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

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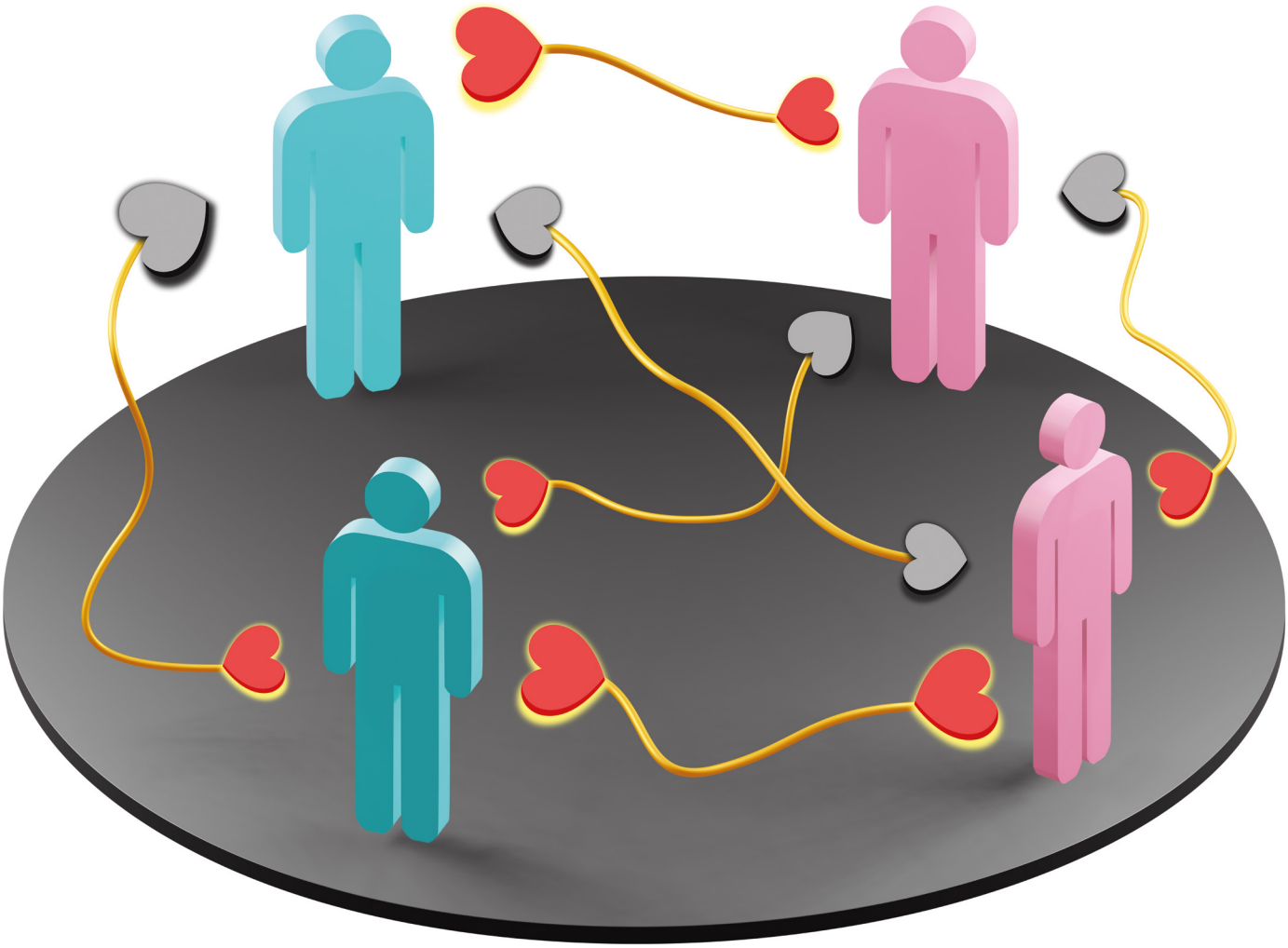


The observation that the interactions between catalytically active microscopic units generically break action-reaction symmetry leads to the discovery of a wealth of self-organization scenarios and exotic phases of active matter. Bridging the scales from individual molecules to macroscopic systems allows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

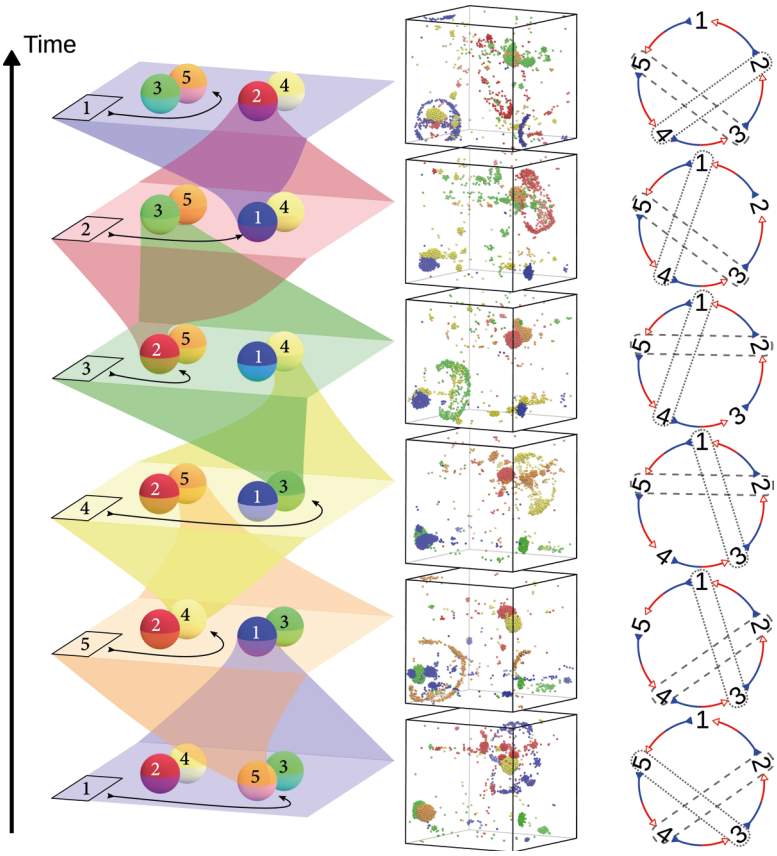
The mechanism behind such non-reciprocal interactions, which have been demonstrated experimentally [2,3], is quite generic: it stems from interfacial phoretic transport processes that amount to a response of every enzyme or active colloid to the gradients of chemicals created by others. In a regime where 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

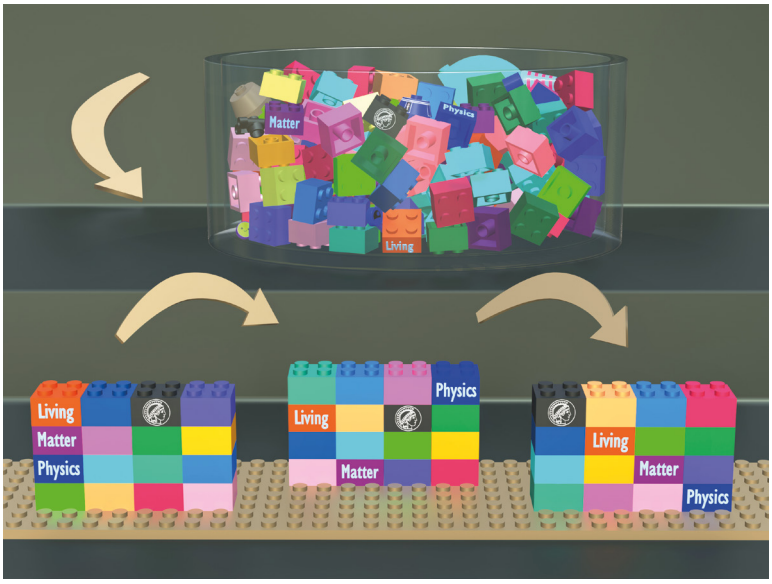
Non-reciprocal interactions can lead to a plethora of novel emergent features. The simplest one is the emergence of polarity in the form of self-organized ● ● ●

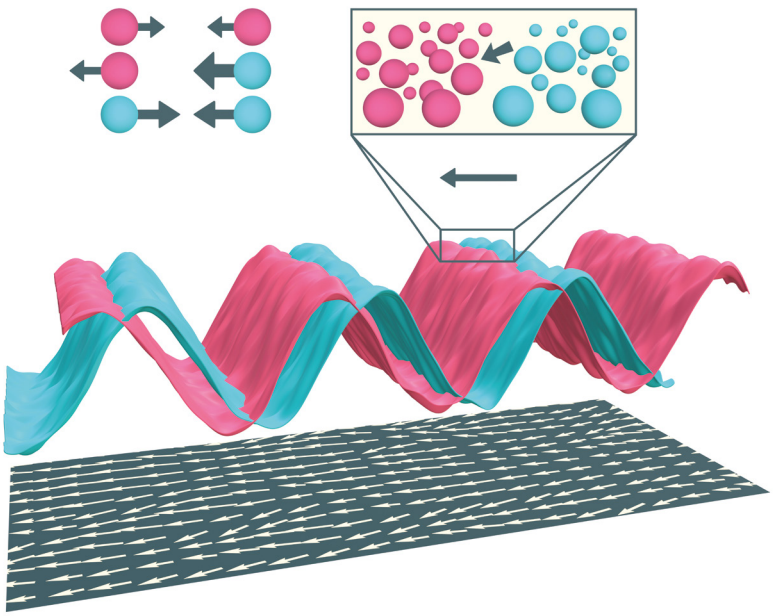
◂ **FIG. 1:** *"O loving hate"*. Non-reciprocal interactions arise naturally between humans, and they lead to complex collective effects. © MPI-DS / Novak & Golestanian



▲ **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

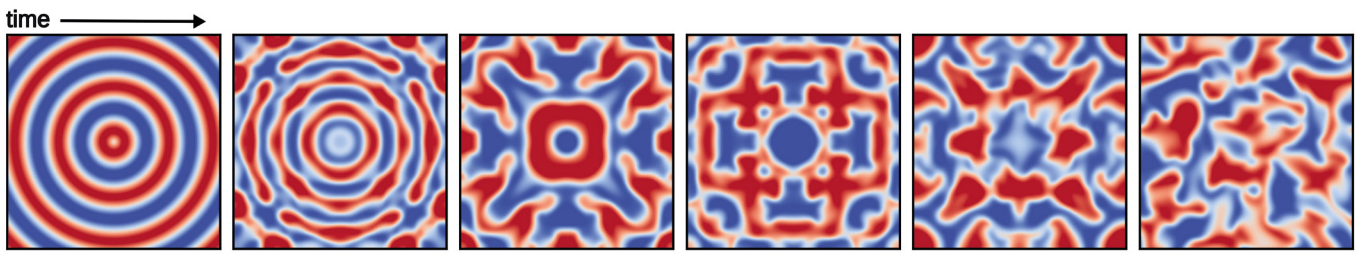
"Here's much to do with hate, but more with love.
Why, then, O brawling love, O loving hate,
O anything of nothing first created,
O heavy lightness, serious vanity,
Misshapen chaos of well-seeming forms,
Feather of lead, bright smoke, cold fire, sick health,
Still-waking sleep that is not what it is.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

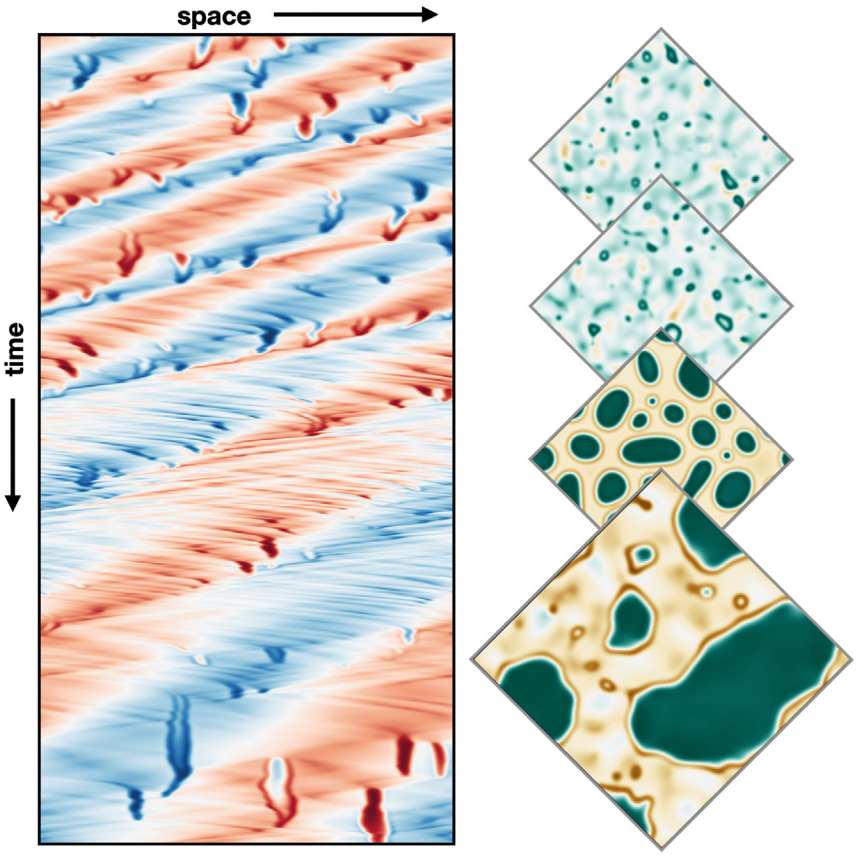
From Romeo and Juliet by William Shakespeare (Act 1, Scene 1)

• • • 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! ■

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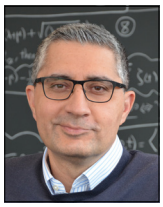
About the Author



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