Nonequilibrium systems under control

Program and abstracts

September 8-12, 2025 | Lorentz center, Leiden

Detailed program available here: https://gingrich.chem.northwestern.edu/neqcontrol/

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2 Abstracts

2.1 Olivier Dauchot | When swarm robotics loses control

On one hand, active fluids are known for their rich collective dynamics, which emerge from dynamical phase transitions. It remains however challenging to control these phases and turn them into functional materials, following the valorisation scheme of liquid crystalline phases into everyday life LCD. On the other hand, while swarm robotics has reached spectacular achievements, as exemplified by the live shows of drones displaying patterns in the night sky, these performances result from powerful central control and fast communication, rather than from smart distributed algorithms. As a matter of fact it remains challenging to program a simple swarm of more than a few tens of robots to perform everyday tasks autonomously and even more to adapt to unanticipated situations.

While active matter lacks control, swarm robotics suffocates under it. Tuning the right amount and form of control is therefore a promising route, yet not less challenging. In this talk, I will illustrate this tension with recent experiments conducted with a swarm of kilobots equipped with different exoskeletons, which determine their dynamical behaviour. I will discuss how, already at the individual agent level, a small change in mechanical design allows for radically different performance in a notoriously complex robotic task. The discussion will then be extended to the case of a task where one can take advantage of the mechanical synergy between two different morphologies. Finally I will move to a collective phototactic task, stress how the morphology can be beneficial or detrimental to the achievement of the task and lay the foundations of a hydrodynamic description of swarm robotics as a learning active liquid.

2.2 Ramin Golestanian | Reflections on dissipation and control in active matter

The intersection of stochastic thermodynamics and active matter is a very exciting and active field with great potential for opening new horizons for both disciplines. I my talk, I will discuss how mechanistic aspects of active matter, which are not adequately represented with the illusive "active force" in force-free systems, can be taken under control and used to accurately quantify dissipation, build thermodynamically- and hydrodynamically-consistent frameworks, and devise control strategies for real active matter.

2.3 Luca Cocconi | Information-optimal mixing at low Reynolds number

Shear-induced enhancement of diffusive mixing, also known as Taylor dispersion, represents a fundamental feature of out-of-equilibrium relaxation processes governed by an advection-diffusion equation. As such, this phenomenon is fundamental to many biological and artificial systems, from the uptake of oxygen, nutrients, or chemical signals in ciliated aquatic microorganisms, to microreactors and "lab-on-a-chip" applications. The design of mixing protocols which optimally leverage this phenomenon is thus a problem of both fundamental and practical importance. We draw on the framework of mutual information as a metric for mixing efficiency at low Reynolds number to formalise shear-induced mixing by a generic planar shear flow as an explicit non-linear optimisation problem, which we solve exactly under different types of (both linear and non-linear) constraints. The bound obtained for the optimisation problem constrained with respect to the total viscous dissipation constitutes a result of particular interest, as it can be interpreted as establishing a minimum energetic cost for erasing information through mixing at low Reynolds number.

2.4 Roberto Di Leonardo | Active billiards: engineering boundaries for the spatial control of confined active particles

Equilibrium systems naturally settle into stationary states that are largely insensitive to boundary conditions or microscopic interaction details. A clear example is the uniform distribution of gas molecules inside a container, regardless of its shape or material. In such cases, control over particle distributions is limited to the use of external fields. By contrast, active matter systems, composed of self-propelled particles such as swimming microorganisms, break detailed balance and exhibit diverse scattering behaviors, leading to strongly boundary-sensitive and heterogeneous spatial distributions. Here we propose a boundary method based on the flux transfer formalism typical of radiometry problems, where surface elements transmit and receive "rays" of active particles with infinite persistence length. Applying this method to Euglena gracilis confined in light-defined billiard geometries, we show how tailored boundaries can concentrate active particles. In particular, we design a multi-stage stacked billiard whose asymmetric connectivity produces exponential amplification of cell density across its length.

Di Leonardo et al. arxiv.org/abs/2410.01916 (to be published in PNAS)

2.5 Daan Mulder | Bit reset protocols that obey activity-constrained speed limits do not minimize work for a given speed

Optimal control theory is an important and active subfield of stochastic thermodynamics. The central question is: how can one optimally apply a time-dependent force to a system, to change it from its initial state to a desired final state, within some finite time, so that this operation requires a minimal amount of work? This question is especially relevant in the context of information processing devices, where energy consumption has become a limiting factor to growth. Hence, optimal control in the context of bit reset, where a single bit is set to a low-entropy state, has been extensively studied.

To find the optimal control protocol beyond the linear response regime, one has to know how the applied force, i.e. the change in energy landscape, changes the dynamics of the system. In the case of a continuous system, these dynamics are encoded by the diffusion constant, and a coherent picture has emerged, relating minimal irreversible entropy production to the duration of the operation and a Wasserstein distance between initial and final distribution.

In the case of discrete systems, a general solution has remained elusive. Here, the dynamics are captured by the rates. Although the energy difference fixes the ratio of the rates, it does not fix their magnitude. In theory, the magnitude can be an arbitrary function of the energy difference. Results have been limited to two-state systems with specific choices of this function, e.g. fixing one of the rates.

Recent years have seen great progress by recasting the question in terms of the total activity, i.e. the average number of jumps between states of the system over the course of the operation, rather than the time that the operation is allowed to take. This perspective has allowed for general expressions for the minimal work as a function of the total activity (or similar quantities), and the minimal total activity required for a given work. The expression for minimal total activity can be recast as an apparent minimal operation time or speed limit, determined by the average activity rate and work done. A maximal activity rate can be justified by appealing to physical restrictions on the underlying transition rates, but it is unclear whether protocols optimized under a constrained activity actually require the lowest work input for a given operation time under these restrictions.

In the context of bit reset, we show that directly minimizing work for a given operation time under constraints on the rates leads to protocols that require significantly less work to perform the operation than the activity-constrained protocol of the same duration. These results are of interest to both theorists and experimentalists working on efficient control of computing devices. We show how the resulting protocols for both optimization schemes differ. One reason for the difference between both optimization schemes is the fact that the activity rate is not constant over the course of the protocol: it depends on both the transition rates and the distribution of the bit, both of which change over the course of the copy operation.

2.6 Alexey Snezhko | Steering Active Colloidal Ensembles via Emergent Collective Memory and Temporal Modulation of Activity

Active colloidal fluids exhibit spontaneous emergence of correlated states, often characterized by complex dynamics and self-organization. The challenge is to develop robust set of principles to facilitate the control and manipulation of emergent active states. It was recently demonstrated that active liquids composed of motile particles can develop and store dynamic state information in seemingly random dynamic arrangements of the particles - revealing a form of hidden order that constitutes a collective memory of the system. Using chiral and achiral motile particle ensembles I will demonstrate how memory at individual particle level as well as collective ensemble memory can be exploited through temporal modulation of activity to steer the collective dynamics of active colloidal systems. The research was supported by the U.S. Department of Energy, Office of Science, Materials Sciences and Engineering Division.

2.7 Luca Giomi | Mechanics of axis formation in Hydra

Abstract: Hydra is a simple multicellular organism with extraordinary regenerative abilities: even a small tissue fragment can regenerate into a fully functional organism. During this process, the actin fibers that make up the muscular system spontaneously align along a common direction, which, over the course of approximately 48 hours, matures into the organism's body axis. In this talk, I will present our recent efforts to model this self-organization process using the framework of active nematic elastomers — solid materials composed of anisotropic building blocks that can autonomously generate uniaxial active stresses. I will demonstrate how the interplay between Hookean elasticity, active nematodynamics, and the spherical topology of regenerating Hydra leads to a condensation of active forces along an apolar axis, ultimately setting the stage for body axis formation. I will conclude by speculating on the potential role of cell signalling pathways in guiding or stabilizing this mechanically driven symmetry breaking.

2.8 John Bechhoefer | An information engine with high performance and efficiency

Information engines are a modern realization of the Maxwell-demon thought experiment that uses feedback to extract work from a single heat bath. In the variant proposed by Szilard, it is possible to efficiently exploit information gathered about the state of a system to extract energy from a heat bath and then store it as work. Previous experimentally realizable designs have either been able to either convert information efficiently to work but not store it or convert information inefficiently to work that is stored. Here, we show that a design consisting of a heavy colloidal particle diffusing in water and trapped by an optical tweezer can exploit measurements of position fluctuations in lateral dimensions to resolve this tension, allowing for efficient work conversion and energy storage.

2.9 Tirthankar Banerjee | Thermodynamic control of condensed matter: Driving equilibrium landscapes

We present a general framework for the optimal control of equilibrium landscapes governed by generic free energy functionals, mobilities, and multiple control parameters. Focusing on the near-quasi-static, small noise regime, we derive explicit expressions for the work performed during slow-driving protocols by expanding around equilibrium solutions. Our approach allows for systematic evaluation of the minimal energetic cost associated with finite-time driving between different states of a system. We characterize optimal protocols in terms of the system's response to an underlying resistance and show how this framework provides a basis for designing energetically efficient protocols in complex, multi-parameter equilibrium systems ranging from nematics and phase-separating liquids to polarizable magnets.

2.10 Alexandre Morin | Control of collective activity to crystallize an oscillator gas

Motility-induced phase separation occurs in assemblies of self-propelled units when activity is coupled negatively to density. By contrast, the consequences of a positive coupling between density and activity on the collective behaviour of active matter remain unexplored. Here we show that collective activity can emerge from such a positive coupling among non-motile building blocks. We perform experiments with self-sustained oscillators powered by contact-charge electrophoresis. Although the oscillators are non-motile by design, they spontaneously form an active gas when confined together. The super-elastic nature of collisions constitutes a positive density–activity coupling and underlies the active gas properties. Elucidating the origin of binary collisions allows us to precisely control the structure of the active gas and its eventual crystallization. Beyond considering the overlooked positive coupling between density and activity, our work suggests that rich collective properties can emerge not only from the symmetry of interactions between active building blocks but also from their adaptable and responsive behaviour.

2.11 Faezeh Khodabandehlou | Controlling quasistatic response

Nonequilibrium conditions allow the use of the time-symmetric fluctuation sector, aka the frenesy, to control response. A prime example is provided by nonequilibrium heat capacities. Given a potential (energy of states) and a far-from-equilibrium driving, we can drastically change the heat capacity by modifying kinetic parameters such as reactivities, barriers and escape rates. That can be illustrated via simple examples, but we speculate that this mechanism may play a crucial role in the development of and evolution toward heat-protection. (Materials with high specific heat can act as insulators.) The case of frenetic control is even broader and directly impacts the type of favoured trajectories by the system.

2.12 Clemens Bechinger | Optimal control of colloidal particles driven by optical tweezers in complex environments

Samuel Monter, Sarah Loos and Clemens Bechinger

The optimal control of finite-time processes on the microscale is of significant theoretical and practical interest, particularly for the energy-efficient operation of nanomachines. While previous studies have primarily focused on transitions between equilibrium states, many biologically and technologically relevant processes occur far from equilibrium. In such nonequilibrium settings, memory, a ubiquitous feature in realistic systems, plays an intricate role, as any driving necessarily excites internal memory modes. This motivates a deeper exploration of optimal control strategies in non-equilibrium regimes. Here, we combine experiments, theory, and computational methods to investigate the transition of a colloidal particle confined in an optical trap between two non-equilibrium steady states (NESS). We identify optimal control protocols that minimize the thermodynamic work during the finite-time transition between two NESS. We compare optimal protocols in viscous and viscoelastic fluid environments, which are common in realistic technical and biological processes and introduce memory due to a delayed response. Regardless of the presence of memory effects, optimal protocols consistently balance energy extraction with dissipation minimization. In the presence of memory, optimal control is achieved if the protocol matches the time response of the environment. These findings offer key insights for designing optimal control strategies for finite-time, non-equilibrium processes in complex environments.

2.13 Mazi Jalaal | Self-Regulating Chiral Fluids

Flows with deformable interfaces are typically controlled by applying external fields or by tailoring the boundaries that interact with the fluid. However, such approaches can be challenging or impractical in many settings. Here, we demonstrate that fluids with broken symmetries can autonomously regulate their mechanical response. First, we present theoretical and computational analyses of a fluid with highly deformable interfaces subjected to capillary stresses and featuring odd viscosity (a parity-violating transport coefficient that arises in chiral fluids). We then describe our experimental efforts to realize and characterize these effects in both biological suspensions and robotic systems.

2.14 Suriyanarayanan Vaikuntanathan | Local imperfect feedback control in non-equilibrium biophysical systems enabled by thermodynamic constraints

Understanding how biological systems achieve robust control despite relying on imperfect local information remains a challenging problem. Here, we consider non-equilibrium models which are generically used to describe natural and synthetic biological processes, such as gene regulation and protein conformational dynamics, and investigate their capacity for effective control using imperfect local feedback mechanisms. We derive a thermodynamic constraint on the response of non-equilibrium steady-state properties to changes in the driving forces. We show that this constraint enables linear, local, and easily implementable feedback rules to achieve environmental tracking and adaptation without consideration of network topology. In particular, we demonstrate that local stability of these feedback dynamics implies global stability for systems with one or two chemical regulators, regardless of the network topology. For higher-dimensional systems, global stability is not guaranteed. However, in part due to simplifications in attractor landscapes implied by our thermodynamic constraint, we find the basin of attraction remains significantly larger than would be expected from linear approximation alone. Our findings provide insight into how biological and synthetically engineered systems can respond effectively to environmental changes given only minimal feedback, without highly engineered interactions or precise parameter tuning.

2.15 Bert Kappen | Stochastic optimal control of open quantum systems

We address the generic problem of optimal quantum state preparation for open quantum systems. It is well known that open quantum systems can be simulated by quantum trajectories described by a stochastic Schrödinger equation. In this context, the state preparation becomes a stochastic optimal control (SOC) problem. The latter requires the solution of the Hamilton-Jacobi-Bellman equation, which is, in general, challenging to solve. A notable exception are the so-called path integral (PI) control problems, for which one can estimate the optimal control solution by direct sampling of the cost objective. In this presentation, I will review the PI control theory and derive a class of quantum state preparation problems that are amenable to PI control techniques, and propose a corresponding algorithm, which we call Quantum Diffusion Control (QDC). QDC employs adaptive importance sampling, a technique where the controls are iteratively improved based on global averages over quantum trajectories. We also demonstrate that QDC, used as an annealer in the environmental coupling strength, finds high accuracy solutions for unitary (noiseless) quantum control problems. We illustrate the effectiveness of our approach through examples of open-loop control for single- and multi-qubit systems.

Ref: https://arxiv.org/abs/2410.18635

2.16 Leticia Cugliandolo | Integrable systems under noise

2.17 Till Welker | Optimal localisation against a flow

We investigate the trade-off between cost and precision for an active particle that is trying to stay close to a given target position while being subject to an external flow. We consider a finite observation time, during which swim speed and mobility are being controlled. While large mobility can make swimming more energy-efficient, it can spoil precision through increased thermal fluctuations.

2.18 Thomas Speck | What to optimize? Dissipation in active matter

The control of a system requires thinking about a goal to be optimized, which is typically implemented as a variational principle with respect to a "cost function". A recent intriguing application in the context of active matter is to "learn" interaction rules with respect to some desired collective behavior. In particular, "entropy production" has been employed as a cost function with the understanding that it measures the thermodynamic cost to keep the system away from thermal equilibrium. I will present our work on how to relate dissipation due to microscopic degrees of freedom to an effective model for self-propelled colloidal particles. This approach allows us to identify the actual heat entering the thermodynamic efficiency with the vision to engineer efficient soft active materials.

2.19 Thomas Bickel | A quasiparticle description of Stokes-Marangoni flows

When a drop of dishwashing liquid is deposited on the surface of water previously sprinkled with pepper, one observes a rapid outward flow that drives the peppercorns towards the edges of the bowl. This simple yet captivating kitchen experiment is a classic demonstration of the Marangoni effect — fluid motion driven by surface tension gradients. Beyond this everyday observation, the Marangoni effect plays a crucial role in a wide range of phenomena, from stabilizing soap films to enabling the self-propulsion of active particles at the water-air interface.

From a theoretical viewpoint, Marangoni flows are governed by the Navier-Stokes equation, which describes fluid motion, and the advection-diffusion equation, which characterizes the transport of surfactants. The problem happens to be highly nonlinear due to the dominance of advection over diffusion, making analytical progress particularly challenging. In this talk, I will show that Marangoni flows in a deep liquid layer and in the viscous regime (Re=0) can be mapped onto an electrostatic problem. This mathematical equivalence provides a simple way to establish novel analytical solutions to the spreading dynamics. More intriguingly, the electrostatic analogy can be extended further down the molecular scale. Indeed, surfactant spreading can be formally described as a set of quasiparticles interacting via an effective Coulomb potential. The spreading dynamics then emerges from Newton's equations of motions, entirely bypassing hydrodynamic considerations. This unconventional analogy therefore offers a fresh and effective perspective on Marangoni flows.

2.20 Yael Roichman | Temperature Out of Thermal Equilibrium: How Far Can You Go?

In this talk, I will present a series of experimental systems driven by athermal (nonequilibrium) fluctuations. For each system, we explore the conditions under which one can define a physically meaningful effective temperature. Specifically, in one system, we compare different definitions of temperature and identify when they converge. In a second system, we test the predictive power of an effective temperature in describing the relaxation towards a steady state when a diffusive contact is formed. Finally, we focus on transitions between different steady-states. We develop a consistent non-equilibrium thermodynamic framework by examining the interplay of thermal and non-equilibrium fluctuations at the level of individual trajectories. Remarkably, this approach leads to a generalized notion of temperature—one that varies with the system's state while remaining consistent with the Second Law of thermodynamics.

2.21 Remi Goerlich | Optimal control for finite-time equilibration: time and energy trade-off in resetting

We derive an optimal protocol which drives a harmonically trapped Brownian particle between two positions within a finite time and with minimal energetic cost. This protocol, enforcing a geodesic evolution, ensures that the system reaches thermal equilibrium at the end of the driving, which can be arbitrarily fast.We show that this protocol has a unique thermodynamic nature, bounding the energetics of other families of optimized driving protocols. We finally demonstrate how this protocol can be applied to finite-time stochastic resetting, where it mitigates the thermodynamic cost of resetting and its ability to expedite search processes.In this context, we unveil a universal trade-off relation between time and energy, which is met by the optimal protocol.

2.22 Marjolein Dijkstra | Self-Learning Soft Matter

Biology is full of beautiful examples of self-assembling systems and molecular machines that can adopt multiple configurations, perform useful work, and store or process information depending on internal and external conditions. These biological systems display exceptional properties that continue to inspire interest from a physical perspective. A central feature is that living organisms operate far from thermodynamic equilibrium, continuously consuming and dissipating energy to sustain life. This energy is converted into mechanical motion, transport, or other functional tasks through diverse non-equilibrium mechanisms—for example, the transport of molecular cargo by kinesin proteins, the beating of bacterial flagella driven by proton transport, or ion pumps that transport ions against concentration gradients to maintain membrane potentials essential for cellular function. Other striking examples include bacteria that can switch their swimming modes between run and tumble, or the human brain—an intricate soft matter system composed mainly of water, salt, and fat—that can store memories, process information, and learn from past experiences by continuously updating synaptic weights. Inspired by such biological principles, we will discuss three types of systems—DNA-coated colloids, DNA tiles, and networks of iontronic channels—that can be trained to perform tasks such as input–output mapping, regression, counting, pattern recognition, and even simple computations.

2.23 Frank Cichos | Programming of Active Particle Propulsion Modes via Optically Controlled Interfacial Flows

Active particles operating at low Reynolds numbers generate distinctive hydrodynamic flow fields that drive distinct non-equilibrium collective phenomena, ranging from spontaneous flow instabilities to coherent pattern formation. While biological microorganisms demonstrate adaptive control over their propulsion signatures in response to environmental cues, synthetic active matter has lacked this programmable control capability, hindering systematic investigation of how dynamic mode switching governs emergent collective behaviors.

We demonstrate that spatially structured temperature fields on synthetic active particle surfaces can dynamically reconfigure the hydrodynamic flow patterns of active colloids, enabling controlled transitions between characteristic propulsion modes termed pusher, puller, and neutral swimming. Employing structured light to create programmable temperature gradients, we program thermo-osmotic slip flows that precisely control the boundary conditions governing propulsion. We experimentally map complete flow fields for each mode and demonstrate rapid, reversible switching between states. This approach provides a novel platform for investigating reconfigurable active matter physics, revealing how morphological changes in the flow fields may emerge as a consequence of a coupling to dynamical environments and their properties at the microscale.

2.24 René Van Roij | Controlling neuromorphic iontronics

Motivated by several surprising microfluidic experiments and inspired by the fantastic energy efficiency of the brain, we study aqueous electrolytes transported through microfluidic channels. In contrast to conventional electronics, which is solely based on voltage-driven transport of electrons through semi-conducting solids, the field of iontronics has a richer palette of driving forces and transportable quantities: not only voltage-driven ionic charge transport but also pressure-driven fluid flow and/or concentration-driven transport of a large variety of dissolved chemicals. Moreover, an aqueous medium allows for chemical reactions that affect the surface charge and for electrokinetic signal transduction, for instance a voltage-driven ("electro-osmotic") fluid flow or a pressure-driven electric ("streaming") current. On the basis of Poisson-Nernst-Planck-Stokes equations, coupled to chemistry as described by Langmuir kinetics for surface exchange reactions or Butler-Volmer equations for electrochemistry, we will focus on a variety of transport problems of aqueous electrolytes driven by static, periodic, and pulsatile voltage- and pressure-drops through microfluidic channels. We will see that a single cone-shaped channel exposed to an AC voltage responds as a volatile memristor at intermediate frequencies, and as a diode and an Ohmic resistor at low and high frequencies, respectively, where the characteristic time scale is set by the (experimentally tunable) channel dimensions [1,2]. Next we predict that Hodgkin-Huxley-inspired iontronic circuits of short (fast) and long (slow) conical channels yield neuromorphic responses akin to (trains of) action potentials [2] and several other neuronic spiking modes [3-5]. Finally we will present our prediction that chemical reactions (modelled by Langmuir kinetics [6]) on the channel surface can give iontronic analogues of (i) fast synaptic long-term potentiation ("learn fast, remember long") and (ii) coincidence detection of electric and chemical signals [7], which are both ingredients for brain-like (Hebbian) learning ("fire together wire together").

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[2] T.M. Kamsma, W.Q. Boon, T. ter Rele, C. Spitoni, and R. van Roij, Iontronic Neuromorphic Signaling with Conical Microfluidic Memristors, Phys. Rev. Lett. 130, 268401 (2023).

[3] T.M Kamsma, E. A. Rossing, C. Spitoni, and R. van Roij, Advanced iontronic spiking modes with multiscale diffusive dynamics in a fluidic circuit, Neuromorph. Comput. Eng. 4, 024003 (2024).

[4] T.M. Kamsma, J. Kim, K. Kim, W.Q. Boon, C. Spitoni, J. Park, and R. van Roij, Brain-inspired computing with fluidic iontronic nanochannels, PNAS 121, e23202242121 (2024).

[5] A. Barnaveli, T.M. Kamsma, W.Q. Boon, and R. van Roij, Pressure-gated microfluidic memristor for pulsatile information processing, Phys. Rev. Appl. 22, 054057 (2024).

[6] W.Q. Boon. M. Dijkstra, and R. van Roij, Coulombic Surface-Ion Interactions Induce Nonlinear and Chemistry-Specific Charging Kinetics, Phys. Rev. Lett. 130, 058001 (2023).

[7] T.M. Kamsma, M. Klop, W.Q. Boon, C. Spitoni, and R. van Roij, Chemically regulated conical channel synapse for neuromorphic and sensing applications, Phys. Rev. Res. 7, 013328 (2025).

2.25 Artur Soriani | Control of active field theories at minimal dissipation

Advances in experimental techniques enable the precise manipulation of a large variety of active systems, which constantly dissipate energy to sustain nonequilibrium phenomena without any equilibrium equivalent. To design novel materials out of active systems, an outstanding challenge is to rationalize how material properties can be optimally controlled by applying external perturbations. However, equilibrium thermodynamics is inadequate to guide the control of such nonequilibrium systems. Therefore, there is a dire need for a novel framework to provide a systematic toolbox for the thermodynamic control of active matter. In this talk, we present an optimization procedure for generic active field theories within a thermodynamically consistent formulation. Central to our approach is the distinction between the protocol heat, which is dissipated only during manipulation, and the total heat, which also accounts for the post-manipulation dissipation. We demonstrate that the latter generically features a global minimum with respect to the protocol duration. We deploy our versatile approach to an active theory of phase separation, and examine the scalings of the optimal protocol duration with respect to activity and system size. Remarkably, we reveal that the landscape of steady-state dissipation regulates the crossover between optimal control strategies for a finite duration.

2.26 Corentin Coulais | Adaptive locomotion of active solids

Active systems composed of energy-generating microscopic constituents are a promising platform to create autonomous functional materials that can, for example, locomote through complex and unpredictable environments. Yet coaxing these energy sources into useful mechanical work has proved challenging. Here we engineer active solids based on centimetre-scale building blocks that perform adaptive locomotion. These prototypes exhibit a non-variational form of elasticity characterized by odd moduli, whose magnitude we predict from microscopics using coarse-grained theories and which we validate experimentally. When interacting with an external environment, these active solids spontaneously undergo limit cycles of shape changes, which naturally lead to locomotion such as rolling and crawling. The robustness of the locomotion is rooted in an emergent feedback loop between the active solid and the environment, which is mediated by elastic deformations and stresses. As a result, our active solids are able to accelerate, adjust their gaits and locomote through a variety of terrains with a similar performance to more complex control strategies implemented by neural networks. Our work establishes active solids as a bridge between materials and robots and suggests decentralized strategies to control the nonlinear dynamics of biological systems, soft materials, and driven nanomechanical devices.

2.27 Maor Eldar | Physical control

The elastic properties of disordered materials depend on the multitude of different internal degrees of freedom, such as particle positions, size, and interactions. Treating these as design parameters that can be varied allows to attain complex response functions. However, manipulating a large number of microscopic degrees of freedom is often not feasible. The goal of our study is to explore whether material properties can be manipulated through low-dimensional external forcing. We build on ideas from physical learning to evaluate the required force, using two schemes – contrastive and Hebbian. Contrastive requires perturbing target degrees of freedom which we wish to manipulate, while Hebbian is only aware of their state. We develop learning schemes and characterize convergence as a function of the number of control and target degrees of freedom. We discuss the relations between the topology and properties of material and its ability to be effectively controlled.

2.28 Rosalba Garcia-Millan | Optimal closed-loop control of active particles

Minimising the energetic cost of moving an active particle in a confining trap over a target distance is a fundamental problem of optimal control of active matter. The control is a closed-loop protocol if it involves information about the particle state, such as its initial position or self-propulsion, and it is an open-loop protocol otherwise. In this talk, I will present recent analytical results where we derive the optimal time-dependent protocol that minimises its associated average work [arXiv:2407.18542, arXiv:2501.18613]. I will show that, while the optimal open-loop protocol is independent of the particle's activity, the optimal closed-loop protocol utilises the initial self-propulsion to lower the overall accumulated work. Depending on parameters, the associated work becomes negative, indicating that the activity of the particle can be harvested to extract work from the system. Moreover, the extractable work reaches a maximum at a finite persistence time.

I will further present a minimal active information engine based on a periodic optimal closed-loop protocol and compare its performance when run by a Run and Tumble Particle or by an Active Ornstein-Uhlenbeck Particle. While the average work is identical in both cases, the work distribution, its fluctuations and the information efficiency of the engine are advantageous when the engine is run by a Run and Tumble Particle.

2.29 Paddy Royall | Active Control with Colloids in 3d: Strings, Sheets and Novel Crystal Excitations

Understanding of collective behaviour in active systems is massively enhanced by minimal models which nevertheless capture its essence. Active colloids provide an important class of model systems, mimicking the exotic collective behaviour of animal groups, such as milling in fish [1], yet in a setting where the interactions which underly the macroscopic phenomena may be precisely controlled. Active colloids furthermore present opportunities for smart actuated materials and microrobots.

Until now, experiments with active colloids have been largely limited to (quasi) 2d systems. We may reasonably expect that moving to three dimensions will bring new phenomena. Here we introduce a 3d active colloidal system for induced charge electrophoresis (3dICEP). Under an AC electric field, this system is active in the plane perpendicular to the field and acquires a dipolar interaction parallel to the field [2].

Our 3dICEP colloids exhibit a complex and intriguing set of unexpected behaviour: travelling strings of particles, which can be described as active polymers [2,3] along with sheet-like and labyrinthine assemblies which fluctuate in a manner reminiscent of biological membranes [2]. Surprisingly, the active sheets and labyrinth break symmetry in a direction perpendicular to the applied field. Finally, and perhaps most remarkably for an overdamped system, the 3d colloidal crystal that forms features long-wavelength fluctuations reminiscent of phonons.

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2.30 Viktor Holubec | Predictive Steering and the Role of Delay in Active Matter

The control of active particles is typically aimed at achieving specific objectives. Here, we consider the case in which individual agents seek to maximize their local alignment with neighbors. We show that when these agents are capable of basic predictions, this modification of the Vicsek model leads to cohesive flocking states even in the absence of confinement or periodic boundaries. Since decision-making and implementation of control strategies require time, we also investigate the effect of response delays on both interacting and non-interacting active particle systems, demonstrating that delay time can serve as a control parameter for the dynamical states of active matter.

2.31 Romane Braun | Phase coherence and disorder-induced wave propagation in micromotor arrays

Machines are designed, assembled, and programmed to convert power into predetermined dynamics and functions. In contrast, living systems such as interacting cells and animal groups, self-organize, synchronize, and perform complex tasks without predefined patterns. Inspired by these decentralized architectures, experiments have shown that minimal systems in which self-propelled robots are elastically coupled can achieve collective motion and oscillatory deformations, two fundamental functionalities observed in nature. However, the focus on self-propulsion, and biological inspiration, has limited the size and range of operation of broader metamachines. In this talk, I will describe the self-organization of microscopic metamachines composed of thousands of 3D-printed rotary motors. Combining experiments, simulations, and theory, I will reveal unprogrammed collective oscillations organized both in space and time.I will first show that frictional forces arrange the motors' handedness into a pristine antiferromagnetic phase. Next, I will demonstrate the spontaneous phase coherence of the rotor dynamics, and explain it as a phase transition à la Kuramoto. Finally, unlike most metamaterials, I will highlight how quenched disorder in these metamachines enables the free propagation of phase waves across regions with mismatched rotation speeds. These results suggest that synthetic metamachines could illuminate self-organization in living and synthetic non-equilibrium matter, and inspire decentralized architectures with unanticipated dynamical capabilities.

2.32 Olivier Pierre-Louis | Control of cluster shape and particle navigation in fluctuating colloidal systems

We have investigated how one can manipulate the shape of a small cluster of colloids (or nanoparticles) using a macroscopic external field in the presence of thermal fluctuations[1, 2, 3]. This problem can be formulated as a minimization of first passage times in configuration space. We obtain the optimal policy to reach an arbitrary target configuration using Dynamic Programming. We then show how the efficiency of Reinforcement-Learning vanishes at the nanoscale due to thermal fluctuations [4].

We have also applied a similar approach to navigation with a discrete policy on a square lattice. We have determined the statistics of the changes in the optimal policy in the presence of frozen disorder [5]. Unexpected strong changes in the optimal policy are found for disorder with low densities of defects.

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