EUROPHYSICSNEWS

The magazine of the European Physical Society

Active Matter

EPS Young Minds
In Berlin we met again

Colloidal
active matter

Physics needs women
as role models!

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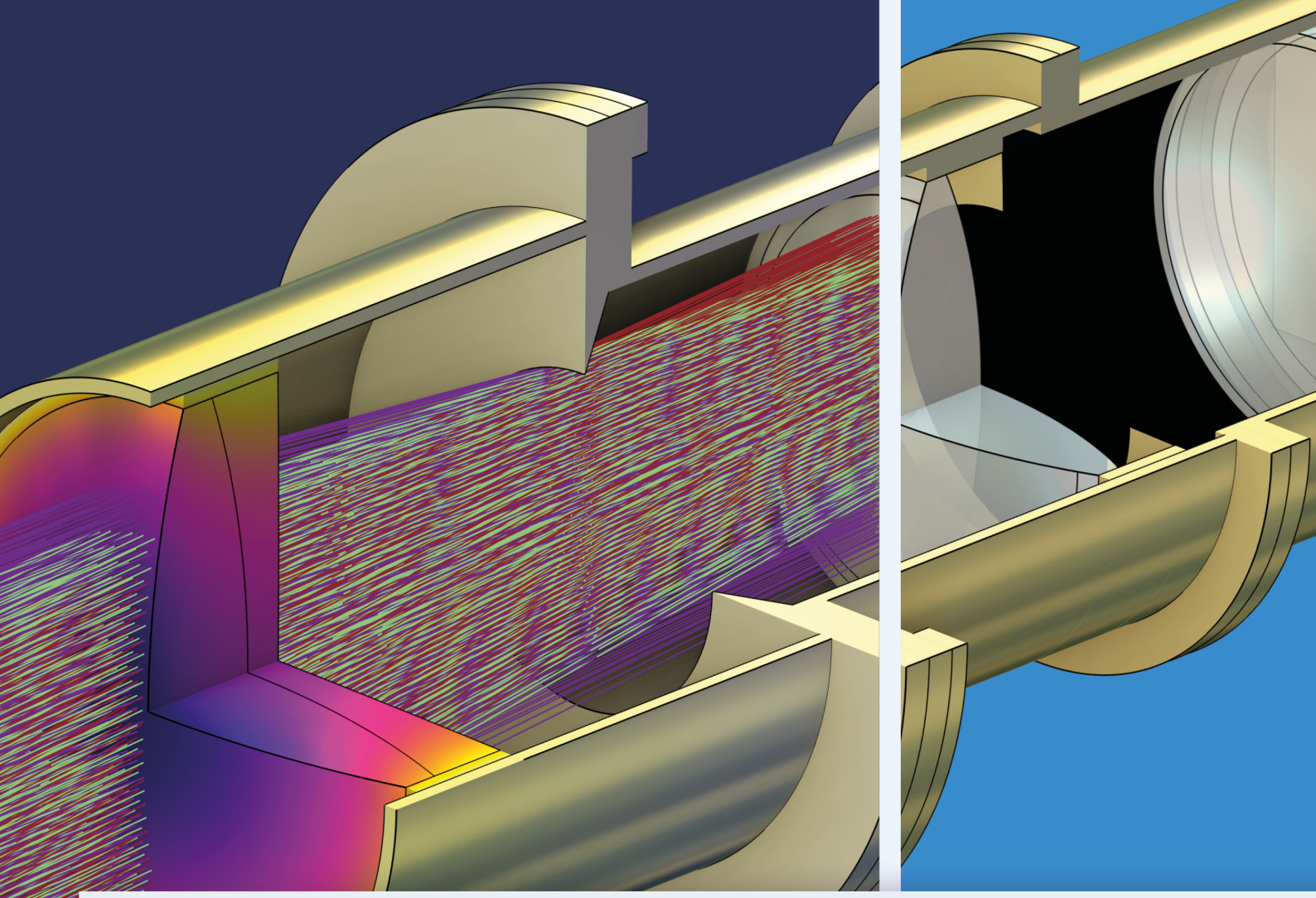

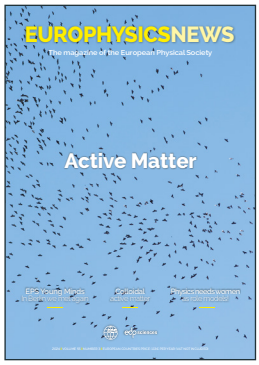

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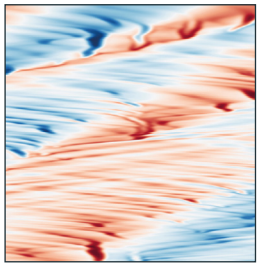
Cover picture: Flocks of birds in the sky. © iStockPhoto.



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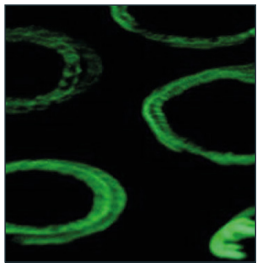
Non-reciprocal active-matter a tale of "loving hate, brawling love" across the scales



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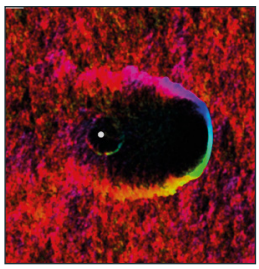
Collective Dynamics in Active Solids



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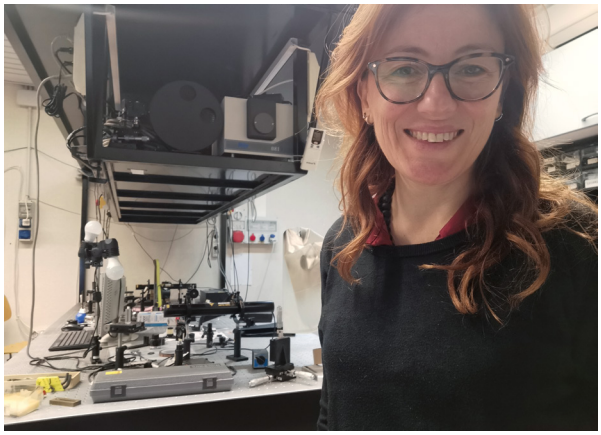
Thirty years of surprises about collective motion

Letter to EPN readers



Dear Readers,
composing an issue of a magazine like EuroPhysics New feels like building a puzzle, or like conducting an orchestra. Fortunately for music, I got the former, but not the latter. This scientific puzzle is my first issue as EPN Editor, marking a new challenge in my career and my history as a member of the European Physical Society. I became a founding member of the EPS Young Minds project in 2010, which I chaired from 2013 to 2016. After I become a member of EPN External Advisory Board. I am taking this little space to thank EPS for this important recognition given to me. Above all to all the pieces of this puzzle: the physicists, the active members of the EPS and the staff who brilliantly manage this magazine. Among these, Els de Wolf whom I warmly thank for the work done before me.

During my years as an EPS member, I have met and worked with many people who have been colleagues, friends, and often mentors. Their work inspired me to understand, beyond scientific research, what my vocations are. The journey has been rich with learning experiences and opportunities to grow. I have been privileged to witness groundbreaking research and innovative projects, all driven by the dedication and passion of the scientific community. This exposure has not only broadened my scientific knowledge but also honed my skills in various aspects of professional and personal development.

Over time, I realized that scientific communication was not only one of my passions but also my chance to contribute as a volunteer to the community. Being able to give back all the experiences that were given to me has been a fulfilling aspect of my journey. Scientific communication bridges the gap between complex research and the broader public, making science accessible and engaging. It plays a crucial role in fostering a scientifically informed society, capable of making educated decisions and appreciating the wonders of scientific discoveries.

I want to start this new adventure with this letter, addressed to you, our readers. I hope that if today you are just readers, tomorrow you will become pieces too of this beautiful puzzle that is Physics & EPN. ■

[EPS EDITORIAL]

EPS and ISE

On April 25th and 26th, I had the pleasure to represent EPS in the policy discussion and the General Assembly of the Initiative for Science in Europe, that took place in Brussels.

The Initiative for Science in Europe (ISE) is an independent association committed to the scientific and technological development across the whole of Europe. It was initiated in 2003 by researchers in the life sciences and was quickly joined by researchers from all other fields. ISE played a central role in the creation of the European Research Council (ERC). Since 2003, ISE has been active in promoting European scientific community's views on the European Framework programmes and their budgets, on open science, and providing science-based advice to policy makers. In 2017, ISE was registered in Strasbourg as an international, independent and non-profit-making association.

ISE provides an independent platform for European learned societies and non-governmental research organisations across all fields of science and technology, including humanities and social sciences. Its main goal is to advocate for independent scientific advice in European policy making, encourage the participation of European scientists in the design and implementation of European research and innovation policies, as well as participation in the European scientific and technological development.

EPS is one of the ISE disciplinary members, accompanied by the European Acoustic Association (EAA), the European Association of Social Anthropologists (EASA), the European Aeronautics Science Network (EASN), the European Association of Social Psychology (EASP), the European Calcified Tissue Society (ECTS), the European Economic Association (EEA), the European Educational Research Association (EERA), the European Geosciences Union (EGU), the European Molecular Biology Organisation (EMBO), the European Plant Science Organisation (EPSO), the Federation of European Biochemical Societies (FEBS) and the International Association for Dental Research (IADR). ISE has also a number of multidisciplinary members: the European Council of Doctoral Candidates and Junior Researchers (Eurodoc), The Marie Curie Alumni Association (MCAA), the Young Academy of Europe (YAE), the Association of ERC Grantees (AERG), and the International Consortium of Research Staff Association (ICoRSA).

One of ISE's main activities is to provide statements and position papers on European science policy matters. According to ISE's viewpoint, European researchers should play a leading role in knowledge advancement, economic progress, as well as the application of science and technology advancements to the benefit of the society.

EPS is the voice of the physics community in Europe, having a role in promoting the interests and views of all European physicists, offering scientific advice to policy makers, and supporting the next generation of physicists. As such, EPS has common vision with the ISE and shares common goals, among which is promoting excellence-based funding programmes for scientific researchers, ensuring independent evidence-based scientific advice in the development of European policies, playing a central role in shaping scientific research in Europe, improving careers of researchers and promoting trans-European networking.

During the meeting in Brussels, I reiterated our commitment to contribute to the ISE's activities, and in particular to be an active partner on science policy matters at the European level. Among EPS's main objectives are to strengthen the position of Europe, orient scientific policy in Europe, and make science attractive without barriers. These objectives lie well in the goals of ISE, establishing a strong partnership between EPS and ISE. Developing synergies with ISE and/or its individual disciplinary members will be beneficial for the accomplishment of a number of our objectives.

In the coming months, I will take part in the scheduled meetings of the ISE Executive Committee reinforcing the relation of our societies and strengthening our collaboration towards shared goals. ■

■ **Mairi Sakellariadou,**
EPS President

In Berlin we met again, The YM Leadership Meeting glamoring the EPS forum of 2024!

Anna Grigoryan, Serina Almassu, and Carmen Martín Valderrama – DOI: https://doi.org/10.1051/epn/2024301

The Young Minds project of the European Physical Society is committed to its foundation as a global connecting hub for physicists and early career scientists from every country in Europe and its surroundings. Therefore, and as every year, the Young Minds project hosts the annual leadership meeting where representatives from every student-run chapter (section) are invited to join us for two outstanding days of scientific research skills and career development in addition to priceless networking opportunities.

This time our participants packed up for a double chance to participate as well in the annual EPS Forum which harpored the YM leadership meeting along with other activities. And the destination ? It was the capital city of science, the hometown of Einstein, and Max Planck, Berlin, where beer, art, and science make the true spirit of the city.

More than 70 participants representing 30 sections from 10 different countries came together at the Henry Ford Building of the Freie University-Berlin, for the YM leadership meeting on the 25th and 26th of March. The meeting was initiated with a warm welcome by the LM organization committee chair, Anna Grigoryan, the EPS Secretary General, Anne Pawsey, and EPS Former Chair, Luc Berge. The meeting could not have proceeded without YM Former Chair Mattia Ostinato's famous overview presentation about the YM project which he used to announce as well some exciting news and the latest of achievements of the EPS and YM project. The core of the meeting came from the following many talks, lectures, and discussions which focused on empowering the students' scientific research skills and broadening their perspectives within and outside academia with a unique range of topics and group of speakers. To further connect with other YM delegates, a networking session was conducted which offered perfect opportunities for the participants to catch up, get to better know each other, and follow-up on the attended talks and lectures. The LM was concluded with the YM activity poster session, where 18 posters were presented by the section's representatives with the corresponding "Young Minds Best activity award by EPL" ceremony, where the two Italian YM sections, PONYS and SPAM Caserta, received the winners certificates from EPL and 250 euros.

Nobel Laureates, Masterclasses, Panel discussions… the LM's hotspots

The Leadership Meeting featured a range of talks and activities focused on the soft skills that scientists require. The first day of the meeting began with Masterclasses on Scientific Writing led by Isabelle Auffret-Babak, EDP Science Senior Publisher, and Anne Ruimy, EDP Publishing Director. After this, Antigone Marino spoke about Impostor Syndrome. The

"From PhD to CEO" panel discussion, in collaboration with OPTICA, was also a highlight. The panelists were Imran Khan, Co-Founder of Keequant, and Jan Kischkat, Co-Founder of Quantune, and the session was chaired by Director OPTICA Europe Claus Roll and Mattia Ostinato. During the discussion, the panelists introduced themselves and answered questions from both the audience and the panel discussion chairs.

The second day of the meeting began with Nobel Prize Laureates' Lectures, which were made possible by the co-location with the EPS Forum. Tatevik Chalyan then gave a lecture on writing a successful grant application, followed by Steven Goldfarb's talk on "Why we bother – the urgency of education and outreach".

Thanks to these special activities, the meeting brought together YM delegates from various countries, as well as many interested students and young researchers from outside of the YM network, making it a great success and the hit of 2024 YM project's year. In addition to the LM program, participants had the opportunity to learn about industrial opportunities and attend lectures from world-class researchers conducted in the EPS Forum.

Young Minds Action Committee would like to express sincere gratitude to the European Physical Society for inviting and accommodating the Leadership Meeting within the EPS Forum and congratulations to the organization for the success of the event. We are thrilled that so many young minds gathered for the meeting and look forward to the Leadership Meeting in 2025.

Carmen Martín Valderrama elected as a new chair of EPS Young Minds

Carmen Martín Valderrama, PhD student at CIC nanoGUNE, Spain, and former member of the YM section in Valladolid, Physics League, received the support of the entire committee and took over the chair position from the YM leadership meeting onwards. She presented an overview of the main points the action committee will work on for the next two years, which consists in (1) improving the internal processes, (2) strengthening the YM network and the relationship with other associations and (3) working on our digital presence, webpage and social media. We thank Mattia for his dedicated work and leadership over the last two years, and we wish Carmen all the best and much success for her tenure. ■

Physics needs women as role models!

In 2024, the EPS released a calendar of physicists (see EPN 55-1) aiming at increasing the visibility of women in science and inspiring youngsters to study physics. Here are the editorials by Lucia Di Ciaccio, Lorena Ballesteros Ferraz, Sébastien R. Mouchet, Riccardo Muolo and Gina Gunaratnam.

Editorial by Lucia Di Ciaccio

Physics is one of the pillars of our Society. It generates fundamental knowledge needed for future technological advances and is an important element for the education of young generations. There are several examples showing that physics has largely contributed to change and improve the human activities.

Physics is a collective enterprise in which all contributions build on the previous ones where diversity in nationality, gender, age is a key of success, as proven by the results obtained often at the research centres that welcome many diverse people.

Indeed, behind all the advances that physics has allowed and that we enjoy every day, there are many scientists of different nationalities, gender and age that driven by the strongest forces of the human beings, passion and curiosity, have experienced the intellectual adventure that brought them to discoveries or great achievements.

The purpose of this calendar of the European Physical Society is to acknowledge this effort highlighting the presence of women in physics.

One of the reasons for this gender-bias choice is that despite many efforts and growing awareness in the Society, women are still under-represented in this discipline especially in higher positions.

Just less than a couple of hundred years ago in many European countries, women were not allowed to attend public institutions of higher education, sometimes their contribution to science was hidden or not recognized and they had to rely on their family support because a paid job in science at university was not admitted for a woman. Many women scientists (Lise Meitner, Emmy Noether, Maria Goeppert-Mayer, to name few of them) needed a great deal of determination to pursue their research and overcome stereotypes.

There has indeed been progress since these times with many laws passed guaranteeing equality between men and women in the job attribution, but a gender gap still exists in the more highly skilled and paid professions.

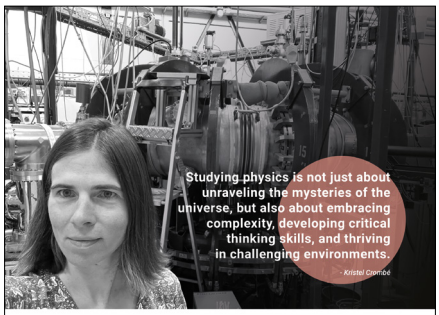
There are several reasons why this gap persists. One of most important is that unfortunately, conscious and especially unconscious gender-biases continue to exist in many, who believe that physics, after all, is rather a man business. Therefore, the aim of this calendar, which presents examples of successful women in physics, is to remind and recognize these many past and present brilliant minds.

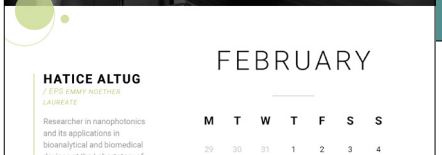
Sometimes women have themselves a gender-bias, thinking that they are not good enough to pursue a career in physics. It is observed that girls have less self-confidence than boys and often "choose" less competitive paths of study, and this affects their future careers and salaries.

While this gender-bias has deep roots in the fact that very young children interiorize gender stereotypes and this must be addressed in the very early stage of life, representing female role models is one of the ways of overcoming this bias. This calendar provides examples of past and present committed female role models.

The talent of everybody is needed to tackle the many challenges of our Society and physics plays a prominent role in that. It is silly to exclude even a tiny fraction of contributions that all diverse human beings can give, at all levels.

Studying physics is an extraordinary adventure, one of the most exciting enterprises for a young person. Through the examples shown in this calendar we hope also to communicate to everybody the passion for science, in particular to the young generations.





Editorial by Lorena Ballesteros Ferraz, Sébastien R. Mouchet, Riccardo Muolo

Physicists have always relied on models to better understand reality. From Newton's theory of gravity and Maxwell's equations to Einstein's relativity, models provide a descriptions of certain phenomena. Without models, there would not be any physics. What we often forget is that physicists themselves are models for younger generations. We learn about their stories, empathize with what they have lived through, and are inspired by their works and their teachings. We know that models have to reflect and describe as much as possible reality. However, the models of physicists, and scientists in general, that we learn at school only reflect a part of reality, due to the phenomenon of epistemicide. This consists in canceling from history all contributions of minority and underrepresented groups, such as women or non-Western researchers. The Matilda effect, for example, coined by historian Margaret Rossiter, describes how women's contributions to science have been wrongly attributed to men.

The lack of representation of women scientists in science classes is one of the factors keeping girls away from scientific degrees. It is, of course, not the only one and more measures are needed to address the issue. The publication of this calendar featuring women in physics by the European Physical Society is a significant step in the direction of equality and diversity.

Developing reliable models can be time-consuming, as evidenced by the ongoing quest for a unifying model that merges quantum physics and general relativity. By providing materials that can be used in classrooms, EPS is offering valuable inspiration to women and girls seeking to pursue careers in physics. It is crucial to have a diverse range of models available, from oil viscosity to the expansion of the universe. This extends to the need for a diverse representation of women models in physics. We need to showcase the contributions of women in physics, regardless of their cultural background, from Nobel Prize winners to early career researchers, who, despite the prejudices of society, keep pushing the limits to achieve their dreams.

Editorial by Gina Gunaratnam

In the recent years, women have become more visible in fields where they are a minority. However, there is still a lack of women in STEM (science, technology, engineering, and mathematics). So, there is a big need to attract more youngsters in these fields. Not only to work as researchers but also as technical staff, lab assistants, IT specialists, to name but a few. The panel of professions related to sciences is wide and requires all talents, girls as much as boys.

The aim of this calendar is to present role models of female physicists. Society does not always send the message: Girls need to be encouraged in their choice of studying science by everyone at every stage of their education: families, teachers, media and the governments. When they show interest in sciences, girls should not be diverted from their objectives, but helped and stimulated in every possible way to facilitate their aspirations. ■

Describing growing tissues in the language of thermodynamics

– DOI: 10.1051/epn/2024302

New analysis shows how key properties of biological tissues can be accurately described in the mathematical language of Onsager's variational principle, widely used to describe continually changing systems in thermodynamics.

A key feature of biological tissues is their inhomogeneity and their ability to grow via cell reproduction. To study this behaviour, it is important to describe it using equations, which account for factors including growth rates, chemical signalling, and tissue structure.

In doing this, researchers aim to develop consistent continuous descriptions of these deeply complex systems: accurately predicting properties such as cell reproduction rates, disorder, and how their growth varies in different space directions, depending on their interactions.

Through new analysis published in EPJ Plus, Joseph Ackermann and Martine Ben Amar at Sorbonne University Paris, show that tissue development can be reliably captured within 'Onsager's variational principle': a mathematical framework used widely in thermodynamics.

Their approach could lead to a deeper understanding of tissue properties across a wide array of scenarios: from essential processes such as embryo development, to harmful ones such as tumour growth.

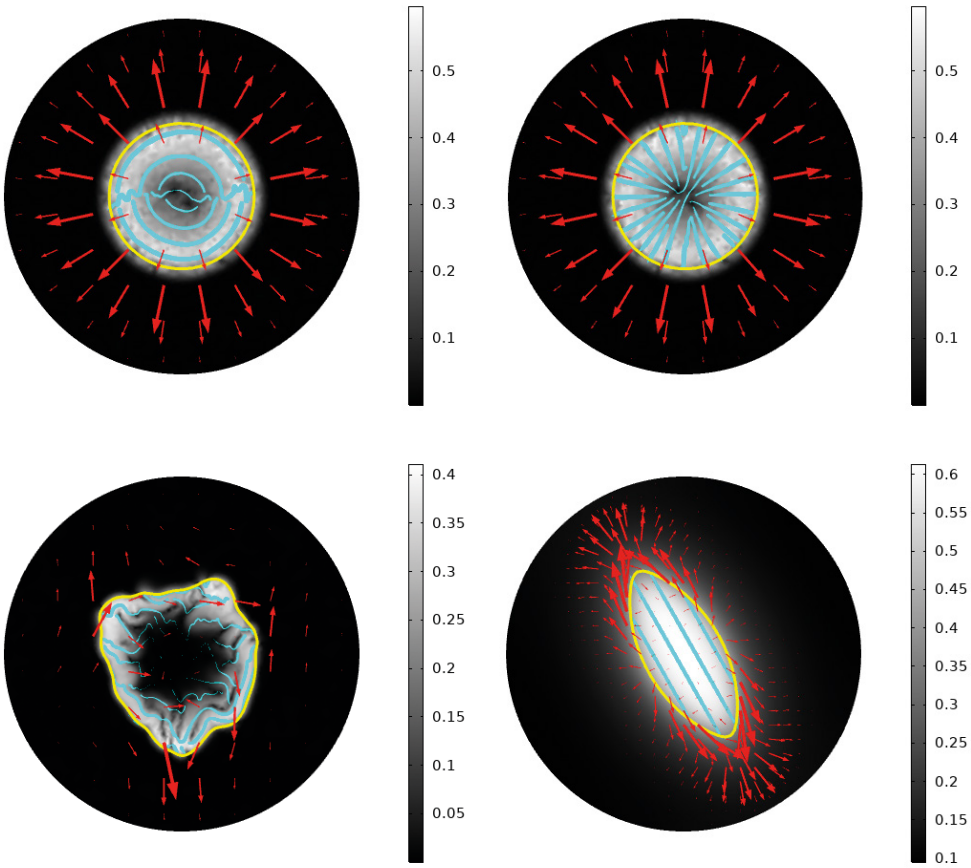
In thermodynamics, Onsager's variational principle describes how systems tend towards a state of minimum dissipation as they are continually altered by their own transformations and their environment. Mathematically, the principle expresses these systems as groups of interconnected equations, each describing the rates of change of certain quantities describing them.

Starting from Onsager's variational principle, new 'momentum' and growth equations are derived, which could better describe the flow of mass and the proliferation, as well as the orientations of cells in biological tissues. Their equations considered the growth and death rates of cells, as well as the chemical reactions driving their activity. This approach could also illustrate the genesis of patterns in growing organs.

Altogether, the duo's work definitively shows how Onsager's variational principle can be a valuable tool for exploring different theoretical scenarios in growing tissues, and how their growth depends on interactions between different cellular-scale properties. ■

Reference

[1] J. Ackerman and M. Ben Amar, *Eur. Phys. J. Plus* **138**, 1103 (2023). https://doi.org/10.1140/epjp/s13360-023-04669-9



▼ Nematic properties determine the structure and the shape of the aggregate.

Colloidal active matter

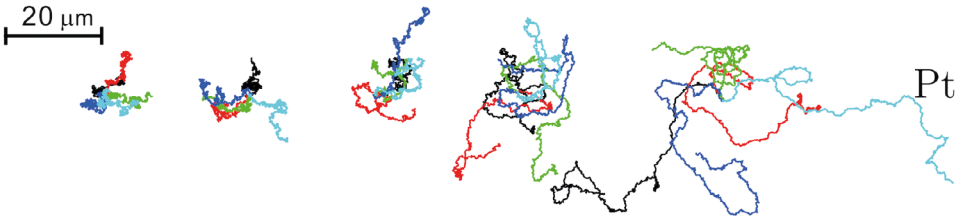
– DOI: 10.1051/epn/2024303

In the last two decades, significant research progress has been made in artificially equipping colloidal particles with their own drive ("motor"). They are then called active particles. In this case, a single active colloid typically moves much faster and more dynamically than a passive one, which follows purely diffusive Brownian motion. Typical particle trajectories are shown in Figure 1.

On average, a self-propelled particle moves ballistically at a constant speed. An active particle thus constantly converts energy into mechanical motion and is damped by the solvent. These irreversible processes permanently generate entropy, the hallmark of non-equilibrium. Only on large time scales does the movement become diffusive again, but with a much larger diffusion coefficient. The motion of an active colloid is also called a persistent random walk, analogous to a walker who remembers his previous direction of movement and mainly continues in the same direction, and its dynamic behaviour is also referred to as active Brownian motion.

Whenever such self-propelled particles with an internal degree of freedom are involved, the resulting system is generally referred to as active matter. This term is also used for macroscopic objects such as robots, while the term colloidal active matter is used for mesoscopic particles including living systems such as microbes, bacteria, sperm, *etc.*

At this point we can give a few examples of artificially imprinted self-propulsion. Firstly, a particle can move by periodically moving limbs. A human swimmer does this by swinging his arms and legs. He also utilises inertia, but on the micrometre scale this becomes increasingly difficult. There is a scallop theorem, which states that in viscous fluids one can only move forwards if one uses a movement pattern that cannot be mirrored in time. This is why many bacteria rotate a flagellar helix, because the sense of rotation makes the movement irreversible in time. Recently, however, there have also been many other mechanisms that manage without mechanical movement. One important mechanism is that the particle itself generates a gradient of some physical variable (temperature, concentration of an additive, *etc.*) and then moves by itself within this gradient. This phenomenon is also known as self-phoresis.



▲ Typical trajectories of self-propelled colloids in two spatial dimensions for increasing activities (from left to right). © https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.048102

An important example of self-phoresis is a solvent enriched with hydrogen peroxide. Hydrogen peroxide decomposes into water and oxygen. If you use a colloidal "Janus particle" with two different substances (such as a plastic particle with a metal cap), the decomposition reaction is catalysed by the metal. This creates a gradient of hydrogen peroxide concentration in which the particle itself moves. Besides this diffusiophoresis also thermo- or electrophoresis are utilised. The activity can also be generated by external fields: a key example of this are so-called Quincke rollers: non-conducting particles that start to rotate under the influence of an oscillating electric field, in random directions perpendicular to the field. In large ensembles, such rotating microspheres can form an ordered stream of particles due to collisions and hydrodynamic interactions. Also magnetic fields can also be used to set (anisotropic) particles in motion in random directions.

In all the systems mentioned, the activity already drives the individual constituents out of equilibrium, as can be seen from the non-time-reversible movements - and thus detailed balance ubiquitous in passive systems is violated. Further fascinating properties emerge when large ensembles of interacting active particles are considered. Characteristics of the collective behaviour of such active many-particle systems are manifold and range from motility-induced phase separation, to polar flocking and active turbulence.

The EPL Focus Issue on Statistical Physics of Self-Propelled Colloids published in October 2023 summarizes current research on various aspects of single and collective dynamics of self-propelled colloidal particles. ■

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[1] Hartmut Löwen, Sabine Klapp and Holger Stark, *EPL 144* 17001 (2023), https://iopscience.iop.org/article/10.1209/0295-5075/acfbae

[2] EPL Focus Issue on Statistical Physics of Self-Propelled Colloids, https://iopscience.iop.org/collections/epl-230203-116

Active matter: the beginning of a rich history, a promising future

by Olivier Dauchot
Gulliver Lab, ESPCI Paris-PSL, 10 rue Vauquelin, 75005 Paris – DOI: 10.1051/epn/2024304

Active matter is a rather recent field of research at the interface between physics, chemistry, life science and engineering. It deals with a class of non-equilibrium many-body systems whose elementary units convert a local energy source into work, for example in the form of directed motion. Living matter is active in essence, whether it's a large group of animals, a colony of bacteria or a tissue of cells. But active matter also includes artificial systems, whether in the form of chemically propelled colloidal suspensions, swimming droplets, vibrated grains, or assemblies of robots. Active matter is the seat of rich collective phenomena, which on large scale translate into new forms of dynamical phase transitions.

The last 30 years have seen an influx of experimental observations and theoretical advances in the description of such phenomena in active liquids. The emergence of collective motion in large groups of animals - flights of starlings, shoals of fish - is the most spectacular manifestation of this and launched the field in the mid 1990s. The paper by Alexandre Solon, presented here, gives a nice overview of the fantastic progress that has been made in the understanding of such collective motions. It also illustrates how these systems challenge our intuition and provide us with unexpected surprises…

Such unexpected behaviors also hold in the simplest form of active matter, that is made of purely repulsive active particles subjected to thermal noise. For instance, pressure is generically not a state variable, and instead depends on the potential defining the wall on which it is exerted. Also, a liquid gas separation takes place, the so-called Motility Induced Phase separation, although the interactions are purely repulsive. In his paper, Heiko Rieger demonstrates how a fluid of such active particles confined in a container exhibit out of equilibrium steady currents, responsible for the fluid climbing along the wall of the container, as in the presence of capillary forces.

More recently, a growing interest in the dense phases of active matter has raised the question of the behavior of active solids. As described in the paper by Olivier Dauchot, several original phenomena such as flowing crystals and synchronous oscillations have been observed, but their full understanding remains to be developed. Active solids will certainly play a central role in the development of metamaterials whose active elementary cell will allow local and autonomous actuation. Obvious applications concern robotics and, more generally, the design of functional materials, but also our tissue mechanics and bioengineering.

It has also recently been realized that an important consequence of activity is the possibility of non-reciprocal interactions, *i.e.*, how a given active entity feels about another active entity is not necessarily the same as how the latter feels about the former. As discussed in Ramin Golestanian's paper, colloidal particles and enzymes exhibit such non-reciprocal interactions when they are catalytically active, leading to a wealth of self-assembly scenarios and new exotic phases of active matter.

Fundamentally, active matter is the place where symmetries and conservation laws, such as time-reversal invariance, Galilean invariance, conservation of momentum, action-reaction principle, that characterize conventional physics, are easily broken or violated. An important next step is to formulate a model-independent statistical physics of such systems. As discussed in the paper by Etienne Fodor, the development of general thermodynamics, *i.e.* the elaboration of the relations between information, work and heat in active systems, is definitely necessary to control active systems, to formulate design rules for active machines, or to develop a predictive theory for biological organizations and functions.

In addition to these important theoretical developments, there are also promising experimental avenues. The increasing mastery of the elementary components of living matter, from DNA, enzymes and proteins to cells, together with the mechanical miniaturization, lead us to anticipate a hybridization between artificial active matter and living active matter, towards a bionic, active and programmable matter with unprecedented possibilities.

More generally, the study of active matter has shed new, transdisciplinary light on all fields where the question of collective dynamics, unconstrained by the laws of thermodynamic equilibrium, arises. This is, of course, the case in animal dynamics, but also in population dynamics, swarm robotics, cognitive and social dynamics, *etc.* The implications for these disciplines are certainly numerous but difficult to predict. ■

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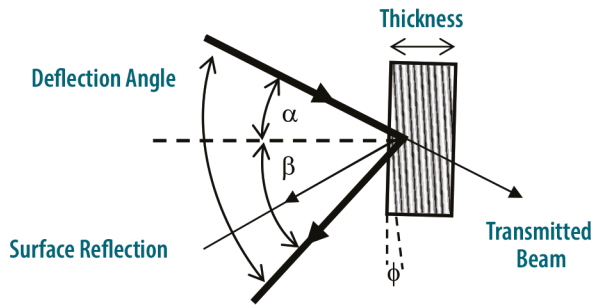

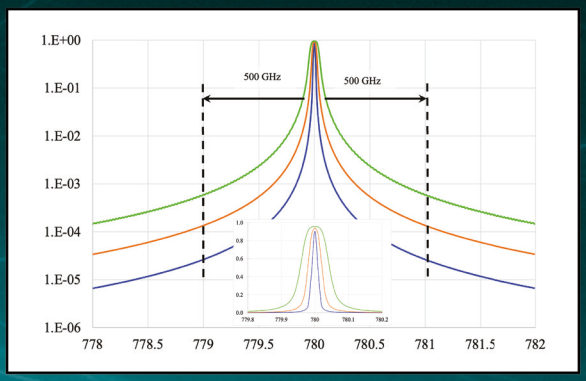

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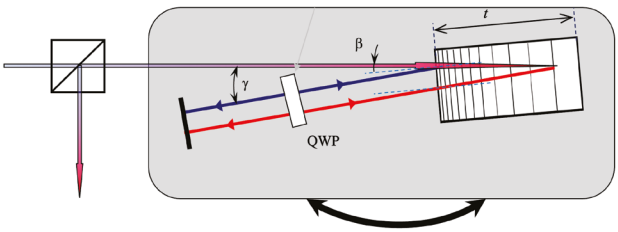
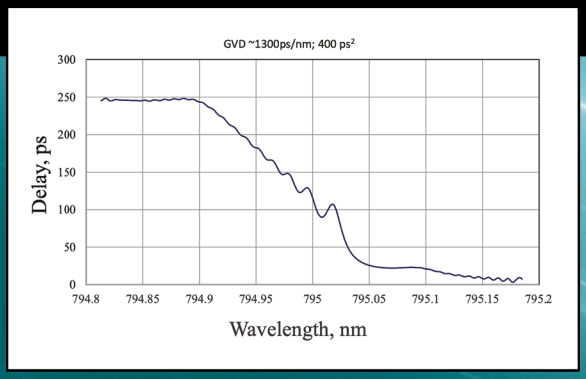


Schematic Diagram of CBG deployment for Qubit Filtering and Control

Group delay dispersion of Chirped Bragg grating (CBG)



PTR glass based highly dispersive CBGs enabled passively stable, efficient, method of fast amplitude modulation compatible for high power laser sources. *[H. Levine at al. "Dispersive optical systems for scalable Raman driving of hyperfine Qubits," Phys. Rev. A 105, 032618 (2022)]*

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NON-RECIPROCAL ACTIVE-MATTER: A TALE OF "LOVING HATE, BRAWLING LOVE" ACROSS THE SCALES

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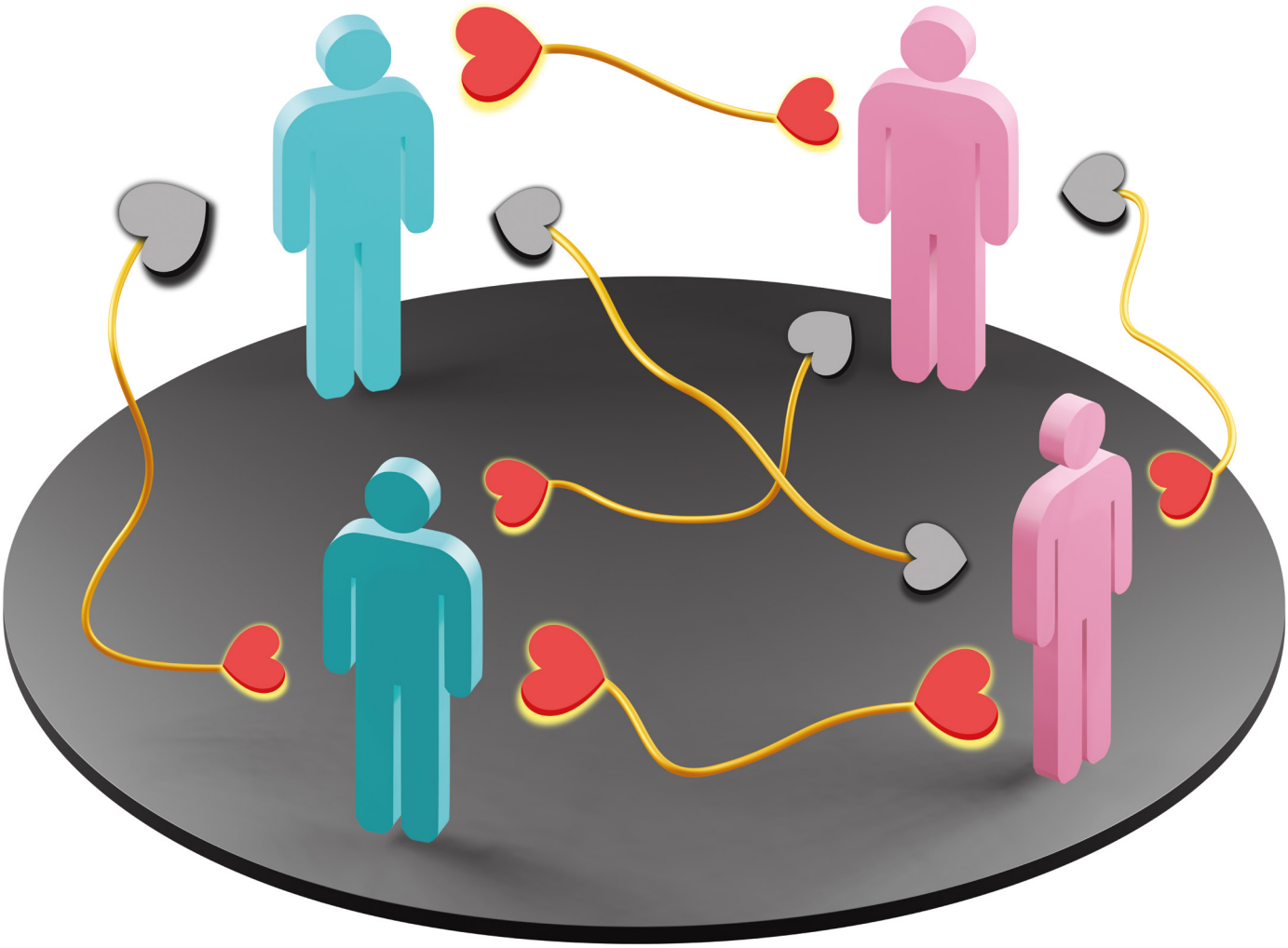


The observation that the interactions between catalytically active microscopic units generically break action-reaction symmetry leads to the discovery of a wealth of self-organization scenarios and exotic phases of active matter. Bridging the scales from individual molecules to macroscopic systems allows us to uncover the general principles governing these emergent properties.

Non-reciprocal interaction

Interactions between humans are in general non-reciprocal, meaning that how person-A feels about person-B is not necessarily the same as how person-B feels about person-A. This leads to potential complexities and frustrations in the collective interactions between many humans (Fig. 1). For humans and other higher organisms, the interactions are determined via decisions based on processing of a spectrum of independent and often conflicting sensory signals, naturally leading to non-reciprocity. It is remarkable, however, that colloidal particles and enzymes exhibit non-reciprocal interactions when they are catalytically active, without the need for the abovementioned sophisticated machinery [1].

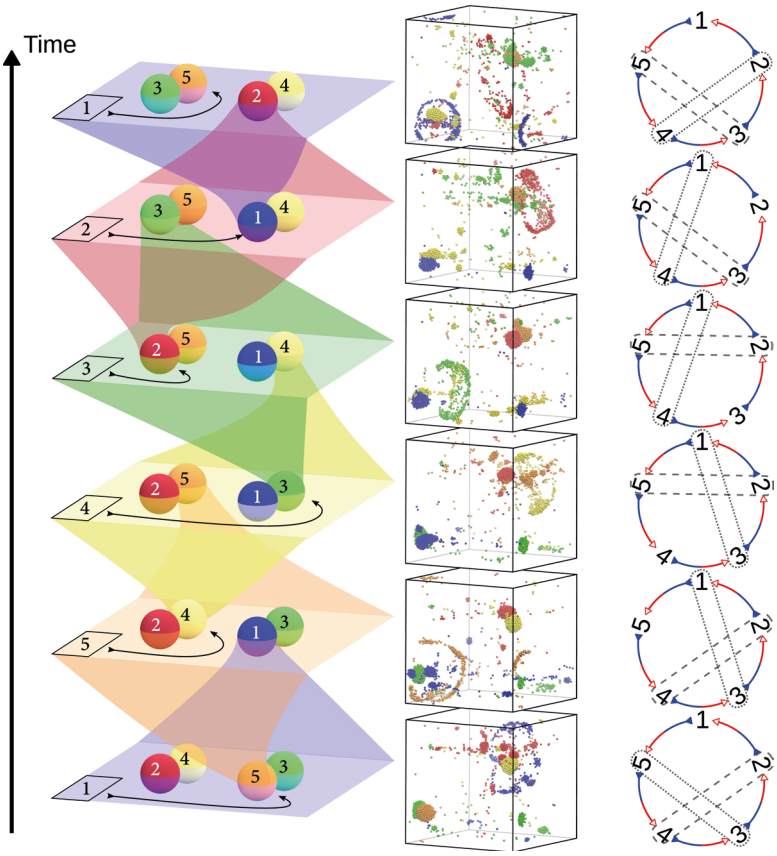
The mechanism behind such non-reciprocal interactions, which have been demonstrated experimentally [2,3], is quite generic: it stems from interfacial phoretic transport processes that amount to a response of every enzyme or active colloid to the gradients of chemicals created by others. In a regime where the chemicals diffuse faster than the enzymes or active colloids, one can invoke a separation of time-scale and consider quasi-stationary chemical concentration profiles, which will be mathematically analogous to gravitational or Coulomb potentials, as solutions to the Poisson equation. The non-reciprocity then originates from the remarkable feature that the mass- or charge-analogue that produces the field for every enzyme or active colloid is generically different from the mass- or charge-analogue that responds the field (generated by others); a characteristic not afforded by classical Newtonian gravity or electromagnetism.

This observation suggests that living systems can be regarded as non-reciprocal active mixtures, which should be classified as active matter [4]; for example, the cytosol of a metabolically active cell comprises a dense mixture of different enzymes whose very metabolic activities constantly generate gradients that they collectively respond to in a non-reciprocal way, including interactions between active and passive components [5], such as (non-catalytic) proteins. It is then plausible to postulate that within the spatiotemporally complex hierarchy of patterns and structures we observe in living systems – all forbidden by equilibrium physics – some may arise from the physics of such non-reciprocal active mixtures. Going to back to the analogy with human relations, to resolve the consequences of such complexities we may have to resort to using oxymoronic descriptions of the type best encapsulated in the words of Romeo (Citation).

Emergent behaviour due to non-reciprocity

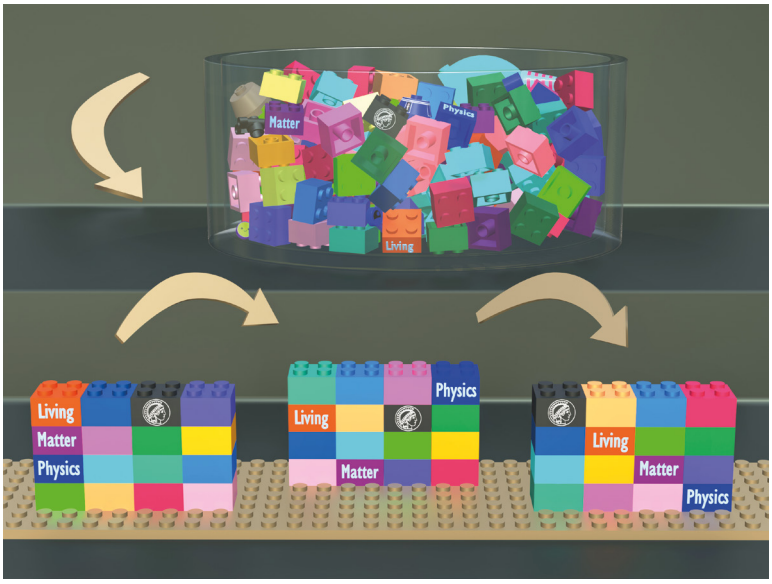
Non-reciprocal interactions can lead to a plethora of novel emergent features. The simplest one is the emergence of polarity in the form of self-organized ● ● ●

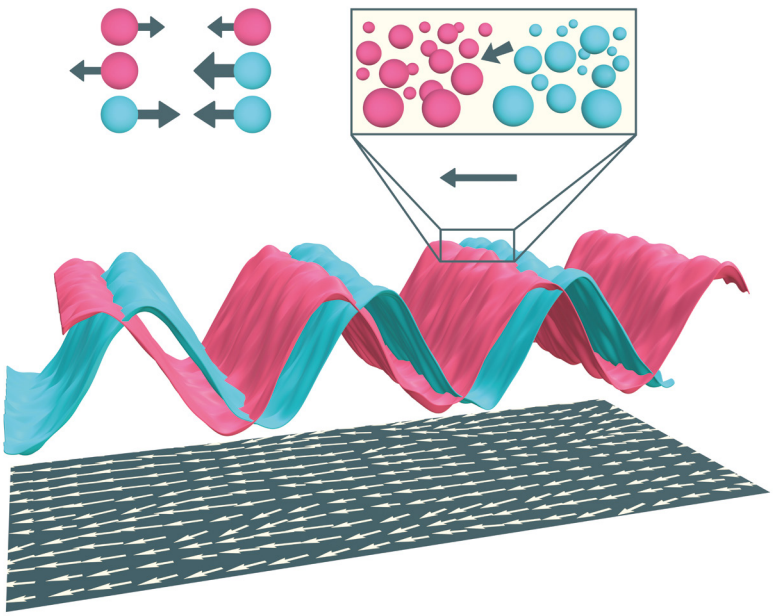
◂ **FIG. 1:** *"O loving hate"*. Non-reciprocal interactions arise naturally between humans, and they lead to complex collective effects. © MPI-DS / Novak & Golestanian



▲ **FIG. 2:** *"O brawling love"*. A collection of a number of enzymes with chasing interactions can lead to spontaneous formation of a swarm with a cyclic pattern of collapse and explosion [7]. (left) Schematic representation of the dynamics, (middle) snapshots of Brownian dynamics simulations, and (right) diagrammatic representation of the non-reciprocal interactions, with the dashed and dotted lines representing respectively the pairs on the left and right of the schematic picture. © MPI-DS / Novak, Ouazan-Reboul, Agudo-Canalejo & Golestanian.

▾ **FIG. 3:** *"O heavy lightness, serious vanity"*. A set of building blocks with non-reciprocal interactions can spontaneously rearrange to form new structures with pre-specified configurations in a programmable and choreographed manner [8]. © MPI-DS / Novak, Osat & Golestanian





▲ FIG. 4: *"O anything of nothing first created"*. Particles of two types (magenta and cyan) interact with themselves reciprocally, and with each other non-reciprocally. The inter-species attraction can give rise to phase separation of every species into coexisting dense and dilute domains and the non-reciprocal interaction will make them form bands that chase each other, leading to the emergence of global polar order and motion in the system while breaking both parity and time-reversal (PT) symmetries [6,9]. © MPI-DS / Novak, Saha, Agudo-Canalejo, Pisegna & Golestanian

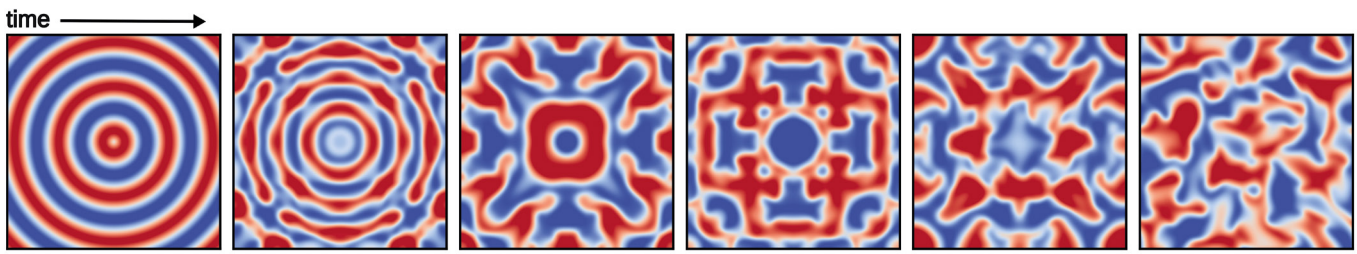
"Here's much to do with hate, but more with love.
Why, then, O brawling love, O loving hate,
O anything of nothing first created,
O heavy lightness, serious vanity,
Misshapen chaos of well-seeming forms,
Feather of lead, bright smoke, cold fire, sick health,
Still-waking sleep that is not what it is.
This love feel I, that feel no love in this."

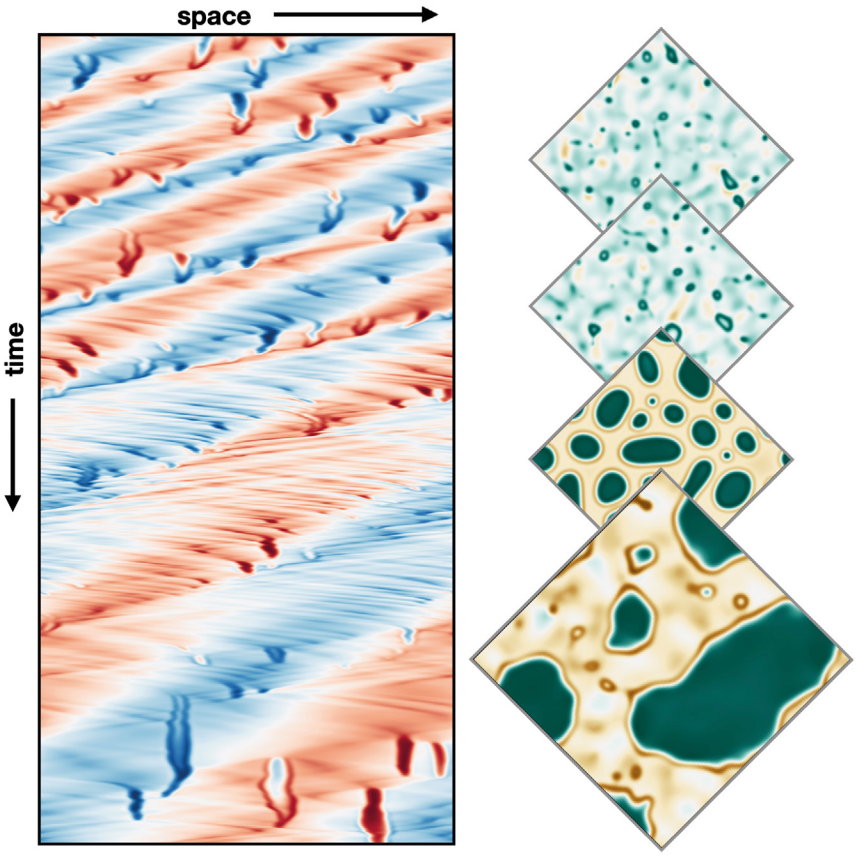
From Romeo and Juliet by William Shakespeare (Act 1, Scene 1)

• • • self-propelled active molecules in a binary mixture composed of non-polar particles with chasing interaction [1]. This is a rather exotic behaviour, as the formation of a composite particle introduces a higher-level symmetry such as polarity, which is unlike more common appearances of composite particles in condensed matter physics – *e.g.*, Cooper-pair, exciton, spin-charge fractionation, etc – that often tend to neutralize characteristics such as polarity or spin [6]. Chasing interactions among more than two species can introduce much more complex behaviour, such as periodic clustering and explosion (Fig. 2) in a system of enzymes that are connected to each other in a cyclic manner in the chemical configuration space (*i.e.* the product of the reaction catalysed by one enzyme is the reactant for the reaction catalysed by the next enzyme and so forth) [7]. This system exhibits behaviour resembling a game of musical chairs involving an odd-even parity effect (Fig. 2), and can help us understand how primitive metabolic cycles may have self-organized at the origin of life [7]. Another feature that can emerge from non-reciprocal interactions is the ability to engineer multifarious self-organization (Fig. 3) in suspensions made of building blocks that can self-assemble into prescribed shapes, and then undergo transitions between these shapes [8]. The shape shifting property of the self-assembled molecular complexes that originates from non-reciprocal interactions allows a system to make use of the same building blocks at different time points to build different structures, mimicking what is commonly performed during the cell-cycle, and resembling the sci-fi dream realized in the terminator movie.

Non-reciprocal active matter can exhibit exotic phases and patterns at the largest scales. Emergence of traveling bands (Fig. 4), which accompanies parity and time-reversal (together with space- and time-translation) symmetry breaking [9,10], is a consequence of the emergent polar symmetry discussed above at the particle level [6]. A variety of complex spatiotemporal patterns, including active turbulence in the viscous regime [11], as well as novel phase transitions, such as spontaneous chiral symmetry breaking [12], can arise from non-reciprocal interactions. The dynamics at the large scale inevitably leads to the emergence of a variety of defects, which may or may not be stable overtime; see *e.g.* Fig. 5 for

▼ FIG. 5: *"Misshapen chaos of well-seeming forms"*. Pattern formation in systems with non-reciprocal interactions [13]. With time, a computer simulation of an unstable target defect that radiates travelling waves (panel 1) evolves through a multitude of four-fold symmetrical patterns (panels 2-4). At later times, this symmetry is lost (panel 5) and a pattern-less chaotic state emerges (panel 6). © MPI-DS / Rana & Golestanian





▸ **FIG. 6:** *"Feather of lead, bright smoke, cold fire, sick health, Still-waking sleep that is not what it is".* Effervescence in a non-reciprocal active mixture with two species associated with imperfect PT symmetry breaking [14]. (left) Nonlinear non-reciprocal interactions lead to a novel form of spatiotemporal chaos where droplets are nucleated at random locations and disappear after existing for a variable amount of time as seen in the kymograph showing the evolution of one of the species. (right) By changing the average density in the system, one observes a relatively long effervescent regime that suddenly gives way to pulsating droplets that coarsen overtime. © MPI-DS / Saha & Golestanian.

the evolution of a defect — via symmetric intermediary forms — to a state with spatiotemporal chaos reminiscent of the so-called chemical turbulence [13]. A rather exotic case arises when the chaotic state exhibits effervescence (bubbliness or fizziness), as seen Fig. 6, where droplets that restore PT symmetry emerge in the system in a dynamic steady-state [14]. Such a state can be tuned to stay in such a state for a long time, before suddenly transitioning to a state where pulsating domains coarsen towards macroscopic phase separation (Fig. 6).

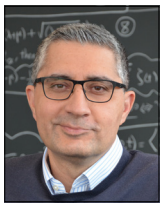
Outlook

Studies of non-reciprocal active matter have served to illustrate and enrich the wealth of new collective properties that can emerge in the intrinsically non-equilibrium living matter systems, while at the same time providing guidelines for future designs of life-like controllable micro-robotic systems with desired emergent functionalities. With this in mind, we can conclude by reminding ourselves of the following very important question: "does new physics lurk inside living matter?" [15]. As the novel non-equilibrium physics of non-reciprocal active matter exemplifies, we can answer this question with an emphatic ay! ■

Acknowledgements

The author wishes to acknowledge his past and present group members and collaborators, and in particular, Jaime Agudo-Canalejo, Viktoryia Novak, Saeed Osat, Vincent Ouazan-Reboul, Giulia Pisegna, Navdeep Rana, and Suropriya Saha, for help in preparing the figures in this contribution.

About the Author



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CAPILLARY ACTION AND STATIONARY CURRENTS IN SCALAR ACTIVE MATTER

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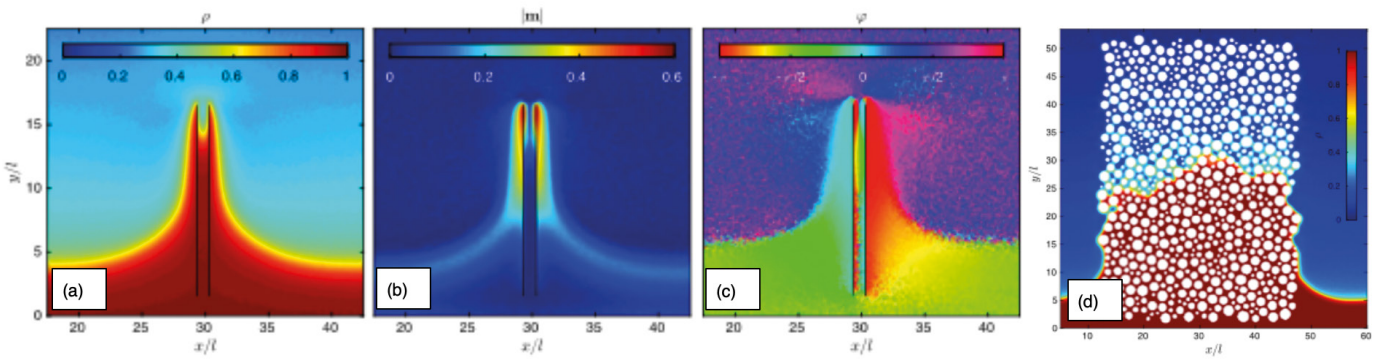
Active matter consists of particles (motile microorganism or active colloids) that consume nutrients or fuel and convert it into a persistent motion, has received a lot of attention due to its intrinsic out-of-equilibrium character on the microscale [1]. The simplest representatives of active matter are spherically symmetric, active Brownian particles (ABPs) [2] without alignment, however, with excluded volume interactions [3,4].

Further representatives of the same class, also called scalar active matter, are, for example, run-and-tumble particles and the active lattice gas. Such systems, although far from equilibrium, are in some sense reminiscent of a passive fluid with attractive interactions, since ABPs slow down during collisions and effectively attract each other. As a result, ABPs undergo a motility-induced phase separation (MIPS) into a coexisting dense and dilute phase [5], accumulate at walls [6], and in corners. Moreover, for a wide class of active systems, *e.g.* non-spherical ABPs, the pressure depends on the precise interactions between the active particles and the confining walls [7].

The investigation of capillary action, the ability of liquids to rise in thin tubes against gravity, has a long history and goes back to Leonardo da Vinci. Its origin is attractive interactions between the liquid molecules and the container walls and the attraction of the liquid molecules among each other causing surface tension. The height of the liquid column in the tube is governed by the balance between the gain in surface energy and the cost in gravitational energy. The classical picture seems to prohibit the appearance of capillarity in systems with purely repulsive interactions, but recently it was predicted that scalar active matter in a gravitational field will rise along vertical walls and inside capillaries [8]. Fig. 1a-c shows the stationary state of an active lattice gas model with repulsive particle-particle and particle-wall interactions, in a gravitational field in the presence of a thin pipe displaying a strongly elevated meniscus, whose height increases with the activity of the system, more precisely algebraically with the Péclet number. Fig. 1d shows how the same model predicts spontaneous imbibition in a porous medium.

These results have been confirmed for conventional sedimenting ABPs active Brownian particles (ABPs) in [9], where also the mechanism leading to the formation of a meniscus rising above the bulk of the sedimentation region has been elucidated. It turned out that the formation of the meniscus is determined by a stationary circular particle current, a vortex, centered at the base of the meniscus, c.f. Fig. 2a-b, whose size and strength ● ● ●



▼ **FIG. 1: (a–c)** Capillary rise of an active lattice gas with capillary width δx/l=1 and capillary height δy/l=12.5. (a) Mean total density ρ(x,y). (b) Absolute value of the mean normalized polarization field. (c) Phase ϕ(x,y). ϕ=0 corresponds to a right-polarization, π/2 to up, - π/2 to down and +/-π to left. **(d)** Spontaneous imbibition of a porous medium, density plot. The white disks are regions of excluded volume representing the porous medium, the spaces in between represent the pores. From [8].

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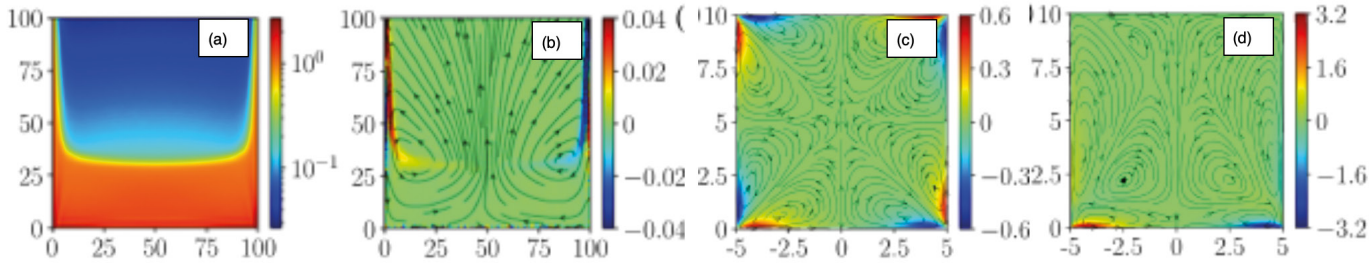
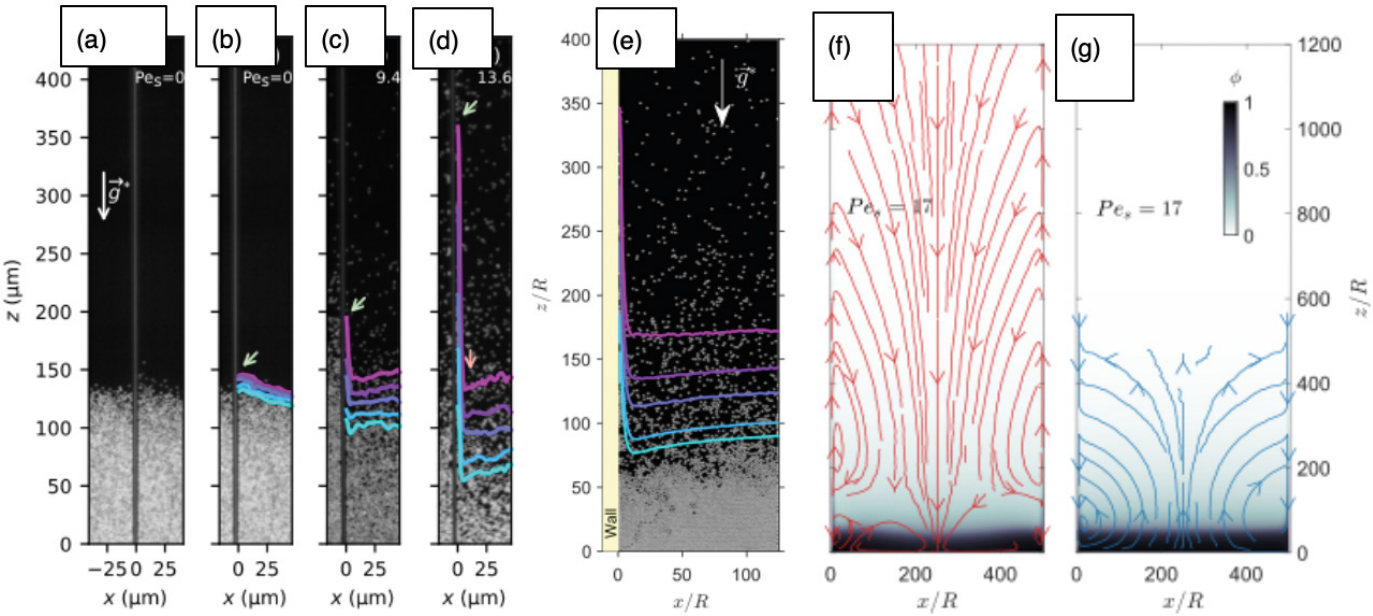


▲ **FIG. 2: (a-b)** ABPs in a gravitational field with repulsive walls, (a) density profile, (b) flux lines of particle current J(r) together with modulus of the curl of J(r) (color code). **(c-d)** Flux lines of particle current for ideal ABPs in a box, (c) without gravitation, (d) with gravitation. From [9].

• • • increase with the ABP activity. The origin of these vortices can be traced back to the confinement of the ABPs in a box: already the stationary state of ideal (non-interacting) ABPs without gravitation displays circular currents that arrange in a highly symmetric way in the eight octants of the box, see Fig. 2c. Gravitation distorts this vortex configuration downward, leaving two major vortices at the two side walls, with a strong downward flow along the walls, see Fig. 2d. Repulsive interactions between the ABPs change this situation only as soon as motility induced phase separation (MIPS) sets in and forms a dense, sedimented liquid region at the bottom, which pushes the center of the vortex upwards towards the liquid-gas interface. Self-propelled particles therefore represent an impressive realization of scalar active matter that forms stationary particle currents - reminiscent of emergent probability fluxes in confined microbial navigation [10] - being able to perform visible work against gravity or any other external field. Somewhat counterintuitively the circular current at the left wall rotates counter-clockwise (and the one at the right wall clockwise), see. Fig. 2b and d, such that particles are not actively pushed upwards along the wall, but instead slide downwards under the influence of gravity. In some distance from the wall, towards the center of the box, the activity elevates the particles again from the sedimented layer into the gas region, where they are then again driven towards wall.

These theoretical predictions [8,9] should be experimentally observable experimentally in active colloids under gravitation. They constitute a class of materials composed of colloidal-scale particles locally converting chemical energy into motility, mimicking micro-organisms. Several new phases of active matter have been observed experimentally in synthetic self-propelled colloids, reminiscent of the aforementioned phenomenology of ensembles of ABPs. An experimental setup that is relevant for the above model predictions is the gravitational sedimentation of gold-platinum Janus colloids immersed in a hydrogen-peroxide bath, which are self-propelled by phoretic effects [11]. Using this

▼ **FIG. 3:** Active Janus colloids climb a wall. **(a)** Experimental set-up: glass wall dipped into a sedimented monolayer of passive colloidal particles at Peclet number Pe=0 under a gravity g. **(b-d)** Iso-density maps of the colloids at Pe=0 (passive case) and for two activities Pe = 9.4 and Pes= 13.6. The iso-density values ϕ are from top to bottom 0.08, 0.12, 0.16, 0.24, and 0.3. The pale green arrow highlights the maximum height of the iso-density curve ϕ = 0.08 at the adsorption layer. The pale red arrow indicates the small depression of the density close to the wall. **(e)** Snapshot of a numerical simulation of an assembly of ABPs under gravity near a wall with alignment Γ ~ = 26 and adhesion strength ~ε = 3:25, respectively, at an activity Pe = 13. F) Numerical streamlines of a velocity field v = J/ρ together with the packing fraction φ for a simultaneously attracting and aligning wall **(f)** and for a neutral wall **(g)**. From [11].



experimental setup, it was demonstrated that active colloids show active capillary rise, see Fig. 3. A dynamic absorption layer at the wall was observed, which roses with increasing activity, c.f. Fig. 3a-d. Due to the absence of MIPS the wetting layer is much thinner and the particle fluxes are reversed, which could be explained by the following additional wall-particle interaction: Fig. 3f shows the flux lines resulting from a simulation for an ABP system in the gaseous phase in a gravitational field and with wall alignment and -adhesion, and Fig. 3g the same system for a neutral wall. Thus, active colloids can actually climb up a wall. Gravity is essential to generate a polarization in the bulk, that is then enhanced by wall-alignment. This polarization, together with activity-dependent wall-adhesion, is most likely responsible for the persistent vertical pumping observed in the system.

These results demonstrate that a vertical wall effectively harvests energy from the microscopic scale to produce a macroscopic work. More generally, a side wall can act as a pump against a force parallel to it, generating a net steady-state flux in the system. These results pave the way for active microfluidic systems, where even a basic config- uration involving walls and gravity could play a role analogous to a generator in an electric circuit. ■

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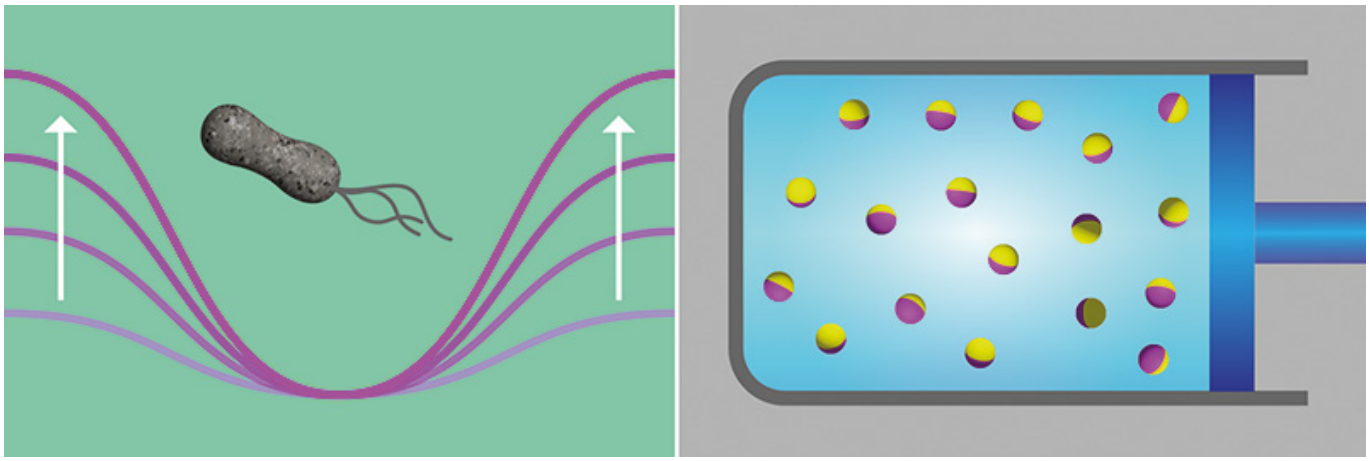

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CONTROLLING ACTIVE MATTER: THE NEED FOR THERMODYNAMIC CONSISTENCY

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An outstanding challenge is to provide a comprehensive framework predicting how to control the collective states of active systems, and how to optimally switch between such states. This agenda requires extending the tools of equilibrium thermodynamics to properly capture and account for the nonequilibrium properties of active matter.

From empirical to optimal control

Active matter encompasses a large class of nonequilibrium systems where individual components convert some energy resources, naturally present in their environment, into mechanical work to produce a sustained dynamics. Such systems can be either biological (*e.g.*, bacterial swarms) or synthetic (*e.g.*, catalytic colloids in a fuel bath). The studies of active matter therefore lie at the interface between Physics, Chemistry and Biology, with many potential applications in material design and biomedicine.

Experimental techniques have demonstrated the ability to alter the collective dynamics of active systems with various types of external perturbations. In many cases, one can simply shine light on the system to specifically trigger activity in space and time. This strategy has been successfully deployed in bacterial swarms [1], where locally modulating density allows one to select target profiles [Fig. 1], and in biomimetic materials of cytoskeletal filaments and molecular motors [2], where promoting and driving topological defects allows one to regulate internal flows [Fig. 1].

In many experiments, the spatiotemporal control of activity is often optimized using system-specific procedures. In general, optimizing the perturbation of active systems to stabilize target patterns has largely remained an empirical effort so far. Then, motivated by recent experimental progress, there is a dire need for a systematic roadmap guiding experiments towards optimal control: how to determine the protocol which most efficiently changes the properties of active systems.

Energetic perspective on control cost

Optimizing control first requires choosing an appropriate cost function. Some theoretical works have defined this cost by penalizing the deviation from target patterns. This approach has led to elegant results on how to best reverse the circulation flow of active nematics [3] (*i.e.*, model for biomimetic materials [2]), and how to best deform an active drop [4] (*i.e.*, model for a single cell). Despite the success of this approach, its implementation largely remains system-specific, so that it is generally challenging to delineate any generic property of the corresponding optimal protocols.

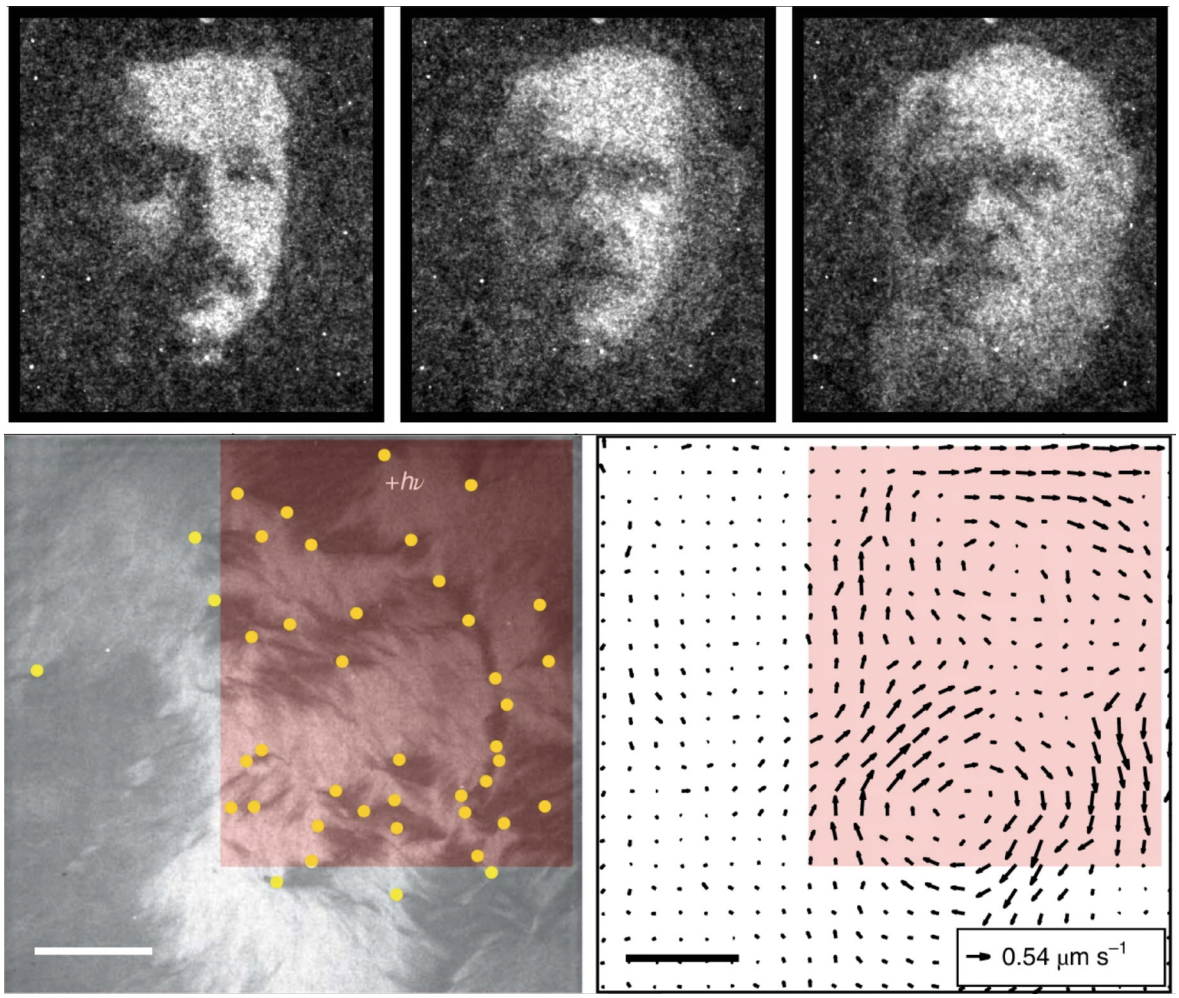
An alternative strategy for defining the control cost is to rely on energetic observables, such as work and heat, derived from generic thermodynamic principles. The work is the energy provided by the operator to enforce a given perturbation; it was actually considered as cost in [4]. The heat is the energy dissipated into the thermostat. In active systems where fluctuations cannot be neglected, one should build on stochastic thermodynamics to determine work and heat as stochastic observables: this was first developed in passive matter [5], and more recently extended to active matter [6].

Measuring work is usually straightforward, since it requires tracking only the degrees of freedom (DOF) of the external perturbation. In contrast, quantifying heat is more involved, since it needs tracking *all* the DOF dissipating energy. This task is generally challenging in active systems, since they include many DOF which are hardly accessible in experiments; typically, chemical DOF converting energy fuel into mechanical work. Remarkably, even from a theoretical perspective, many active models deliberately discard these underlying DOF, thus neglecting important contributions to the total dissipated heat.

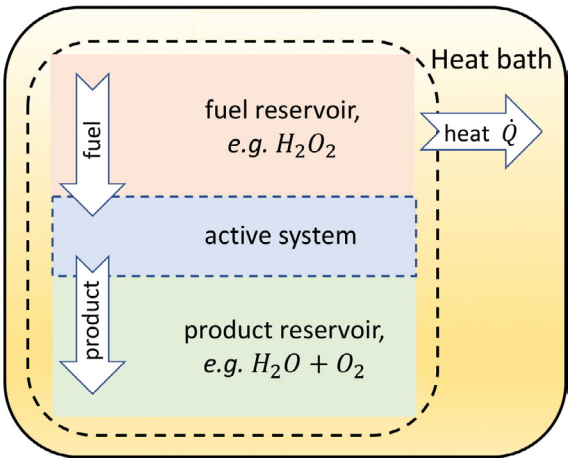
Thermodynamically consistent models

Most active models have been primarily designed to reproduce patterns, as observed experimentally, with only little care given to their energetic interpretation. Ongoing effort strives to build a novel generation of thermodynamically consistent (TC) models which provide an unambiguous quantification of heat by properly accounting for all sources of dissipation [7, 8, 9]. To this end, the main idea is to explicitly describe how the system couples with the external reservoirs fueling the activity of individual components [Fig. 2].

A remarkable by-product of TC models is that they are amenable to consistently evaluating heat at various levels of descriptions, from particles to fields. • • •



◂ **FIG. 1:** (Top) Controlling the local activity of bacterial swarms with external light allows one to switch density patterns: from Einstein's to Darwin's portrait, respectively in left and right panels; adapted from [1]. (Bottom) Illuminating a mixture of filaments and molecular motors (light shed only on red area) favors the formation of defects (yellow points) and enhances velocity flows (black arrows); scale bar 20 μm, adapted from [2].

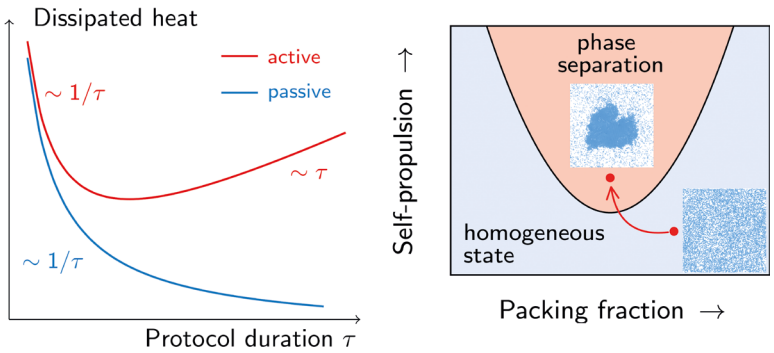


▲ **FIG. 2:** Schematics of an active system in contact with a thermostat (heat bath) and two chemostats (fuel and product); adapted from [8]. Fixing the chemical potential difference between fuel and product sustains chemical reactions in the active system, which in turn maintains its components out of equilibrium. TC models explicitly account for the dissipation stemming from these reactions.

Indeed, when models are formulated in terms of particles, the emerging collective states are often best analyzed at the hydrodynamic level. Yet, coarse-graining the dynamics typically involves some approximate closures which discard some fields, thus leading to underestimate the hydrodynamic heat. Recent methods have shown how to circumvent this issue with TC models [9, 10]: they allow one to directly evaluate heat from the field dynamics without any discrepancy with respect to its particle-based counterpart.

In practice, although TC models clearly provide the relevant platform to quantify and optimize heat, only a few of such models have been developed in active matter so far. The challenge is to reformulate existing active models, whose energetics is often ambiguous, to enforce a proper thermodynamic consistency while maintaining their rich phenomenology intact.

▼ **FIG. 3:** (Left) The RB approach predicts that the dissipated heat decays like the inverse of the protocol duration when controlling passive matter, whereas it has instead a non-monotonic behavior when controlling active matter. (Right) A typical protocol to switch the collective state of active particles consists in controlling their self-propulsion and packing fraction. For instance, it can lead to induce transitions between homogeneous and phase-separated states.



Optimal control from response theory

The main challenge in controlling active matter is to properly rationalize the interplay between (i) how activity shapes collective behaviors, and (ii) how the system relaxes as a response to perturbations. To this end, a useful strategy consists in considering as a reference the quasistatic protocol (QP), which slowly drives the system through steady states, and examining the effect of weak deviations. This response-based (RB) approach allows one to build the functional dependence of heat on the protocol by measuring some appropriate correlations in the unperturbed dynamics. The optimal protocol then follow from a standard minimization of the corresponding functional.

In passive systems, the QP always achieves the least dissipated heat, as expected from equilibrium thermodynamics; for a finite protocol duration, the optimal protocol follows the geodesics of some thermodynamic metrics [11]. In contrast, active systems dissipate energy at a constant rate even at rest (*i.e.*, in the absence of perturbation) to sustain their dynamics out of equilibrium, so that the QP is no longer optimal. Instead, the heat is now minimal for a finite protocol duration: it achieves the best trade-off between the dissipation stemming from internal activity (predominant for long duration) and that due to external perturbation (predominant for short duration) [Fig. 3]. The optimal protocol is no longer given by geodesics, but can still be deduced from a straightforward variational principle [12].

The main advantage of the RB approach is its versatility: it provides a systematic roadmap which can be deployed in a large variety of systems. In passive matter, it was shown useful both in experiments (*e.g.*, folding DNA hairpins [13]) and in theoretical models (*e.g.*, flipping the magnetization of spin systems [14]). In active matter, it was only used in minimal models so far, for a harmonically confined particle and for an assembly of repulsive particles [12]. Since many experiments have already shown how to accurately measure the response of active systems, the RB approach has the potential to foster future experimental studies on optimal control.

Remarkably, this framework can be straightforwardly adapted to other cost functions than heat and work. In practice, choosing any cost which is time-extensive in the unperturbed dynamics (*e.g.*, currents in active matter) will yield the same non-monotonic behavior as how heat varies with protocol duration. Importantly, despite being clearly versatile and easily adaptable, the RB approach remains inherently limited by assuming smooth protocols, which discards any abrupt change potentially yielding lower cost, and long protocol duration, which always drives the system slower than its typical relaxation.

Control of active phase transitions

The ability to optimally control active matter opens unprecedented perspectives for material design. Specifically, it offers the tools to craft systems which not only feature exotic phases, but which can now also optimally switch between such phases [Fig. 3]. In that respect, optimal control is the relevant framework to guide the design of active actuators which selectively change their properties according to specific perturbation. Efficiently switching actuators then requires predicting the optimal protocol driving active systems through phase transitions.

Using the RB approach for this agenda entails several challenges. Indeed, crossing phase boundaries typically involves exploring states with long relaxation times, which requires even longer protocol duration to ensure slow driving. Moreover, for discontinuous transitions with noise-activated events (*e.g.*, density nucleation in phase separation), the cost function usually no longer depends smoothly on control parameters, which conflicts with some assumptions of the RB framework. To overcome these difficulties, one could rely on spatially dependent control [14], for instance to reliably shape phase interfaces, and also gain further insights from some recent machine-learning methods [15]. ■

About the Author

Étienne Fodor is an ATTRACT Fellow (Fonds National de la Recherche, grant 14389168) at the University of Luxembourg. He was an Oppenheimer Research Fellow at the University of Cambridge, and obtained his PhD at Université Paris Diderot.

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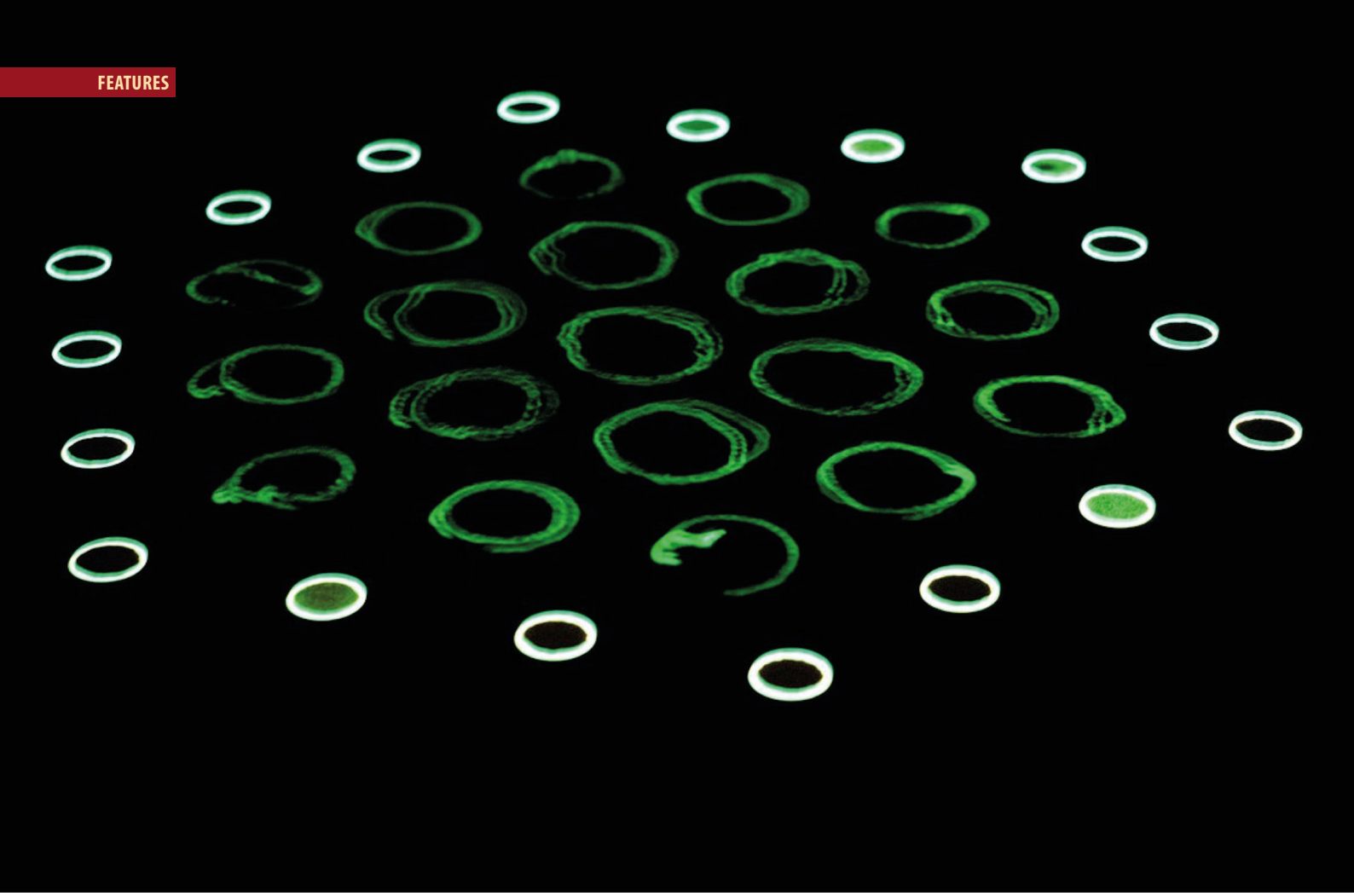

COLLECTIVE DYNAMICS IN ACTIVE SOLIDS

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

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

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

However, there are circumstances in which the analogy

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

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

Artificial Walkers

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

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

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

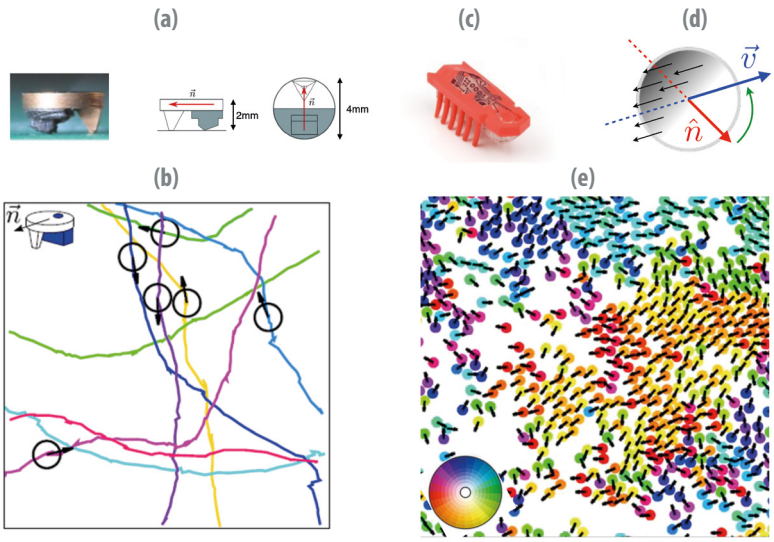
Permanent flow in Crystal

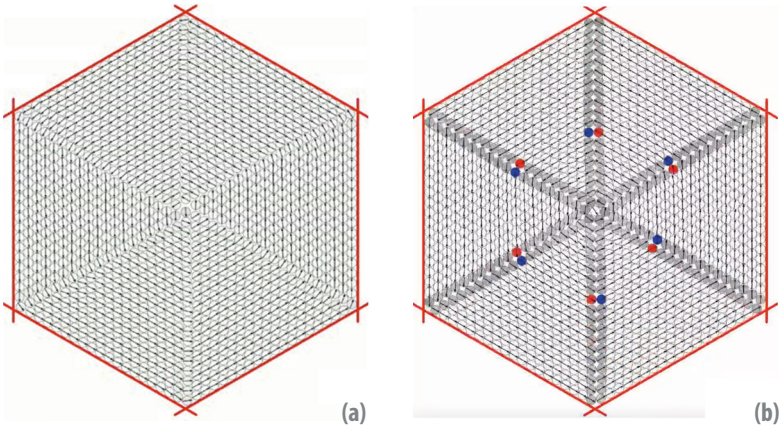
The high-density confinement of an assembly of disks, all the same diameter, leads to the formation of a crystalline structure on a triangular lattice. The crystallization of hard disks at thermodynamic equilibrium is very specific and was the subject of important work in the 1970s [7], which earned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

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

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

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





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

Collective actuation of an elastic network

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

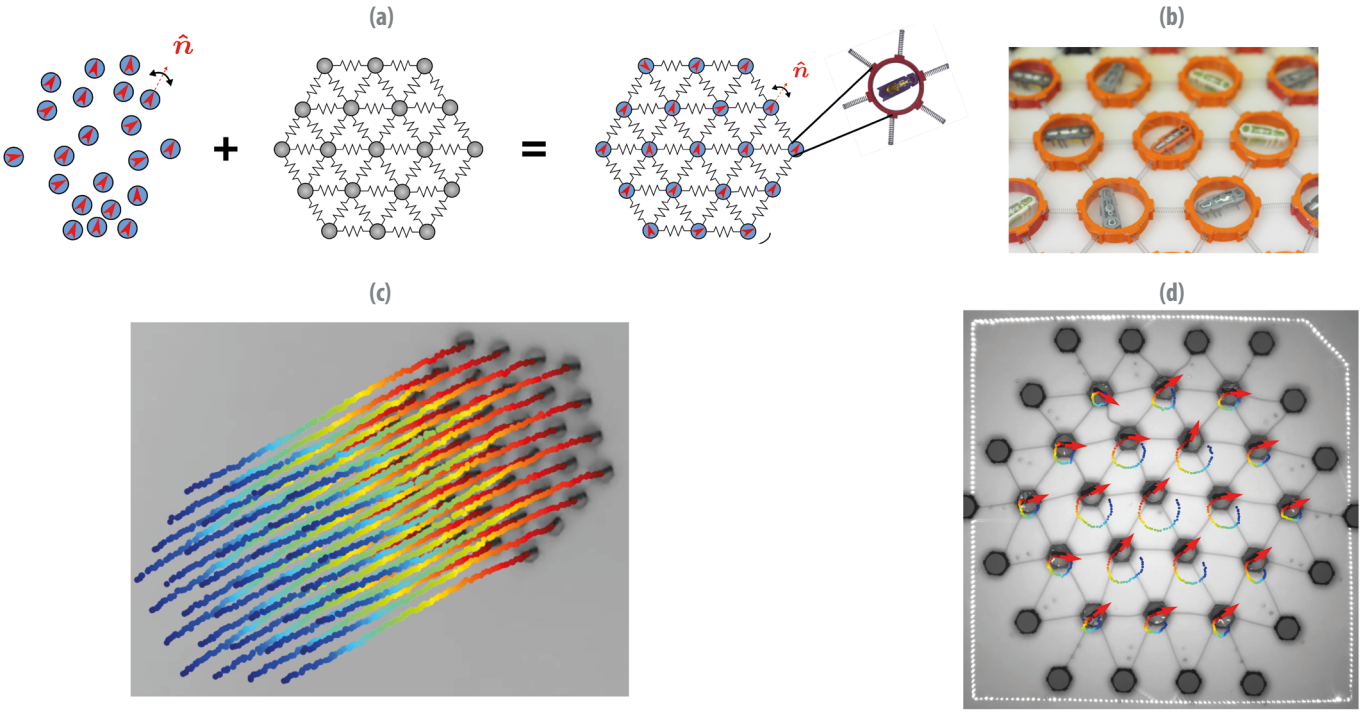
To answer this question, we now turn to our second model system, a hybridization between the physics of elastic solids and that of active liquids (Fig.3-a). It consists in trapping mobile entities within an elastic structure, while leaving them free to reorient [10]. In practice, Hexbugs© are trapped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

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

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

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

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



Conclusion and perspectives

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

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

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

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

About the Author

Olivier Dauchot is a CNRS Research Director, Head of the Gulliver laboratory, at ESPCI-Paris PSL. His research focuses on Collective effects in Soft Matter, which he studies in model experimental systems. He presently concentrates on active matter and programmable matter.

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THIRTY YEARS OF SURPRISES ABOUT COLLECTIVE MOTION

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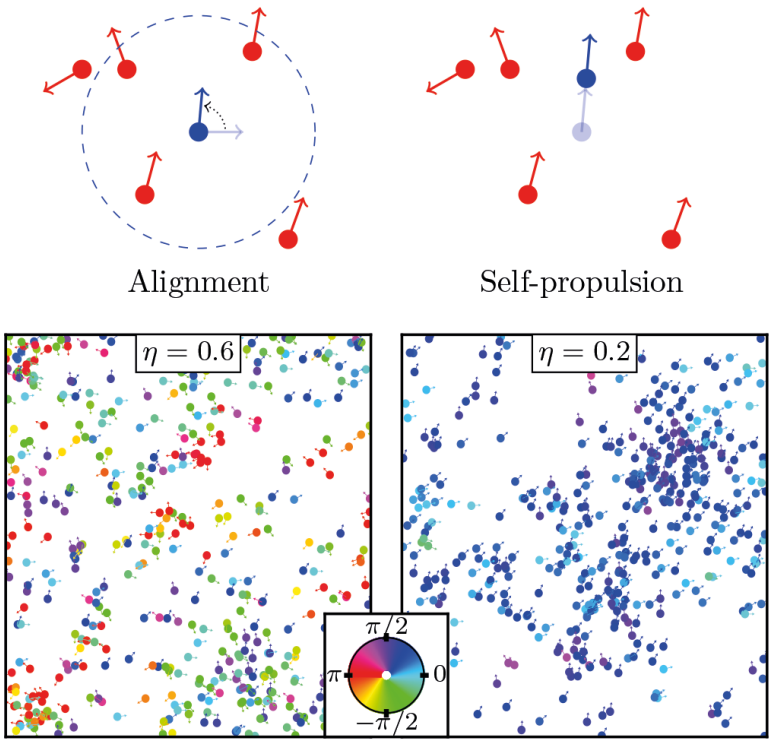
Why do large groups of starlings perform their fascinating murmurations over our cities before sunset? This question is best left to zoologists or poets. Understanding how they do it, however, brought up surprisingly rich physics and has led to many interesting developments over the last thirty years.

A model for collective motion

Animals moving in groups, be they birds in a flock, fish in a school, wildebeests in a herd or humans in a crowd, share basic common behaviours. They are all "self-propelled particles" that can use their own energy source to move and tend to coordinate their headings with their neighbours. A minimal model of collective motion that contains just these two ingredients, self-propulsion and a local alignment, was introduced by Tamás Vicsek and coworkers [1] in 1995.

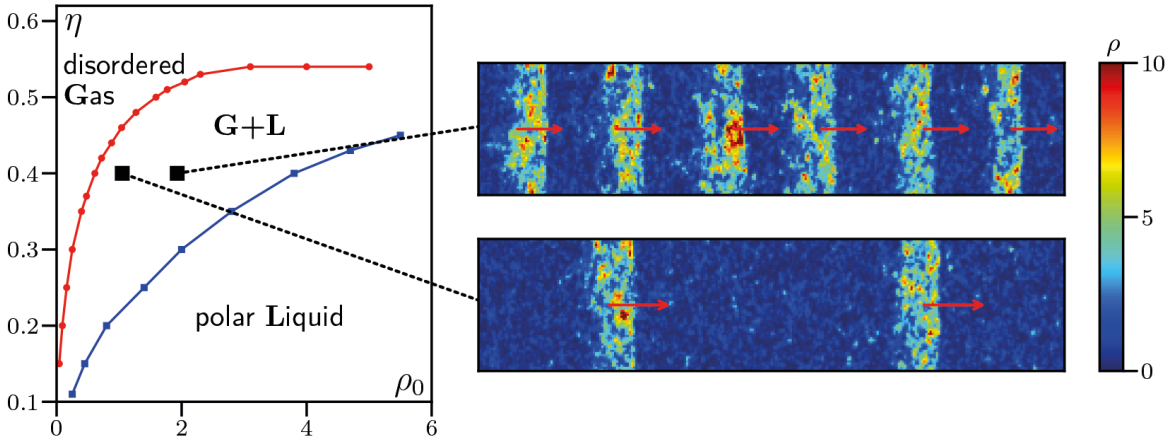
The rules of the model, illustrated in figure 1, could not be simpler. It features a fixed number N of particles at positions $\mathbf{r}_i$ ($i = 1 \ldots N$) in two-dimensional space, moving at constant speed v_0 in direction $\mathbf{n}_i = (\cos\theta_i, \sin\theta_i)$ parameterised by the angle θ_i. At each time increment, the particles compute the mean heading $\langle\theta_j(t)\rangle_{\mathcal{N}i}$ of their neighbours, within a fixed interaction radius, and align imperfectly with this direction $\theta_j(t+1) = \langle\theta_j(t)\rangle_{\mathcal{N}i} + \eta\xi_i$ where ξ_i is a random number drawn uniformly between $-\pi$ and π. The parameter η quantifies the error in the alignment process from perfect alignment $\eta = 0$ to picking completely random directions $\eta = 1$. The particles then move in their new direction $\mathbf{r}_i(t+1) = \mathbf{r}_i(t) + v_0\mathbf{n}_i$ This model is, of course, not the most realistic. For example, the model introduced earlier by computer graphics expert Craig Reynolds, that was used to convincingly emulate animal groups in movies, contains additional rules to avoid collisions and spreading of flocks [2]. Nevertheless, the Vicsek model is a good tool to uncover the generic physics at play in collective motion.



▼ FIG. 1: Top: Schematic illustration of the dynamics in the Vicsek model. Bottom: Typical states obtained at high and low noise.

The active phases of matter

Figure 1 (bottom) shows the result of computer simulations for different values of the noise strength η. One can see that, decreasing the noise, the system transitions from a disordered state in which particles are moving incoherently to an ordered state in which all particles move, in average, in the same direction. This seemingly unsurprising fact is actually highly non-trivial. Indeed, the equilibrium counterpart of the Vicsek model is a magnetic system of classical spins $\mathbf{n}_i$ with fixed positions in space and ferromagnetic alignment. But it is well established that, in two dimensions, an ordered state is impossible in such systems: it does not resist the effect of fluctuations. In more technical terms, the spontaneous breaking of a continuous symmetry is impossible in 2d equilibrium systems with short-range interactions, a fact known as the Hohenberg-Mermin-Wagner (HMW) theorem. On the contrary, because of self-propulsion, which continuously dissipates energy and thus drives the system out of equilibrium, the Vicsek model evades the HMW theorem and exhibits a new phase of matter. This opened the way to "active matter" that studies the effect of activity in different systems, and gave rise to active Brownian particles, active nematics, active solids, *etc.*, several of which are discussed in this issue.



◂ **FIG. 2:** Phase diagram of the Vicsek model and two snapshots of the density field at liquid-gas coexistence showing a microphase separation. Adapted from [5].

What are the properties of this new phase of collectively moving particles? To elucidate this question, John Toner and Yuhai Tu, have introduced and examined continuum equations that describe the large scale evolution of the density and velocity fields of such active fluids [3].

They are somewhat similar to the Navier-Stokes equations describing regular passive fluids with the crucial difference that an active fluid flows spontaneously, acquiring a preferred velocity, so that the equations are not Galilean invariant. Physically, there is a preferred reference frame, that of the substrate on which the particles are moving.

Analysis of the Toner-Tu equations and numerical simulations of the Vicsek model show a complex mode structure: two sound modes that mix density and velocity perturbations propagate at different speeds which, in addition, depend on the direction of propagation. As a result, the density and velocity fluctuations possess long-ranged correlations, decaying as power laws in space and time.

For example, the equal-time correlations of velocity fluctuations $C_v(\mathbf{r}) = \langle \mathbf{v}(\mathbf{r}) \cdot \mathbf{v}(0) \rangle - \langle \mathbf{v} \rangle^2$ decay with distance like $C_v(\mathbf{r}) \propto |\mathbf{r}|^{-\kappa}$ with possibly different exponents κ for $\mathbf{r}$ vectors parallel and orthogonal to the mean direction of motion $\langle \mathbf{v} \rangle$ (the value of the scaling exponents is still debated to this day). Such scale-free behaviour, often associated with critical points, is observed here generically, in all the ordered phase. Concrete consequences include transverse super-diffusion — in a time t, a particle travels a typical distance in the direction transverse to the mean motion $\Delta r_\perp \propto t^\nu$ with $\nu \approx 2/3$ in between diffusive $\nu = 1/2$ and ballistic $\nu = 1$ transport — and giant number fluctuations – the fluctuations ΔN of the number of particles N in a box goes as $\Delta N \propto \langle N \rangle^\alpha$ with $\alpha > 1/2$, the value that would be expected based on the central limit theorem for a system correlated only on short distances. Scale-free correlations have indeed been measured in real flocks of starlings, and they are believed to provide an efficient mechanism to enhance the global response to external perturbations such as an attacking predator [4].

Transition to collective motion

Because of the resemblance, already emphasised, of the Vicsek model with magnetic systems, we could expect the transition towards the ordered state to proceed in a similar manner as the continuous transition between paramagnetic and ferromagnetic phases. This is what Vicsek and coworkers reported in their original paper [1] but that turned out to be incorrect on closer inspection (and much higher CPU power). The onset of collective motion actually resembles a liquid-gas transition, with a phase diagram (figure 2) that contains a coexistence region in addition to the homogeneous ordered and disordered phases.

Note that the possibility of such a phase coexistence is nothing trivial. It would seem to require cohesive interactions that hold together the two phases, which are usually provided by intermolecular forces (hydrogen bonding and van der Waals forces) but are completely absent from the Vicsek model. The form of the phase coexistence itself is peculiar. It features an ordered liquid, which is thus moving, and a disordered gas but the coexistence is not between two domains of macroscopic size, as in a usual liquid-gas phase separation. One observes instead microphase separation with a liquid phase taking the form of many traveling bands of a fixed size.

Increasing the density, and thus the fraction of liquid, increases the number of bands rather than their size, as seen in Fig. 2. The description of this type of phase coexistence offers interesting theoretical challenges. Indeed, deterministic "mean-field" equations incorrectly predict a standard phase separation between two macroscopic domains, and the microphase pattern is thus imposed by fluctuations, by a mechanism that is not fully elucidated.

Obstacles and disorder

The results described so far have been obtained in an idealised setting: perfectly identical particles in an infinite and perfectly homogeneous environment. Real flocks are of course more... real! Recent studies have thus focused on incorporating additional ingredients in models of collective motion such as the Vicsek model.

Adding just a single small obstacle inside the ordered phase is enough to reveal new surprising features. Indeed, contrary to passive systems in which such a small perturbation can only have a local effect, a single obstacle is enough to destabilise the ordered phase of the Vicsek model [6]. It can trigger the counter-propagating dense bands shown in Fig. 3 that, ultimately, destroy the ordered state. Pushing the logic further, this leads us to realise that, instead of an obstacle, a large fluctuation happening spontaneously, could have the same effect. Even if such events are rare, they occur at a finite rate, so that we expect ordered flocks, in most cases, to be metastable states: on large time scales they are destabilised, giving way to a disordered state [7]. This, once again, violates our intuition coming from magnetic systems, for which being stable to small (spin wave) fluctuations also means being fully stable because large fluctuations are suppressed by surface tension.

Going toward more realistic models, several different sources of disorder can be taken into account. The particles need not be identical. Their characteristics (velocity, noise) are in principle distributed more or less broadly around a mean value. One can also consider the case of several coexisting species with different properties and potentially different goals, opening a zoo of new possible behaviours due to non-reciprocal interactions between species (see the feature article by Ramin Golestanian).

The environment may itself be disordered, which can be modelled in several ways, from spatially varying parameters to randomly placed obstacles. In the latter case, the flocks typically concentrate along rivers, as shown in Fig. 3 (right), in which they can get trapped, leading to ergodicity breaking [8]. In addition, it has been shown that the slightest anisotropy in the environment affects dramatically the phenomenology seen in the Vicsek model [9], in particular suppressing long-range correlations and the microphase separation shown in Fig. 2.

Overall, the recent studies about the effect of disorder and anisotropy on collective motion tend to show that flocks are much more sensitive to external conditions than their passive magnetic counterparts. This makes it all the more important to understand these effects, if one is to control collectively moving particles in realistic settings.

Engineering active materials

In parallel to the theoretical developments summarised above, in the last 15 years, great progress was made in engineering fluids of active particles. Perhaps most impressively, micrometer-sized beads propelled by the electrohydrodynamic "Quincke" instability have been made to flock by millions in various settings [10]. Practical applications for such spontaneously flowing fluids are yet to come but will certainly depend on our ability to understand in details their rich physics. ■

About the Author

Alexandre Solon is a CNRS research scientist based in Sorbonne Université, Paris, France. He has worked on a variety of problems related to the statistical physics of active matter and other nonequilibrium systems.

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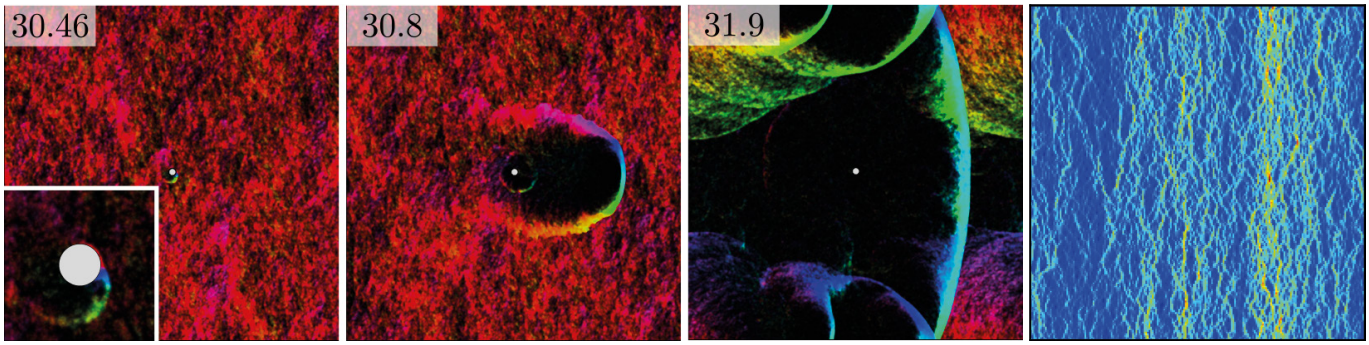

▼ **FIG. 3:** Left: A small obstacle (white dot at the centre) triggers a counter-propagating wave that destroys the ordered state in the Vicsek model. Time is indicated in units of 1000 iterations. Same colour code as in Fig. 1. Reproduced with permission from [6]. Right: Average density of particles in the Vicsek model (density $\rho_0 = 1$, noise $\eta = 0.2$, size 400×400) with a density $\rho_{obs} = 0.1$ of randomly placed obstacles. Same colour code as in Fig. 2 (right).

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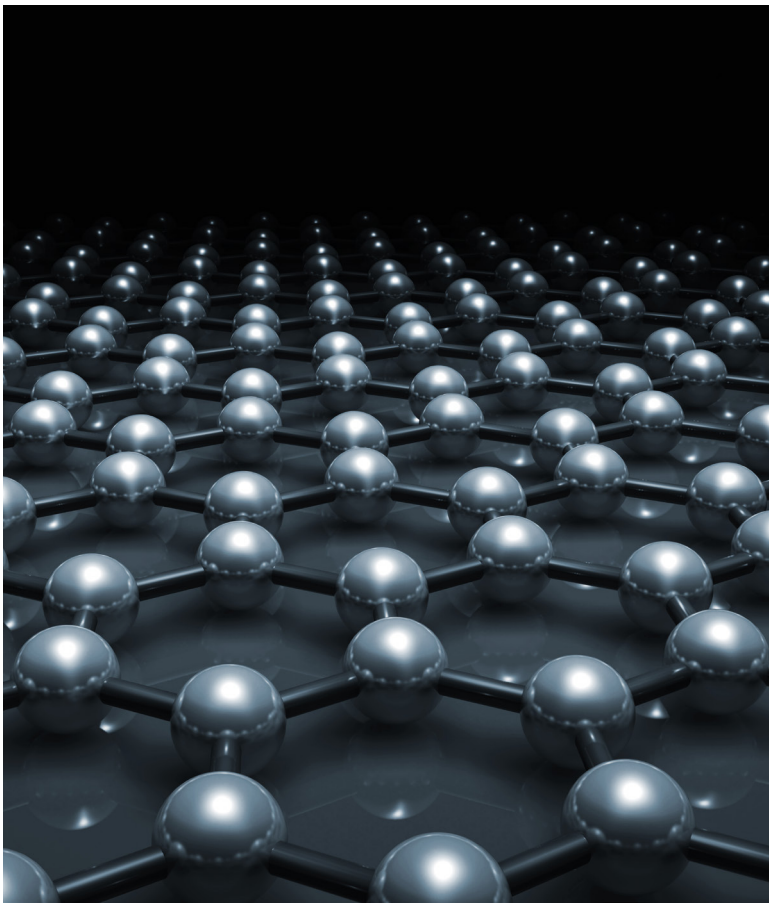

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