Slender and Active

Mechanics of Emerging Materials and Systems

4 December 2025
International Centre for Mathematical Sciences,
The Bayes Centre, Edinburgh, UK

IOP Institute of Physics

Programme

9:20 AM - 9:40 AM	Registration and Refreshments
9:40 AM - 9:45 AM	Introduction
9:45 AM - 10:25 AM	**Invited Speaker: Tanniemola Liverpool** University of Bristol, UK Travelling strings and sheets of active dipolar colloids
10:25 AM - 10:40 AM	**Contributed Speaker: Matthew Butler** University of Strathclyde, UK Chemo-elasto-hydrodynamics of self-propelled slender filaments
10:40 AM - 10:55 AM	**Contributed Speaker: Andreas Menzel** Otto von Guericke University, Germany Dynamics of non-Newtonian active suspensions
10:55 AM - 11:15 AM	Morning Break
11:15 AM - 11:55 AM	**Invited Speaker: Tyler Shendruk** The University of Edinburgh, UK Polymeric filaments in active nematic turbulence
11:55 AM - 12:10 PM	**Contributed Speaker: Rahil Valani** University of Oxford, UK Nematic Order from Phase Synchronization of Shape Oscillations
12:10 PM - 12:25 PM	**Contributed Speaker: Jack Binysh** University of Amsterdam, The Netherlands Wave coarsening drives time crystallization in active solids
12:25 PM - 1:55 PM	Lunch
1:55 PM - 2:35 PM	**Invited Speaker: Hermes Bloomfield-Gadêlha** University of Bristol, UK Animating Matter: Reaction–Diffusion Patterns from Molecular Motors to Cilia and Robots
2:35 PM - 2:50 PM	**Contributed Speaker: Paul Baconnier** Amolf, The Netherlands Autonomous switching of locomotion behaviors in ciliary walkers
2:50 PM - 3:05 PM	**Contributed Speaker: Martin Van Hecke** Amolf Amsterdam and Leiden University, The Netherlands ABCs: Active Bistable Components
3:05 PM - 3:25 PM	Afternoon Break

3:25 PM - 4:05 PM	**Invited Speaker: Rastko Sknepnek** University of Dundee, UK Cell-level modelling of active forces in early-stage development
4:05 PM - 4:20 PM	**Contributed Speaker: Balázs Németh** University of Cambridge, UK Nonreciprocal constitutive laws for oriented active solids
4:20 PM - 4:35 PM	**Contributed Speaker: Mohamed Warda** University of Cambridge, UK Elastohydrodynamic instabilities of a soft robotic arm in a viscous fluid

Invited Speakers

Animating Matter: Reaction–Diffusion Patterns from Molecular Motors to Cilia and Robots

Hermes Bloomfield-Gadêlha
[1]*University of Bristol, United Kingdom*

This talk from the Polymaths Lab (https://www.polymaths-lab.com), Bristol, follows the journey from molecular machines to robotic systems that move, sense, and think through matter itself. We explore how molecular motors inside cells self-organise to make cilia and flagella beat, and how their 3D structure shapes their rhythmic motion. A pattern-formation model based on chemo-mechanical coupling (Cass & Gadelha, Nature Communications 2023) captures the cilium's wave as a self-generated pattern requiring no external sensing of the fluid. Internal dissipation from the motors alone reduces the physical interactions to a simple reaction–diffusion system for patterns of motion, matching experimental data from sperm and algal beating. A 3D multiphysics model further shows that planarity of motion emerges spontaneously from teams of molecular machines competing within their whip-like structure. High-speed 3D microscopy reveals that sperm generate counter-rotating vortices and spin like tops to swim straight, even with asymmetric beats (Ren & Gadelha, Advanced Science 2024). Extending these ideas into robotics, the Polymaths Lab builds micro-devices and soft robotic systems that display similar self-emergent behaviours—such as artificial muscles and octopus-like circuits exhibiting forms of embodied intelligence (Yue et al., Science Robotics 2025).

Travelling strings and sheets of active dipolar colloids

Tanniemola Liverpool[1]
[1]University of Bristol, United Kingdom

Motivated by recent experiments on electrically driven active dipolar colloids, we study collections of self-propelled dipolar particles which spontaneously form a variety of self-propelled aggregates at low packing fractions. We compare explicit Brownian dynamics simulations with a theory based on an (active) generalisation of the Rouse model of flexible polymers/membranes.

Polymeric filaments in active nematic turbulence

Tyler Shendruk[1], Zahra Valei[1]
[1]The University of Edinburgh, United Kingdom

Polymers play a key role in many complex biomaterials in which intrinsic activity drives the system out of equilibrium. While previous studies have focused on active filaments in passive fluids or passive polymers in athermal baths, passive polymers in actively flowing liquid crystals are particularly interesting. This is because of the interplay between the broken symmetry of the anisotropic medium, nonequilibrium activity and the conformational degrees of freedom of the macromolecules. We numerically study the conformation and dynamics of individual flexible filaments coupled to the velocity field of 2D extensile active turbulence. We find diffusivity increases with activity until the onset of turbulence. The high-activity saturation is due to competition between active forcing and conformational changes. Long polymers are stretched by activity and develop an effective persistence, while short polymers are compressed. Although the observed extension is analogous to coil-stretch transitions of polymers in traditional inertial turbulence, the compression of short polymers is due to activity-induced curvature. This demonstrates how activity represents a pathway by which biological systems can control the steady-state structural properties of filamentous macromolecules.

Cell-level modelling of active forces in early-stage development

Rastko Sknepnek[1]
[1]University of Dundee, United Kingdom

Gastrulation, the early stage of embryonic development, is an essential, highly conserved process in the development of all vertebrate embryos, including humans. During gastrulation, the embryo transforms from a single layer of epithelial cells into a three-layered structure of three major embryonic cell types, the ectoderm, the mesoderm and endoderm, in a process involving large scale cell and tissue movements. When not executed properly, it causes abortion of development and, in milder cases, leads to a wide range of congenital defects. The cellular mechanisms controlling gastrulation, when activated in the wrong place or at the wrong time, result in severe disease in adult life, such as cancer and malfunctioning of the immune system. Gastrulation requires the integration of critical cell behaviours such as cell differentiation, division, and movement through chemical and mechanical cell-cell signalling, to achieve the morphogenesis essential for proper functions. These interactions between signalling and cell behaviours create complex feedback loops between tissue, cell, and molecular length- and timescales that have evolved to enable the robust formation of complex multi-cellular structures. In this talk, using the vertex model for cell-level description of epithelial tissues, we will discuss how various forms of active processes, such as mechano-chemical feedback, cell growth, division, ingression, etc. couple to cell mechanics and lead to pattern formation and flows in model tissues. We will also make qualitative comparisons to the primitive steak formation (i.e. the gastrulation) in chick embryos.

Oral Talks

Autonomous switching of locomotion behaviors in ciliary walkers

Sumit Mohanty[1,2], Paul Baconnier[1,3], Harmannus A. H. Schomaker[1], Alberto Comoretto[1], Martin van Hecke[1,3], Johannes T.B. Overvelde[1,2]
[1]AMOLF, Netherlands, [2]Eindhoven University, Netherlands, [3]Leiden University, Netherlands

The locomotion of living organisms has long inspired artificial systems designed to replicate their complex behaviors. Remarkably, a wide range of brainless microorganisms employ arrays of soft cilia, which drive multiple distinct locomotion gaits, while autonomously changing behavior in response to environmental cues. Drawing on this inspiration, we introduce a new class of vibrated ciliary walkers that use an array of synthetic buckled cilia to achieve multimodal locomotion and, crucially, autonomous behavior switching based on interactions with the environment. We show, using a simplified model of a vertically vibrated bistable buckled cilium, how bimodal locomotion and autonomous switching naturally emerge. Extending this principle, we demonstrate that expanding the number of buckled configurations of the cilia gives rise to additional locomotion modes, which we rationalize with rigid active solid models. Finally, we examine assemblies of confined ciliary walkers and reveal how inter-walker interactions shape their locomotion statistics. Our results establish a scalable and physically grounded strategy to mimic the capabilities of natural locomotors, and lay the foundation for decentralized, autonomous robotic collectives.

Wave coarsening drives time crystallization in active solids

Dr Jack Binysh[1], Jonas Veenstra, Vito Seinen, Ruter Naber, Damien Robledo-Poisson, Andres Hunt, Wim van Saarloos, Anton Souslov, Corentin Coulais
[1]*University Of Amsterdam, Netherlands*

When metals are magnetized, emulsions phase separate, or galaxies cluster, domain walls and patterns form and irremediably coarsen over time. Such coarsening is universally driven by diffusive relaxation toward equilibrium. Here, we discover an inertial counterpart - wave coarsening - in active elastic media, where vibrations emerge and spontaneously grow in wavelength, period, and amplitude, before a globally synchronized state called a time crystal forms. We observe wave coarsening in one- and two-dimensional solids and capture its dynamical scaling. We further arrest the process by breaking momentum conservation and reveal a far-from-equilibrium nonlinear analogue to chiral topological edge modes. Our work unveils the crucial role of symmetries in the formation of time crystals and opens avenues for the control of nonlinear vibrations in active materials.

Chemo-elasto-hydrodynamics of self-propelled slender filaments

Matthew Butler[1], Ben Walker[2], Tom Montenegro-Johnson[3], Panayiota Katsamba[4]
[1]University Of Strathclyde, United Kingdom, [2]UCL, United Kingdom, [3]University of Warwick, United Kingdom, [4]Cyprus University of Technology, Cyprus

Chemically-active particles are an artificial prototype for active matter. These submerged objects self-propel by consuming a fuel in the surrounding fluid: surface chemical reactions alter the local solute concentration, and solute-surface interactions cause any resulting concentration gradients to drive slip flows close to the surface. We theoretically investigate how slender elastic filaments move under this propulsion mechanism by combining an asymptotically-accurate slender body theory for calculating the slip flows with a computationally efficient method for simulating the elasto-hydrodynamics of filaments. By considering canonical examples of surface chemical patterning, we explore the suite of dynamic behaviour of chemo-elasto-hydrodynamic filaments in simulations across a wide range of material stiffnesses. As the filament becomes more deformable, the dynamic behaviour progresses from rigid motion, through buckling and out-of-plane transitions, towards chaos.

Dynamics of non-Newtonian active suspensions

Henning Reinken[1], **Andreas Menzel**[1]
[1]Otto von Guericke University Magdeburg, Germany

Slender self-propelling bacteria, such as Bacillus subtilis, in dense suspension show dynamic vortex states, called active mesoscale turbulence. In contrast to externally driven, regular turbulence, these states feature characteristic sizes of the vortices. The energy input occurs on the microscopic, bacterial scale. Several previous investigations addressed the features of these states.

We study by theoretical and computational tools such turbulence-like dynamic states for thin films of active suspensions of non-Newtonian rheology. Particularly, shear-thickening and shear-thinning suspensions are addressed. On the one hand, shear thickening of active suspensions slows down the dynamics and elongates the vortices [1]. Remarkably, the vortices lock into a regular, rectangular lattice structure. On the other hand, shear thinning of active suspensions leads to a hysteretic regime of the emergence of turbulent states as a function of activity [2]. In this regime, the suspensions become heterogeneous and show spatial coexistence of turbulent and non-turbulent regions. Our observations point to the possibility of an underlying transition of directed percolation.

Additionally, we analysed the role of elasticity and viscoelasticity on the general dynamics of thin active films on substrates [3,4]. We derived a diagram of dynamical states as a function of the degree of elasticity and activity. Besides disordered and orientationally ordered states, we observe that elasticity can lead to winding motion in stripe-like states and to states of imperfect circular motion.

In parts, the signature of such states has been observed in previous experiments. We wish to stimulate by our work further experimental realizations and investigations.

We thank the German Research Foundation (DFG) for support.

[1] H. Reinken, A. M. Menzel, Phys. Rev. Lett. 132, 138301 (2024).
[2] H. Reinken, A. M. Menzel, Commun. Phys. 8, 270 (2025).
[3] H. Reinken, A. M. Menzel, Arxiv Preprint, arXiv:2502.04802 (2025).
[4] H. Reinken, A. M. Menzel, Arxiv Preprint, arXiv:2502.06294 (2025).

Nonreciprocal constitutive laws for oriented active solids

Mr Balázs Németh[1], Takuya Kobayashi[2], Ronojoy Adhikari[1]
[1]Department of Applied Mathematics and Theoretical Physics, University Of Cambridge, United Kingdom,
[2]Department of Chemical Engineering, Kyoto University, Japan

We present an overdamped continuum description of oriented active solids in which interactions respect the symmetries of space but do not obey the principle of action and reaction. Taking position and orientation as kinematic variables, we examine the conservation of the linear and angular momentum variables in an elementary volume. We find that nonreciprocal interactions yield, in addition to the areal stresses and moment stresses of classical elasticity, volumetric forces and torques that act as local sources of momentum and angular momentum. Since, by symmetry, these can only depend on the strains, nonreciprocity requires the extension of constitutive modeling to strain-dependent volumetric forces and torques. Using Cartan's method of moving frames and Curie's principle, we derive the materially linear constitutive law that underpins the nonreciprocal, geometrically nonlinear elasticity of the continuum. We study this constitutive law exhaustively for a one-dimensional active solid and identify striking nonreciprocal effects - traveling waves, linear instabilities, spontaneous motion of and about the center of mass - that are absent in a passive, reciprocally interacting solid. Numerical simulations of a particulate active solid model, consisting of a linear assembly of hydrodynamically interacting active particles, yields long-wavelength behavior that is in excellent agreement with theory. Our study provides the foundation for a principled macroscopic mechanics of oriented active solids with symmetry-invariant, nonreciprocal microscopic interactions.

Nematic Order from Phase Synchronization of Shape Oscillations

Ioannis Hadjifrangiskou[1], Sumesh Thampi[2], Dr Rahil Valani[1]
[1]University Of Oxford, United Kingdom, [2]Indian Institute of Technology Madras, India

We use a minimal model to show that nematic order can emerge in suspensions of non-interacting, deformable, elongated particles subjected to oscillatory shear flow. The ordering arises purely from phase synchronization of particle shape and orientation oscillations with the external drive. A similar phenomenon occurs for deformable active particles undergoing shape oscillations in steady shear flow. I will present how deformability enables synchronized collective states corresponding to stable limit cycles and Arnold tongues in parameter space. These findings reveal a robust mechanism for flow-induced self-organization, offering new design principles for soft and active materials.

ABCs: Active Bistable Components

Martin Van Hecke[1]
[1]*Amolf Amsterdam and Leiden University, Netherlands*

The bistability of slender structures allows them to function as ‘material bits’, which has been explored for mechanical memory, sequential shape morphing and computing1-4. Such elements are passive - their force-displacement curve has a positive area. Here we show that active bistable elements, with negative area under the curve, can be realized by supplying an active force to a passive bistable element in one of its two states. We discuss a mechanical realization of such active bistable elements based on stick-slip-switch motion. We then show that abstract hysteron models provide a unified description of both passive and active bistable structures, and that their self-loops - so far seen as a nuisance - precisely stem from active energy injection5. We finally suggest that active bistable elements are well known in the context of, e.g., spiking neuron networks, where they are associated with negative differential resistance.

1 T Chen, M Pauly and PM Reis, A reprogrammable mechanical metamaterial with stable memory. Nature 589 386 (2021).
2 3 AS Meeussen and M van Hecke, Multistable sheets with rewritable patterns for switchable shape-morphing, Nature 621 516 (2023)
3 LJ Kwakernaak and M van Hecke, Counting and Sequential Information Processing in Mechanical Metamaterials, PRL 130 268204 (2023)
4 J Liu et al, Controlled pathways and sequential information processing in serially coupled mechanical hysterons, PNAS 121 e2308414121 (2024)
5 P Baconnier and M van Hecke, Dynamic self-loops in networks of passive and active binary elements, arXiv:2412.12658v3 (2024)

Elastohydrodynamic instabilities of a soft robotic arm in a viscous fluid

Mohamed Warda[1], Ronojoy Adhikari[1]
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The design and control of soft robots operating in fluid environments requires a careful understanding of the interplay between large elastic body deformations and hydrodynamic forces. Our work studies the interplay between these forces in a driven soft robotic arm and identifies a novel instability that arises from the interplay of these two kinds of interactions. Our model for the soft robotic arm is a Cosserat rod, which allows for stretch, shear and bend degrees of freedom. We drive this model with a constant pressure applied to one end of a rod that is clamped at the other end. We find that that within a range of finite pressures, the robotic arm undergoes an instability that causes it to spontaneously oscillate. This is reminiscent of the classic follower force problem that has been extensively studied in the literature. The novelty of allowing stretch and shear degrees of freedom, ignored in previous studies, leads to an upper bound of pressure, beyond which the rod is rendered stable. In contrast, in the classic follower force problem, the rod is always unstable for pressures above a critical threshold. This counterintuitive sequence of bifurcations underscores the subtle nature of the elastohydrodynamic coupling in Cosserat rods and emphasizes their importance for the control of the viscous dynamics of soft robots.

Our work has implications for the emerging field of soft robotics in viscous environments, where inertia is negligible and hydrodynamic forces are well approximated by Stokes friction. In this limit, the Cosserat equations of motion have the character of a geometric field theory, which we exploit to devise novel structure-preserving geometric integrators for the problem.

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