Swarm-Smart: Group motion and decision making in experiments and theory

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Doubly Stochastic Local Interaction Models for Coordinated Marching

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The talk presented two results on modeling coordinated collective motion in continuous and discretized environments. The models assume interactions between agents upon encounters, and the decisions on the the marching directions after meetings are assumed to be probabilistic.
In some interesting cases one can prove convergence to alignment of the marching directions, suggesting that such models could capture the interesting coordinated marching phenomena observed experimentally in locusts moving around in various arenas.

(The work presented is based on research within the framework of a joint project with TAU and Bar-Ilan, and the Technion contributors were Michael Amir, Dr. David Dovrat and Thomas Dages.)

Individual and group variability in collective motion: lessons from the locust model

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The emergence of collective motion in groups of organisms (or artificial agents) is accepted to be dependent on local interactions among the individuals composing the group. A major aspect of collective motion is coordination and synchrony in movement, features that may be facilitated by similarity among the individuals, or by group homogeneity. Nevertheless, recent years have seen growing interest in the role of variability and heterogeneity in collective behavior.
Locust are a quintessential example of animal swarming, the collective motion comprising a hallmark of their behavior in practically all life stages. The ecological as well as economic impact of locust swarms facilitated studies of their behavior and dynamics. In the context of variability and collective motion, locusts allow studying the interaction between variability and collective motion at different levels or aspects.
In recent years we investigate the intricate interactions between the natural variability among individuals, and the homogenizing effect of the group, working to generate synchronization and maintain coherence of locust swarms. We demonstrated that locust groups develop unique, group-specific behavioral characteristics, reflected in large intergroup and small intragroup variance. Following individual locust in changing social contexts, we were further able to identify a level of variability related to the behavioral state of the individual. It was found that taking part or experiencing collective motion, induce unique kinematics and a distinct long-lasting behavioral mode we term a “collective-motion-state”. These different aspects of variability are suggested to be instrumental in increasing the robustness and stability of swarms.

One additional and extremely important source of variability in locusts is that related to locust-density-dependent phase polyphenism. Recently, we have set to explore the dynamics of the transformation of isolated, solitary locusts into the swarming phase and its interactions with the emergence of collective motion.

The high-throughput revolution in movement ecology, and its potential contributions for studying group motion in the wild

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Movement shapes how animals interact, survive and thrive in a dynamic world. Technological advances are now transforming movement ecology into a big-data discipline, enabling rapid, cost-effective generation of large amounts of data on movements of animals in the wild. High-throughput systems provide new research opportunities beyond simply enlarging datasets and sample sizes, allowing thorough investigations of fine-scale variation among individuals, the true nature of biological interactions, behavioral decisions in response to the physical and anthropogenic environment, and behavioral shifts across spatiotemporal scales. In this talk, I will overview the emerging high-throughput technologies in movement ecology research, and present examples for biological insights uniquely gained from big high-resolution datasets, focusing on group motion of wild animals in particular.

Hiding information from your friends: a cryptographic principle for caching and retrieval behaviors

Oren Forkosh, The Hebrew University of Jerusalem

The brain's extraordinary abilities are often associated with its ability to learn and adapt. But memory has its limitations; especially when faced with the task of retrieving tens or even hundreds of thousands of cached food items annually - such as in the case of scatter-hoarding animals. Here, we present how the brain might use cryptographic principles instead of plasticity when faced with such challenges. The model we use is based on hippocampal spatial cells, which respond to an animal’s positional attention, such as when the animal enters a specific region (place-cells) or gazes at a particular location (spatial-view-cells). We know that the region that activates each spatial cell remains consistent across subsequent visits to the same area but not between areas. This remapping, combined with the uniqueness of cognitive maps, produces a persistent crypto-hash function for both food caching and retrieval. This mechanism also produces temporal information that helps animals with food caching order preference, for example, to retrieve perishable food items sooner. This mechanism might also help animals locate mates while avoiding predators by having similar neural maps.

Foraging decision making in the real world - the bat's point of view

Yossi Yovel, Tel Aviv University

Bats are extreme aviators and amazing navigators. Many bat species nightly commute dozens of kilometres in search of food, and some bat species annually migrate over thousands of kilometres. Studying bats in their natural environment has always been extremely challenging because of their small size (mostly <50 gr) and agile nature. We have recently developed novel miniature technology allowing us to GPS-tag small bats, thus opening a new window to document their behaviour in the wild. We have used this technology to track bat pups over 5 months from birth to adulthood. Following the bats' full movement history allowed us to show that they use novel short-cuts which are typical for cognitive-map based navigation. Using miniature microphones placed on the, we can also infer their foraging success and social behaviour. This novel technology thus allows us to document and model foraging decision making in real-life large scale and over long time periods.

Biophysics underlying the swarm to biofilm transition

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Bacteria organize in a variety of collective states, from swarming, which has been attributed to rapid surface exploration, to biofilms, which are highly dense immobile communities attributed to stress resistance. It has been suggested that biofilm and swarming are oppositely controlled, making this transition particularly interesting for understanding the ability of bacterial colonies to adapt to challenging environments. Here, the swarm to biofilm transition is studied experimentally by analysing the bacterial dynamics both on the individual and collective scales. We show that both biological and physical processes facilitate the transition - a few individual cells that initiate the biofilm program cause nucleation of large, scale-free stationary aggregates of trapped swarm cells. Around aggregates, cells continue swarming almost unobstructed, while inside, trapped cells slowly join the biofilm. While our experimental findings rule out previously suggested purely physical effects as a trigger for biofilm formation, they show how physical processes, such as clustering and jamming, accelerate biofilm formation.

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Adversarial Robotics: From Teamwork to Swarms

Noa Agmon, Bar-Ilan University

Developing robots for a wide range of goals requires addressing their ability to perform tasks as physical agents with specific characteristics, and the ways in which they act within and respond to their surroundings. As proximity to dangerous or hostile entities is among the foremost motives for using robots, it is therefore crucial to account for the presence of adversaries in robotic environments. The talk will describe several key research threads examining the ability of robotic teams and swarms to (strategically) handle adversity, which strongly relies on the knowledge the robots have on the environment and the opponent, and the coordination scheme between the robots.

The entropy of collective motion patterns

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One of the main challenges in the research of collective motion phenomena lies in quantitative characterization of the dynamics. Statistical physics provides some widely used tools, such as correlation functions, density fluctuations and approximations to known processes (e.g. Markov or reaction-diffusion). These can be used, with some partial success, to classify collective states and compare swarming regimes. However, one of the major tools of statistical physics – the entropy – has seldom been used.

Entropy is one of the principle thermodynamic variables and its definition can be extended to nonequilibrium systems based on its relation to information (Shannon entropy). However, applying this impossible.

The reason is essentially "technical" – a crude estimate shows that a system of *N* individuals moving in *D* dimensions would require an order of 10^{ND} samples.

In this talk, I present a new method that relates the entropy to other integrated, macroscopic propertie: advantage of using entropy to characterize collective motion is demonstrated in a few examples.

Spin models for decision-making on the move

Nir Gov, Weizmann Institute of Sciences

We present a spin-based model for the mechanism by which groups of animals in a cohesive group reach consensus regarding their direction of motion, when faced with several optional targets. The model allows to expose the nature of the compromise-to-decision transition observed in flock simulations of this process, with the number of group members acting as the inverse temperature of the spin model.

The same model is then applied to the navigation of a single animal, and shown to describe it very well, considering that animals distort the observed space in a way that enhances angular differences around the heading direction. The resultant trajectories, with a hierarchy of bifurcations, is observed in a fly, locust and fish, suggesting a universal mechanism.

Posters

Distributed on-line reinforcement learning in a swarm of sterically interacting robots

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While naturally occurring swarms thrive when crowded, physical interactions in robotic swarms are either avoided or carefully controlled, thus limiting their operational density. Designing behavioral strategies under such circumstances remains a challenge, even though it may o_er an opportunity for exploring morpho-functional self-organized behaviors. Here we explicitly consider dense swarms of robots where physical interactions are inevitable. We _nd that an a priori minor di_erence in the mechanical design of the robots leads to signi_cant di_erences in their dynamical behaviors when they evolve in crowded environments. We design Morphobots, which are Kilobots augmented with a 3D-printed exoskeleton. The exoskeleton not only signi_cantly improves the motility and stability of the Kilobots, it also allows to encode physically two contrasting dynamical behaviors in response to an external force or a collision. This di_erence translates into distinct performances during self-organized aggregation when addressing a phototactic task. Having characterized the dynamical mechanism at the root of these di_erences, we implement a decentralized on-line evolutionary reinforcement learning algorithm in a swarm of Morphobots. We demonstrate the learning e_ciency and show that the learning reduces the dependency on the morphology. We present a kinetic model that links the reward function to an e_ective phototactic policy. Our results are of relevance for the deployment of robust swarms of robots in a real environment, where robots are deemed to collide, and to be exposed to external forces.

[1] Ben Zion M Y, Bredeche N, Dauchot O, 2021. arXiv:2111.06953.

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Visual-based decision making in desert locust collective motion

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Swarming locusts present a quintessential example of animal collective motion. The swarm's coordinated, synchronized mass-movement is dependent on local interactions among individuals in the group, and on their swift and appropriate decision-making. The formation and sustention of locust swarms predominantly relies on visual interactions, within an exceptionally complex and noisy visual surroundings.

Utilizing behavioral monitoring and neurophysiological recording of individual locusts in a specially designed and carefully controlled experimental set-up we identified and characterized swarming-related visual cues, and investigated their effect on the individual's decision-making process.

The observed behavioral responses revealed the use of a match filter in the visual system, filtering stimuli with speed beneath that of a walking conspecific by way of an appropriate speed threshold. A clear threshold was also evident in identifying motion coherence levels, or common group direction, suggested to further contribute to the swarm integrity. The simultaneous presentation of stimuli with various sizes revealed a tendency for preferred alignment with larger stimuli, probably reflecting increased attention to neighboring locusts over distant ones. These findings were also supported by our neurophysiologic investigation. Recordings from the descending contralateral movement detector (DCMD) interneuron, a well described motion sensitive visual pathway, revealed consistently different neurophysiological responses to visual stimuli with different speeds, sizes, and coherence levels. Further relevant characteristics of the visual stimuli, potentially affecting the DCMD responses and to this end also behavior, include position of the stimulus within the field of view, contrast ratio, and of course direction of motion.

Locusts proved to be a valuable model for the study of visual-based collective motion. Our results emphasize the instrumental role of visual perception in collective-motion-related decision making. They exemplify the complex cognitive mechanisms underlying locust visual processing in a cluttered and noisy environment.

Spatial Consensus-Prevention in Robotic Swarms

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Abstract

The consensus problem, which examines the possibility of reaching an agreement, is a fundamental problem in distributed systems, multi-agent systems and swarm robotics. In this paper we define the *consensus-prevention* problem, which examines the canonical swarm robotic consensus problem from an adversarial point of view: how (if at all) is it possible to lead a swarm into a disagreement, that is, prevent them from reaching an agreement. We focus on consensus-prevention in physically grounded tasks, concentrating on influencing the direction of movement of a flocking swarm and guaranteeing that the swarm will never converge to the same direction by the use of external, predefined agents, referred to as *diverting agents*.

We formally define the notion of disagreement within a flock, and propose a way of measuring it. We show a correlation between the consensus-prevention problem and the coalition formation problem, whose players aim at maximizing the disagreement measure. While the general problem of optimizing disagreement between flocking agents is NP-hard, we focus on a case which is solvable in polynomial time, using a variant of the graph clustering problem where the clusters constitute the desired coalitions. Finally, we demonstrate in simulation the impact of the number of diverting agents on the disagreement measure in different scenarios, and discuss the limitations of the diverting agents in dynamic settings.

Learning Models for Homogeneous Multi-Agent Systems

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Training Reinforcement Learning (RL) policies for a robot requires an extensive amount of data recorded while interacting with the environment. Acquiring such a policy on a real robot is a tedious and time-consuming task. It may also cause mechanical wear and pose danger. This is more challenging in a multi-agent system where individual data is required from each agent. While training in simulations is the common approach due to efficiency and low-cost, they rarely describe the real world. Consequently, policies trained in simulations and transferred to the real robot usually perform poorly. Such problem is commonly known as the reality gap or sim2real transfer. In our work, we present a novel real-to-sim-to-real framework to bridge the reality gap for homogeneous multi-agent systems with application to large-scale deployment in swarm robotics. First, we propose to use a designated deep neural-network to learn a data-based transition model

of a single agent. Second, we propose to invest a limited amount of real data from one agent in a deep generative model. Then, training the transition model with synthetic data sampled from the generative model is shown to be at least equivalent to real data and, in some cases, improve accuracy. The generative model can also be disseminated along with open-source hardware for easier usage. Next, we simulate a swarm by applying the transition model for each agent. We show experiments on two different types of miniature mobile robots: a two-wheeled car and a fish-inspired swimming robot, in which multi-agent RL policies are trained in the simulation and successfully transferred to the real-world. The proposed approach is an important step towards large-scale decentralized control of a robotic swarm.

Ants resort to majority concession to reach democratic consensus in the presence of a persistent minority

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Abstract

Social groups often need to overcome differences in individual interests and knowledge to reach consensus decisions. Here, we combine experiments and modeling to study conflict resolution in emigrating ant colonies during binary nest selection. We find that cohesive emigration, without fragmentation, is achieved only by intermediate-sized colonies. We then impose a conflict regarding the desired emigration target between colony subgroups. This is achieved using an automated selective gate system that manipulates the information accessible to each ant. Under this conflict, we find that individuals concede their potential benefit to promote social consensus. In particular, colonies resolve the conflict imposed by a persistent minority through ‘‘majority concession,’’ wherein a majority of ants that hold first-hand knowledge regarding the superior quality nest choose to reside in the inferior one. This outcome is unlikely in social groups of selfish individuals and emphasizes the importance of group cohesion in eusocial societies.

Swarming Bandits: A Rational and Practical Model of Swarm Robotic Tasks

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A swarm is a multi-agent system in which robots base their decisions only on local interactions with the other robots and the environment. Local interactions limit the robots’ abilities, allowing them to perceive and act only with respect to a subset of the other robots, and preventing them from coordinating explicitly with all members of the system. Despite these challenging constraints, swarms are often observed in real-world phenomena, and inspired technology for many

robotics applications. A key open challenge in swarm research is to be able to provide guarantees on the global behavior of the swarm, given their individual decision rules and local interactions. The reverse is also an open challenge: given the required guaranteed global behavior, how should the individual behave and make decisions?
This thesis proposes a new game-theoretic model for swarms. It ties local decision-making with theoretical guarantees of stability and global rewards. Using simple reinforcement-learning with a reward that is computed locally by each robot, it is able to make guarantees about the emerging global results. Specifically, we show that the utility of the swarm is maximized as robots maximize the time they spent on their task. This allows each single robot to evaluate the efficacy of a collision-avoidance action based on the time it frees up for its own swarm task execution. We use a multi-arm bandit framework to allow each individual agent to learn the collision-avoidance actions that are best. Then, we show how to shape the reward used in the learning process, so that it takes into account the marginal contribution of the robot to the swarm. While the marginal contribution is not directly accessible by the robot, it can be approximated effectively based on its own experience. We evaluate the model empirically, using a popular 3D robotics physics-based simulation, in which a cooperative swarm is engaged in foraging, a popular canonical task. We compare the results to those achieved by the state of the art, and show superior results.

Physical characteristics of mixed-species swarming colonies

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Bacterial swarming is an intricate type of collective motion in which cells rapidly migrate in groups on surfaces. Swarming assists bacteria in dissemination and expansion, providing them with a better access to nutrients. Swarm cells experience reduction of the viscosity of the medium and defense from harsh environmental conditions. Study of bacterial swarming helps in understanding the phenomenon of collective motion of individuals among the group which can be seen in nature at different scales. Bacterial swarm studies were so far conducted on homogeneous populations, which cannot be compared with natural environments that consist of more than one species in the same niche. In this work we show the inter-species interactions in swarming colonies, even if the interactions are largely physical based. Here we study swarming of mixed populations by using Bacillus subtilis and Serratia marcescens, two model swarm species that are known to swarm well in axenic situations. We show that the two species, although swarm jointly, do not mix well on the swarm plane, and rather form a heterogenous structure leading to robust dynamics. On the macroscopic scale, ratio of each species in the mix determines the structure of the colony, the distribution of the species in it and the rate of colonial expansion. Microscopic collective

dynamics of the mixed-species colony shows a significant difference compared to the single species colonies, with a higher bacterial speed and normal statistics with Gaussian distributions of velocities. Mixed liquid cultures yield higher reproduction rates for both species, and chemotaxis assays between the
species are negative. The results are unique as they open a door for new studies of rapidly moving mixed
populations and point to the significant microscopic and macroscopic effects that one species may have on
another.
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Backswimmer Inspired Miniature Robot with Buoyancy Auto-Regulation through Controlled Nucleation and Release of Microbubbles

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Abstract: The backswimmer fly is an aquatic insect, capable of regulating its buoyancy underwater. Its abdomen is covered with hemoglobin cells, used to bind and release oxygen, reversibly. Upon entering water, the fly entraps an air bubble in a superhydrophobic hairy structure on its abdomen for respiration. This bubble, however, can change its volume through regulated oxygen flow from the abdominal hemoglobin cells. In this way, it can reach neutral buoyancy without further energy consumption. In this study, we develop a small, centimeter scale, backswimmer inspired robot (BackBot) with auto-buoyancy regulation through controlled nucleation and release of microbubbles. The bubbles nucleate and grow directly on onboard electrodes through electrolysis, regulated by low voltage. We use 3D printing to introduce a three-dimensional bubble-entrapping cellular structure, in order to create a stable external gas reservoir. To reduce buoyancy forces, the bubbles are released through linear mechanical vibrations, decoupled from the robot's body. Through pressure sensing and a Proportional Integral Derivative control loop mechanism, the robot auto-regulates its buoyancy to reach neutral floatation underwater within seconds. This mechanism can promote the replacement of traditional and physically larger buoyancy regulation systems, such as pistons and pressurized tanks, and to enable the miniaturization of Autonomous Underwater Vehicles

Vision-Based Collective Motion Model: A Locust Inspired Reductionist Approach*

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Abstract
Naturally occurring collective motion is an omnipresent fascinating phenomenon that has been long studied within different scientific fields, using various approaches. Swarming individuals are believed to aggregate, coordinate and move only utilizing local social clues projected by conspecifics in their vicinity. Major theoretical studies assume perfect information availability, where agents' input relies on exact knowledge of inter-agent distances and velocities. However, the key sensory modality that is responsible, in nature, for the acquisition of environmental information is often overlooked. With its central role in animal perception, vision was chosen as the sole source of information. In our work, we demonstrate a vision-based collective motion model, relying purely on visually available parameters, inspired by the case study of locust marching bands. We address the challenge of visual occlusion, common in crowded swarms, by comparing three approaches an agent can use to interpret partially occluded visual information. In silico experiments show the feasibility of our model and its three extensions. While all models display similar convergence rates to an ordered state, they differ in the respective computational requirements they demand from an agent.

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Memory and conformity, but not competition, explain spatial partitioning between neighboring fruit bat colonies

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Spatial partitioning between neighboring colonies is now considered a widespread phenomenon in colonial species, reported mainly in marine birds. Partitioning is suspected to emerge due to various processes, such as competition, diet specialization, memory, information transfer, or even "foraging cultures." Yet, empirical evidence to verify this phenomenon in other taxa and tease apart the relative contribution of these underlying processes remains scarce, mostly due to insufficient movement data (temporal resolution and number of individuals). Here, we use high throughput movement data (at 0.125 Hz) of 107 individuals belonging to two neighboring colonies of the Egyptian fruit bat (*Rousettus aegyptiacus*) in the wild, using the ATLAS revers-GPS system in the Hula Valley, Israel. Based on comparisons between agent-based mechanistic models and observed spatial partitioning patterns, we show that (1) Partitioning of both area and tree-resources were small (<10% overlap) and that these values were stable across fruit seasons. More importantly, partitioning could not have emerged if the bats' movement was only limited by food availability and travel distances, as most commonly hypothesized. (2) memory and conformity of tree-use (reflecting information transfer), but neither density-dependent nor between-colony competition, explain how partitioning is sustained. We discuss how elucidating the mechanisms that shape spatial partitioning among colonies of various wild species, foraging on resources with different levels of predictability, are relevant for understanding the ecology and evolution of space use, sociality, and animal welfare cultures

Unbalanced essential fatty acid diet impairs honey bee nursing behavior and accelerates task transitions

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Abstract

Group level processes emerge out of interactions among individual components which comprise the system. Disruption of these interactions by environmental stressors can cause a breakdown of the system, with negative consequences for group function. Honey bees (*Apis mellifera*) are eusocial insects that form highly structured societies with an age dependent division of labor. The nursing of immature bees in the larval stage for example, is performed by younger workers, while older workers perform tasks outside the colony, like foraging for resources. Imbalanced nutrition is one environmental stressor that can have negative consequences for individuals and groups. An overabundance of omega 6 relative to omega 3 fatty acids (omega 6:3 ratio = 5) in the honey bee diet for example, decreases larvae rearing success and shortens the lifespan of workers compared to those fed a balanced omega 6:3 diet (ratio = 1). This suggests that a high omega 6:3 diet alters nurse-larvae interactions, and through shorter worker lifespan may lead to earlier behavioral task transitions. We tested these hypotheses by tagging 1-day old honey bees with individually identifiable barcodes, and then feeding them either a high ratio or balanced diet until they were 8 days old. They were then released into a common garden hive and their behavior video monitored. Individual nurse bees fed a high ratio diet visited fewer larvae that were successfully reared to pupation, while also visiting them less frequently than bees fed a balanced diet. Furthermore, bees fed a high ratio diet embarked on foraging flights at a younger age than bees fed a balanced diet. These findings suggest that consumption of a high omega 6:3 diet disrupts nurse-larvae interactions, while also accelerating the movement of bees through the division of labor, both of which can be detrimental to colony growth and survival.

Fish decision-making on the move

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Abstract

The natural motion of animals and humans requires decision-making regarding their travel direction, which is explored here by a theoretical Ising spin model for fish decision-making on the move. The Ising model is applied to neurons in the brain of the fish that chase leaders (virtual fish), representing the fish's decision-making processes. Recent experiments in Couzin's lab at Konstanz University and simulations in our group demonstrate a reasonable fit between the experimental data and the theoretical model for a real fish's one-dimensional movement following virtual fish targets. Here we extended the model into two dimensions. We used Langevin equations to represent the fish's noisy parameters which affect its movement, which enable quicker and better integration in time than the previous Gillespie method. We have examined two models for motion in two dimensions to describe the velocity magnitude: First, we explored spring-like interactions that affect the absolute velocity, and secondly, we explored a tail-waving model. In the latter model, the tail forcing from each burst is included by Gillespie simulation to randomize the beating of the tail by giving its force and rate. We extract these values to be approximately based on the observed tail beating of the real fish. The tail waving model provides similar dynamics of the speed and position as in the experiment and stands the test of comparison with an experiment with broken symmetry, which enables us to better understand the suitable model for fish decision-making processes regarding its movement within its shoal. This model will provide the foundation for modeling a shoal of fish swimming together by using the Ising model for their neural activity.

Vasco Worlitzer