Mathematics and Biology II: Mathematics and Science of Behavior

April 27 – May 1, 2026

Monday, April 27, 2026

Time	Event / Speaker	Presentation Title
9:00 – 9:30 am	Breakfast	—
9:30 – 10:15 am	Deborah Gordon (Stanford University)	The dynamics of collective behavior in changing environments
10:15 – 10:30 am	Discussion	—
10:30 – 11:00 am	Tea Break	—
11:00 – 11:45 am	Hungtang Ko (Tufts University)	Collective mechanical intelligence: how fluid environments mediate self-organization of swarms
11:45 am – 12:00 pm	Discussion	—
12:00 – 1:30 pm	Catered Lunch	—
1:30 – 2:15 pm	Albert Kao (UMass Boston)	The limits and potential of collective wisdom
2:15 – 2:30 pm	Discussion	—
2:30 – 3:15 pm	Ann Kennedy (Scripps Research Institute)	Neural mechanisms that gate the expression of motivated behaviors
3:15 – 4:30 pm	Discussion	—
4:30 – 5:30 pm	CMSA Colloquium: Ofer Feinerman (Weizmann Institute of Science)	Enacted collective cognition: Brainless problem-solving in weaver ants

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Deborah Gordon: Collective behavior operates without central control, using interactions among participants adjust to changing conditions. There is enormous diversity in the dynamics of collective behavior, including in the rate of response to conditions, in feedback regimes that set whether interactions stimulate or inhibit activity, and the extent of centralization or modularity of information flow. An ecological perspective suggests how this diversity of collective behavior reflects the dynamics of the environment, including its stability, the ratio of resources spent to resources gained, and the distribution of resources in time and space. As examples, I will discuss field studies and modelling of the regulation of foraging behavior in two species of ants, Harvester ant colonies in the desert regulate foraging to manage high costs, in water loss, to obtain scattered and stable resources. They use a centralized system, with the default to remain inactive unless stimulated, that is slow to adjust foraging activity. In contrast, the turtle ant colonies form trail networks in the canopy of the tropical forest, in unstable conditions where activity costs are low, to find and collect ephemeral and patchy resources. They use a highly modular system, with the default to sustain activity unless inhibited, that can rapidly adjust trail networks to changing resources and conditions.

Hungtang Ko: Biological collectives across scales self-organize within fluid environments. The mechanical coupling between swarming agents and fluid fields provides opportunities for both passive self-assembly and active, fluid-mediated communication. However, while sporadic evidence of collective mechanical intelligence exists, its underlying mechanisms remain elusive. In this talk, I will focus on two key systems: fire ant rafts and fish schools. Using a combination of experiments and mathematical models, I will show that fire ant rafts leverage passive interfacial forces for self-assembly and self-stabilization. Furthermore, I will demonstrate how schools of giant danio utilize mechanically intelligent formations in 3D, and discuss how swarm robotics may provide the key to future research in collective mechanical intelligence.

Albert Kao: Over the past several years, many studies have demonstrated, both in theory and in experiments, the ability of groups to make better decisions than individuals — a phenomenon known as collective wisdom. However, the task types and experimental paradigms used vary considerably, making comparisons across studies, and consequently a unified theory of collective wisdom, difficult. Here, I derive a measure called the effective group size which allows for such comparisons. I use this measure to demonstrate several limitations to collective wisdom, including when groups are large, when there are correlations in opinions in the group, and when information is passed down in chains. In addition, collective wisdom is fragile in the face of an individual who has a disproportionate amount of power, even if far from being a dictator.

Ann Kennedy: In order to survive and reproduce, animals must set and weigh off goals in a way that is adaptive and responsive to the context of the environment. Intense evolutionary pressure has wired these algorithms of survival into the connectivity and gene expression patterns of the brain. In this talk, I will present our lab's recent work on the structure of animal behavior and its neural correlates, showing how theory and modeling can uncover the computational mechanisms by which the brain sets survival goals and weighs off competing survival needs. I will first show how at the macroscopic level, models of behavior as a feedback control system can help uncover control principles by which pressing survival needs can override less urgent drives. Next, I will present new work exploring how macroscopic drives are translated into moment-to-moment behavioral choices.

Ofer Feinerman: Unlike most ants, weaver ants construct their nests by pulling together leaves. Because individual ants are small relative to the leaves, they assemble their bodies into temporary tools that bend the leaves into a hollow structure, later stabilized with larval silk. Remarkably, they achieve functional nests across a wide range of leaf shapes and configurations, suggesting that this distributed system is capable of solving complex, open-ended problems. To understand how this is possible, we performed laboratory experiments using controlled leaf configurations. In simple cases, we show that ants can rely on a zipping heuristic that produces closed nests, and we use differential geometry to demonstrate how flexible leaves are transformed into rigid structures. Crucially, this zipping behavior forms a feedback loop in which ants continuously read and modify the evolving structure. In this sense, the nest itself functions as a shared physical information system. This suggests that cognition in this system is not located within individual ants, but is enacted through the co-dynamics of the colony and the structure it builds. We present preliminary experiments with more complex leaf configurations, showing that this process can solve increasingly challenging construction problems. Together, these results point to a distributed, brainless, and enactive form of cognition.

Tuesday, April 28, 2026

Time	Event / Speaker	Presentation Title
9:00 – 9:30 am	Breakfast	—
9:30 – 10:15 am	Ben de Bivort (Harvard University)	Bayesian Inference on biophysical models of connectomes
10:15 – 10:30 am	Discussion	—
10:30 – 11:00 am	Trainee talk: Yasuko Isoe (Harvard University)	Divergent spatiotemporal integration of whole-field visual motion in medaka and zebrafish larvae
11:00 – 11:30 am	Trainee talk: Siddharth Jayakumar (Harvard University)	Mice follow scent trails using predictive policies
11:30 am – 12:00 pm	Discussion	—
12:00 – 1:30 pm	Catered Lunch	—
1:30 – 2:15 pm	Noah Cowan (Johns Hopkins University)	Toward a Control Theory for Active Sensing
2:15 – 2:30 pm	Discussion	—
2:30 – 3:15 pm	Robert Datta (Harvard Medical School)	Unveiling structure in natural behavior
3:15 – 4:30 pm	Discussion	—

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Ben de Bivort: Recent progress in connectomics has opened new frontiers for understanding the underlying principles of neural circuits. By leveraging high-resolution maps of synaptic connections, computational models can simulate neural dynamics with unprecedented detail. However, it remains challenging to parsimoniously integrate circuit activity data with connectomic information to make biological insights. We propose a Bayesian framework as a principled method for bringing to bear existing data, enabling uncertainty quantification for inferring parameters of interest, as well as for predicted circuit outputs. To demonstrate this approach, we implement a simple spiking neuron model using leaky-integrate-and-fire dynamics in the Drosophila olfactory circuit, incorporating available firing rate data. We evaluate how models with varying levels of biological detail fit experimental data and examine how training on different subsets of data influences model predictions.

Yasuko Isoe: Cross-species comparisons offer powerful leverage for identifying conserved and divergent neural computations underlying innate behavior. Visual motion integration is a fundamental operation that stabilizes an animal's position relative to its environment, yet how its underlying algorithms vary across closely related vertebrate brains remains poorly understood. We investigated how zebrafish (Danio rerio) and medaka (Oryzias latipes) larvae implement visual motion integration using both free-swimming behavioral assays and head-fixed, tail-free preparations, the latter allowing us to confirm and extend our findings under precise stimulus control. Using whole-field motion stimuli, we found that the two species employ distinct spatiotemporal filtering strategies. Medaka pool motion signals over larger visual fields and weight peripheral inputs more strongly, whereas zebrafish rely more on motion signals directly beneath the body. Temporally, zebrafish respond robustly to brief stimuli, while medaka require longer stimulus durations and sustain motion-driven activity well after stimulus offset. Decomposition of turning behavior revealed separable control modules for large and small corrective maneuvers, with species differences arising primarily from prolonged temporal integration in medaka. Together, our results demonstrate how alterations in basic computational motifs — spatiotemporal pooling, gain, and persistence — can generate divergent visuomotor strategies across closely related vertebrate brains, offering a window into the evolutionary diversification of sensorimotor computation.

Siddharth Jayakumar: Animals must extract reliable information from noisy sensory signals. In olfaction, this is especially challenging, since cues are sparse and must be actively sampled. We asked how mice navigate odor trails under these conditions. Using an "infinite" paper treadmill, we find that mice rapidly learn to track trails with high precision. Disrupting bilateral sampling introduces systematic, lateralized errors, consistent with a comparison of signals across the two sides. Individual inhalations near the trail trigger rapid corrective movements. Interestingly, we find that mice do not follow trails purely reactively: deviations in tracking at unexpected trail bends reflected recent history, indicating the use of short-term memory. We have begun to investigate the neural substrates of this behavior, focusing on how sensory signals and predictive information are represented in the brain. Broadly, our results suggest that odor-guided navigation depends on combining immediate sensory input with a short-term internal estimate, enabling reliable tracking despite sparse cues.

Noah Cowan: Active sensing is often defined as "movement for the purpose of sensing." Here, I take a different perspective—that active sensing in biological systems is not a distinct class of behaviors, but rather a set of movement phenomena that arise from a control objective. Biological sensors adapt to persistent stimuli, acting like high-pass filters that tend to block "DC." Such "change-detecting" sensors can support efficient coding with a high dynamic range, and in engineering, bio-inspired event cameras are similar: they transmit information only when a pixel changes and, as such, are extremely fast and make efficient use of bandwidth for the right applications. However, such "AC" sensors pose technical challenges for control. Specifically, event-like biological sensors can cause a nonlinear system (1) to lose local linear observability, and (2) to become impossible to stabilize about an equilibrium point (Biswas, Sontag, Cowan, Eur J Control, 2025). Active sensing behaviors must emerge for stable control, even in the somewhat paradoxical setting where the task-level goal is to remain stationary. Here, I will discuss my lab's progress in analyzing how animals use active sensing behaviors to format sensory information, enhancing observability and control. I will also present our efforts to formalize controller synthesis with event-like sensors.

Robert Datta: Ethologists describing animals in the wild have long appreciated that naturalistic, self-motivated behavior is built from modules that are linked together over time into predictable sequences. Many such sequences are built to extract information from the environment. And yet, it remains unclear how the brain regulates the selection of individual behavioral modules for expression at any given moment, or how it dynamically composes these modules into the fluid behaviors observed when animals act of their own volition, and in the absence of experimental restraint, task structure or explicit reward. Here we use novel methods for characterizing spontaneous mouse behavior to reveal mechanisms used by the brain to create the architecture of self-guided behavior.

Wednesday, April 29, 2026

Time	**Event / Speaker**	**Presentation Title**
9:00 – 9:30 am	Breakfast	—
9:30 – 10:15 am	Kristin Branson (HHMI)	How can generative AI help us understand animal behavior?
10:15 – 10:30 am	Discussion	—
10:30 – 11:00 am	Tea Break	—
11:00 – 11:30 am	Trainee talk: Golnar Gharooni Fard (Harvard University)	The Geometry and Dynamics of Embodied Cognition: From Collective Architecture to Interspecies Navigation
11:30 am – 12:00 pm	Trainee talk: Wenyi Zhang	Mechanisms of Setpoint Control in Drosophila Navigation System
12:00 – 1:30 pm	Catered Lunch	—
1:30 – 2:15 pm	Bence Ölveczky (Harvard University)	Using neuro-biomechanical simulations to probe neural control of learned skills
2:15 – 2:30 pm	Discussion	—
2:30 – 3:15 pm	Pavan Ramdya (EPFL)	Object manipulation and affordance learning in Drosophila
3:15 – 4:30 pm	Discussion	—

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Kristin Branson: Understanding animal behavior at an algorithmic level — what animals attend to, how they form internal world models, goals, and plans, and how state maps to action — remains a central challenge in neuroethology. Large-scale behavioral experiments now produce trajectory datasets of extraordinary scale and complexity, but existing approaches necessarily compress this complexity to just a few dimensions. We argue that generative AI offers a path toward rich, query-able models of the data. We adapt transformer-based sequence modeling to multi-agent animal keypoint trajectories, treating behavior forecasting as analogous to next-token prediction. Our agent-based network inputs biologically-motivated sensory representations and outputs the distribution of future pose velocities. Our model captures statistical properties of the behavioral distribution. We have built a Python library that encapsulates the complexity of transforms relating raw keypoints and model inputs and outputs to make these tools extensible by the NeuroAI community and accessible to theorists and experimentalists. Finally, we argue that mechanistic interpretability methods allow us to query trained models through the natural framework of artificial neuroethology experiments.

Golnar Gharooni Fard: Biological behavior is fundamentally an emergent property of the coupling between an agent's physical form, its environment, and local interaction rules. In this talk, I explore the mathematical principles of this "embodied cognition" across two distinct scales: the stigmergic spatial memory of honeybee collectives and the real-time dynamic coordination of human-bird mutualism. I'll start by discussing static embodied intelligence through the lens of honeycomb construction. Using 3D-printed foundations to introduce controlled geometric frustration (including misalignment angles and lattice shifts) I demonstrate how honeybee collectives resolve structural mismatches through the adaptive placement of topological defects. I will show how these complex behavioral responses can be modeled as a physics-based potential minimization problem, proving that the hive's "intelligence" is a distributed response to local geometric cues. In the second part, I transition to "dynamic" coordination by examining the mutualistic search for honeybee nests between humans and honeyguide birds in Africa. Unlike the persistent memory of the wax comb, this interspecies cooperation requires real-time processing of noisy, stochastic signals. I present a data-driven model of this interaction as a coupled tracking problem. By analyzing the interplay between human engagement and a leaky integrator memory constant, I identify the sweet spots of temporal integration required to successfully filter bird behavior and maintain goal-oriented navigation. Together, these two projects demonstrate that a data-driven physics-inspired modeling framework, can uncover the fundamental rules of agent-environment coupling that drive adaptive behavior across biological scales.

Wenyi Zhang: Navigation provides a powerful system for studying how animals balance behavioral persistence with flexibility. During navigation, fruit flies often default to fast straight walking (or "menotaxis") in a barren environment, maintaining a stable heading setpoint over a long period of time. Conversely, when the local environment is enriched with sensory stimuli, flies often explore the environment with more frequent heading changes, either through directed steering driven by a sequence of updating setpoints, or through undirected turning driven by temporarily lifting the setpoint control. Although this framework suggests a central role for the setpoint in guiding navigation, the neural mechanisms for flexible setpoint control remain unclear. Here we identified hΔA, a central complex cell type involved in setpoint control. In an aversive heat paradigm, hΔA played an important role in the fly's sensory-driven deviation from the menotactic goal direction. We characterized hΔA population activity and found that it carries two separable activity components: a bump-like signal that encodes a slowly varying travel-direction-related setpoint, and a spatially uniform signal associated with turning. We further identified modulatory inputs to hΔA that shape hΔA activity. Together, these results support a model in which short- and long-timescale setpoints compete for steering control, and suggest a circuit mechanism by which flies balance directional persistence with flexible reorientation under changing sensory conditions.

Bence Ölveczky: The goal of my lab is to decipher the circuit logic by which the brain learns and controls motor skills. The standard mechanistic approach is to dissect the underlying circuits brain area-by-brain area, inferring function by relating recordings and perturbations within each to behavior. This runs into fundamental problems in highly recurrent systems, where activity in any one node is shaped by the dynamics of the whole, a problem compounded by the fact that the circuits we probe control a complex biomechanical body and not measurable features of behavior. I will discuss these challenges and present results suggesting that neuro-biomechanical simulation, leveraging advances in physics simulation and AI, can offer a powerful alternative window into the neural circuits underlying learned skills.

Pavan Ramdya: Many animals must manipulate objects to perform tasks like pushing away debris when navigating over complex, natural terrain. For previously unseen objects, efficient manipulation requires that their affordances–the possible actions one can perform upon them–first be learned through experience. However, the behavioral and neural mechanisms underlying the learning of object affordances remain largely unknown. To address this gap, we show that adult Drosophila melanogaster flies can learn to push novel spherical objects without being given any explicit reward. To do this, flies appear to learn the ball's pushability affordance: pushing is delayed when animals are first exposed to an immobile ball, and manipulating one ball accelerates pushing of a second one in a new context. Behavioral quantification of a large-scale neural silencing screen reveals that specific visual projection neurons and olfactory sensory neurons regulate initial reactions to the object while dopaminergic neurons and the mushroom bodies, a center for learning and memory in insects, are critical for generalizing object affordances. These findings open the door to a mechanistic understanding of object manipulation and affordance learning.

Thursday, April 30, 2026

Time	Event / Speaker	Presentation Title
9:00 – 9:30 am	Breakfast	—
9:30 – 10:15 am	Pulkit Agrawal (MIT)	What Robots Are Missing: Force Intelligence and Lifelong Learning
10:15 – 10:30 am	Discussion	—
10:30 – 11:00 am	Tea Break	—
11:00 – 11:45 am	Antonio C. Costa (Sorbonne University/Paris Brain Institute)	Unraveling the structure of behavioral variation: a dynamical approach to naturalistic data
11:45 am – 12:00 pm	Discussion	—
12:00 – 1:30 pm	Catered Lunch	—
1:30 – 2:15 pm	Elizabeth Tibbetts (University of Michigan)	What paper wasps can teach us about the evolution of animal minds
2:15 – 2:30 pm	Discussion	—
2:30 – 3:15 pm	Robert Wood (Harvard University)	The Mechanical Side of Artificial Intelligence
3:15 – 4:00 pm	Discussion and break	—
4:00 – 5:00 pm	George Lauder (Harvard University)	Fish schooling behavior from kinematics to hydrodynamics to energetics

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Pulkit Agrawal: Modern robots can plan sophisticated motions, yet they remain slow, brittle, and unreliable on tasks humans find effortless. The missing piece is not better planning, but better force reasoning: knowing when, where, and how much force to apply under uncertainty and across diverse tasks. Force intelligence, I argue, is a unifying principle for scalable robotics—bridging dexterous manipulation and whole-body control. However, even a force-aware robot that cannot learn from its own experience will remain brittle. Today's systems are effectively frozen after training, unable to adapt once deployed. Real-world autonomy instead demands learning in deployment: the ability to improve continuously from interactions, failures, and successes. In this talk, I will present our lab's recent work on lifelong learning and outline a future path for how combining it with force-centric design could enable reliable, useful robots in the real world.

Antonio C. Costa: Animal behavior varies widely, both within the same individual over time and between individuals. While often overlooked, this variation reflects hidden control variables and mechanisms that were shaped by evolution. For example, variation in behavioral traits can help populations withstand environmental change, while atypical motor patterns in neurological disorders may offer clues for personalized therapies. Comparing such complex behaviors is difficult. When dynamics are nonlinear and unfold over multiple timescales, standard metrics based on summary statistics often miss meaningful differences. To address this, we introduce a framework that encodes multiscale dynamics to compare behavior from data. By modeling nonlinear dynamics probabilistically (using transfer operators inferred from time-series data), we define a distance metric that captures behavioral differences across timescales. Tailored to finite, noisy datasets, our approach identifies principal axes of variation and enables rigorous clustering of individual trajectories. We demonstrate this framework in various biological systems, including bacterial chemotaxis and larval zebrafish locomotion, where the inferred axes of behavioral variation reflect underlying physiological variables and developmental histories.

Elizabeth Tibbetts: Why do animals differ in their cognitive abilities? Some animals fail at apparently simple tasks, while others have a remarkable capacity to collect, retain, and use information from the environment to guide their behavior. Although paper wasps brains are smaller than a grain of rice, Tibbetts will show that wasps can perform seemingly complex behaviors like individual face recognition, transitive inference, social eavesdropping, and concept learning. She will also describe experiments that take advantage of natural variation in behavior within and among wasp species to test how social interactions shape the development and evolution of cognitive abilities.

Robert Wood: Artificial Intelligence research typically focuses on perception, learning, and control methods to enable autonomous agents, including robots, to make and act on decisions in real-world scenarios. However, even the most capable AI without a well-designed physical structure is of minimal use for canonical robotics tasks. Our research is focused on the design, mechanics, materials, and manufacturing of novel robot platforms that make perception, control, or action easier or more robust for natural, unstructured, and often unpredictable environments. Key principles in this pursuit include bioinspired designs, smart materials for novel sensors and actuators, and the development of multi-scale, multi-material manufacturing methods. This talk will illustrate this philosophy by highlighting the creation of three classes of robots with unique hardware challenges: bioinspired microrobots, soft-bodied robots for manipulation, and robots for interacting with delicate marine life.

George Lauder: Do fish moving in a school reduce their energetic costs compared to swimming alone? If so, how does collective motion reduce the energy needed to move? Only within the last two years have experimental studies directly demonstrated that fish swimming in a group have lower energy expenditure than solitary locomotion. Most studies of how fish move in a collective have focused on understanding the potential benefits of swimming in fixed relative positions. But recent experiments on fish schooling behavior have revealed that fish within the school are nearly constantly rearranging their relative positions. In this talk I will show how fish in a school can save energy even if they do not maintain fixed positions. Analyses of water flow patterns within fish schools have been used to resolve this “paradox” and show that fish movement within a school creates hydrodynamic shelters with zones of reduced flow velocity that nearby fish can take advantage of.