations of the duality operation in parameter space and in operator space. When additional constraints due to system specific features are present, a purely group theoretic approach is no longer sufficient. To overcome this complication, we reformulate the existence of a duality as a minimization problem which is amenable to standard optimization and numerical continuation algorithms. Combined with existing procedures to physically implement coupled-resonator Hamiltonians, our approach enables on demand design of photonic, mechanical, thermal, or electronic metamaterials with dualities.

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3. Training Opportunities: A description of Opportunities for training during the reporting period. **8000 character limit.**

- a. Hint: If the research is not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, please type "Nothing to Report" in response section.
 - b. Hint Continued: Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.
 - c. **ENTER RESPONSE HERE:** Nothing to Report
- 4. Results Dissemination: A description of dissemination during the reporting period. **8000 character limit.**
 - a. Hint: If there is nothing significant to report during this reporting period, type "Nothing to Report" in the response section.
 - b. Hint Continued: Describe how the results have been disseminated to communities of interest. Include any outreach activities that have been undertaken to reach members of communities who are not usually aware of these research activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.
 - c. **ENTER RESPONSE HERE:** Nothing to Report
- 5. Plans for Next Reporting Period: **8000 character limit.**
 - a. Hint: If there are no changes to the agency-approved application or plan for this effort, type "Nothing to Report" in the response section.
 - b. Hint Continued: Describe briefly what you plan to do during the next reporting period to accomplish goals and objectives.
 - c. **ENTER RESPONSE HERE:** Nothing to Report
- 6. Honors and Awards: Honors and Awards received during the reporting period.
 - a. **ENTER RESPONSE HERE:** Nothing to Report
- 7. Technology Transfer (patent applications, inventions, licenses, interaction with DoD laboratories)
 - a. **ENTER RESPONSE HERE:** Nothing to Report

8. Participants: Please confirm for each if a National Academy Member and enter any countries of international collaboration
- a. Vincenzo Vitelli (PI)
 - i. National Academy Member:
 - 1. **ENTER RESPONSE HERE:** NO
 - ii. International Collaboration:
 - 1. **ENTER RESPONSE HERE:** Corentin Coualais (Amolf, Netherlands)
 - iii. Person months - 3
 - b. Jonathan Colen (GRA)
 - i. National Academy Member:
 - 1. **ENTER RESPONSE HERE:** NO
 - ii. International Collaboration:
 - 1. **ENTER RESPONSE HERE:** None
 - iii. Person months - 5
 - c. Colin Scheibner (GRA)
 - i. National Academy Member:
 - 1. **ENTER RESPONSE HERE:** NO
 - ii. International Collaboration:
 - 1. **ENTER RESPONSE HERE:** None
 - iii. Person months - 1
 - d. Matthew Schmitt (GRA)
 - i. National Academy Member:
 - 1. **ENTER RESPONSE HERE:** NO
 - ii. International Collaboration:
 - 1. **ENTER RESPONSE HERE:** None
 - iii. Person months - 1
 - e. Howard Timlin (Undergraduate RA)
 - i. National Academy Member:
 - 1. **ENTER RESPONSE HERE:** NO
 - ii. International Collaboration:
 - 1. **ENTER RESPONSE HERE:** None
 - iii. Person months – 2.5
 - f. Michel Fruchart (Postdoc)
 - i. National Academy Member:
 - 1. **ENTER RESPONSE HERE:** NO
 - ii. International Collaboration:
 - 1. **ENTER RESPONSE HERE:** None
 - iii. Person months – 0.5
 - g. Nitin Upadhyaya (Postdoc)
 - i. National Academy Member:
 - 1. **ENTER RESPONSE HERE:** NO
 - ii. International Collaboration:
 - 1. **ENTER RESPONSE HERE:** None
 - iii. Person months - 6

9. Students

- a. Number of students receiving STEM degrees during the reporting period
 - i. **ENTER RESPONSE HERE:**
- b. Number of undergraduate and graduate STEM participants during the reporting period:
 - i. **ENTER RESPONSES HERE: 4 (Jonathan Colen, Colin Scheibner, Matthew Schmitt, and Howard Timlin)**

10. Products: Any Publications, Proceedings, Manuscripts etc. for this project period?

[1] Braverman, L., Scheibner, C., VanSaders, B. Vitelli, V. Topological defects in solids with odd elasticity. *Phys. Rev. Lett.* (2021) <https://doi.org/10.1103/PhysRevLett.127.268001>

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