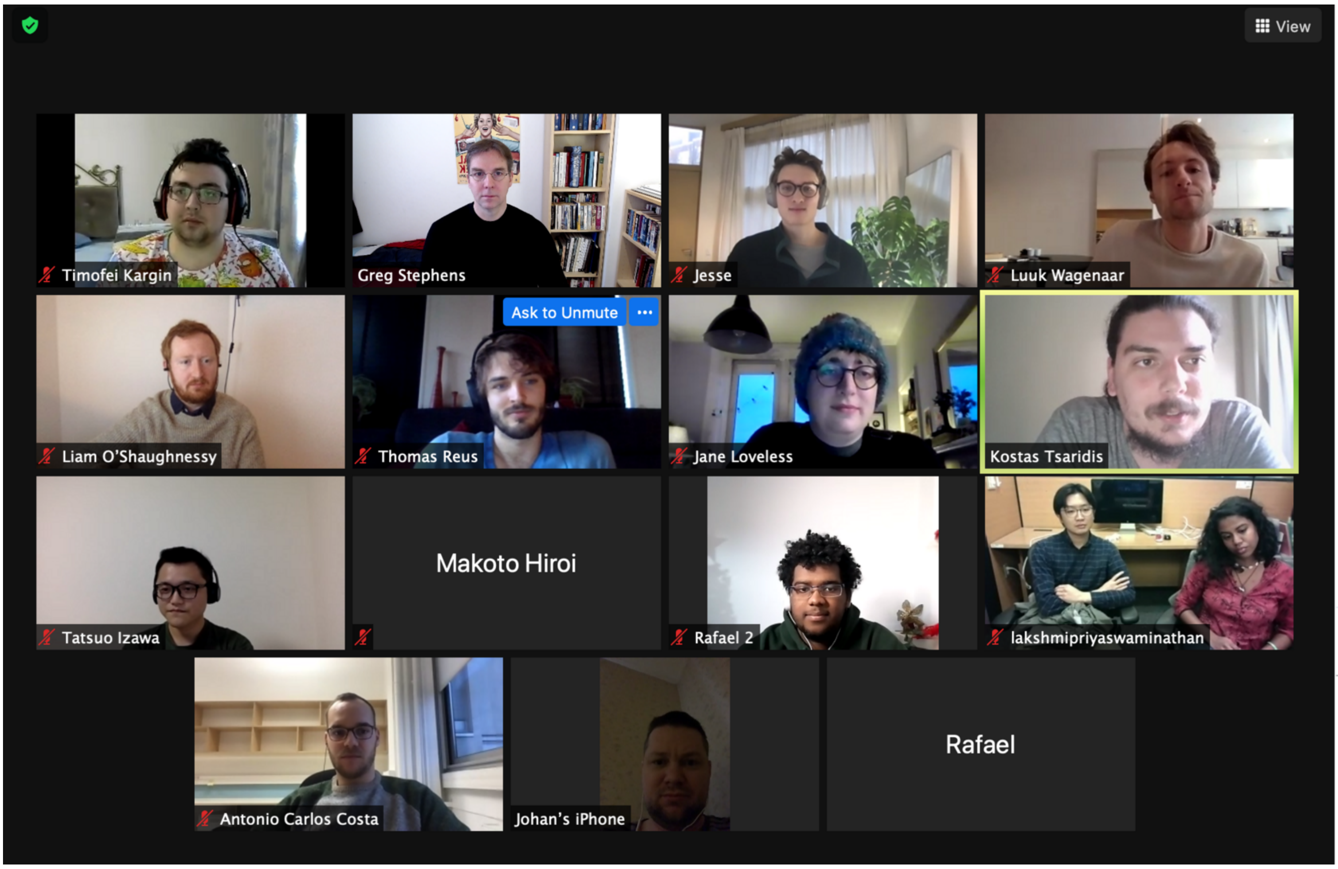
OIST OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY

Biological Physics Theory Unit (Greg Stephens)

FY2020 Annual Report

Biological Physics Theory Unit
Professor Greg J Stephens



Abstract

FY2020 was dominated by an external factor-the COVID-19 pandemic. COVID-related travel restrictions meant that all of our activities moved online. For this we were prepared; the Stephens Group has long been holding regulaor Zoom meetings and interacting scientifically through Slack. But our newer group members were often stuck in their home countires and social isolation was challenging. Despite the challenges, we worked seemingly even more closely as a team, both creating new lines of research and publishing widely across our ongoing projects.

1. Staff

- Prof. Greg J. Stephens
- Ms. Naoko Ogura-Gayler, Research Administrator
- Dr. Makoto Hiroi, Postdoctoral Scholar
- Dr. Jane Loveless, Postdoctoral Scholar
- Ms. Laetitia Hebert, Software Engineer

- Mr. Tatsuo Izawa, Technician
- Mr. Akira Kawano, Graduate Student (joint with Masai Unit)
- Ms. Lakshmi Swaminathan, Graduate Student (joint with Uusisaari Unit)
- Mr. Liam O'Shaughnessy, Visiting Research Student
- Mr. Antonio Carlos Costa, Visiting Research Student
- Mr. Simon Goorney, Research Intern
- Mr. Timofei Kargin, Research Intern

2. Collaborations

2.1 HFSP Program Grant

- The physics of social behavior in the 3-dimensional shoaling of zebrafish
- Type of collaboration: Joint research
- Researchers:
    - Professor Ichiro Masai, OIST Graduate University
    - Professor Joshua Shaevitz, Princeton University

2.2 Physics of Social Insect Behavior

- Type of collaboration: Joint research
- Researchers:
    - Professor Orit Peleg, University of Colorado
    - Professor Kasia Bozek, University of Cologne
    - Professor Sasha Mikheyev, OIST Graduate University

2.3 Dynamical Appoaches to Complex Systems

- Type of collaboration: Joint research
- Researchers:
    - Dr. David Jordon, Cambridge University

2.4 Physics of Squid Behavior

- Type of collaboration: Joint research
- Researchers:
    - Prof Sam Reiter, OIST Graduate University

3. Activities and Findings

3.1 Research Highlights

Behavior of Single Organisms (Tosif Ahamed, Antonio Costa, Laetitia Hebert, Jane Loveless, Lakshmi Swaminathan)

Our work on the behavior of single organisms offers our most mature demonstration for what we mean by "physics of behavior''. We address two primary questions: How do we characterize and understand the variability of posture-scale behavior and how can we use this variability to infer behavioral strategies and control? We integrate statistical physics, dynamical systems and information theory, using both a conventional ``forward'' style in which we create and explore models and their consequences, but also importantly in the ``inverse'' where we interrogate precision measurements to infer important quantitative concepts directly from data. We believe that such an inverse approach is an essential component in understanding animal behavior for which we may not know *a priori* the right universality class or even the most relevant theoretical concepts. We developed a new technique of state space reconstruction, with which we examined the behavior of the nematode worm *C. elegans* **(Ahamed et al)**. Our analysis revealed a low-dimensional chaotic attractor with interpretable dimensions and symmetric Lyapunov spectrum in the dynamics. In our deterministic picture, behavioral dynamics are an aperiodic wandering among an infinite number of unstable period orbits. The Lyapunov symmetry is indicative of damped-driven Hamiltonian dynamics underlying the worm's behavior and may point to the importance of elastic body biomechanics for control (work in progress). We are now expanding our dynamical ideas with an approach based on maximally-predictive ensemble dynamics. Within a reconstructed state space, we analyze dynamics through transfer operators; trading non-linear trajectory dynamics for linear, ensemble evolution, akin to the difference between Langevin and Fokker-Planck dynamics. Our ensemble approach (soon available as a preprint) connects stochastic and deterministic systems, and enables the principled detection of long-lived dynamics and collective states-points we explore in both model systems and data. Finally, in support of our modeling and theoretical work we have also developed new, deep learning techniques with associated, freely-available software for pose estimation in the worm **(Hebert et al)**, opening new imaging data and experiments for precise posture analysis.

Social Behavior in the Pairwise Fighting of Zebrafish in 3D (Simon Goorney, Makoto Hiroi, Tatsuo Izawa, Liam O'Shaughnessy, Akira Kawano)

Our collaborative, interdisciplinary team has produced a system capable of high spatiotemporal 3D imaging of multiple body points, across multiple fish, while maintaining individual identity. In the process, we developed an optically-transparent interior cage to control boundary reflections which strongly interfere with the tracking, and our own behavioral protocols to repeatedly generate fighting interactions. While our current focus is on the fighting behavior of male zebrafish, we are leveraging our imaging experience to understand the social behavior of squid in collaboration with the Computational Neuroethology Unit at OIST and led by group member Makoto Hiroi, as well as additional directions in zebrafish social behavior.

Two-body fighting behavior occurs throughout the animal kingdom to settle dominance disputes. Qualitatively, fights appear as a sequence of repeated, stereotyped dynamics that lead, ultimately, to a winner. Quantitatively however, little is known about the shorter-time behaviors that compose a fight and the longer-time dynamics of the dominance decision. We study fighting behavior in pairs of male zebrafish imaged at high spatiotemporal resolution in 3D. We leverage advances in convolutional neural networks to track multiple bodypoints of both fish while maintaining organism identity. We use these bodypoints to uncover key features of contest behavior; the fight onset is apparent through static and dynamic displays, followed by escalating aggression, culminating in distinct posture characteristics indicative of submission and dominance. Our approach offers a new system for the quantitative analysis of strongly-coupled social dynamics which can broadly inform models of mutual assessment.

Collective Behavior in Insect Colonies (Kasia Bozek, Yoann Portugal, Laetitia Hebert)

From cells in tissue, to bird flocks, to human crowds, living systems displaya stunning variety of group behavior. Yet a quantitative understanding of such interesting phenomena requires first tracking a significant fraction of the group members in natural conditions, a substantial and ongoing challenge. Through a series of computational advances we have developed the first method for markerless tracking of approximately all individuals in a colony of honey bees *Apis mellifera* **(Bozek et al, 2021)**. Social insects and honey bees prominently among them are remarkable for their own interesting natural behavior and also allow for colony-wide measurement and experimental manipulation. We leveraged advances in machine vision to solve two interrelated problems: (1) detection of highly similar objects in dense configurations and (2) matching of these detections into trajectories based on subtle visual features which are largely invisible to the human eye. Markerless methods can reveal important dynamics in brood and food stores which are otherwise difficult to measure, and will facilitate further advances by easing the burden and disturbance of manual labeling, also allowing in principle for the recording of multiple colonies. We additionally applied our tracking techniques to understand honey bee scenting **(Nguyen et al)**, and these efforts are now part of a more general collaboration in collective insect behavior with the Peleg group. Our techniques can also be generalized to other crowded systems where dense tracking is required, for example in our collaborative work in organoids **(Kok et al).** We are currently seeking appropriate modeling directions for these high-dimensional systems.

3.2 Professional Activiites

- GJ Stephens, Co-organizer (with G Berman) Emory-TMLS Physics of Behavior Virtual Workshop, April 30th (2020)
- GJ Stephens, Co-organizer (with O Peleg), Physics of Social Behavior Focus Session, APS March Meeting, Online Mar 15-19 (2021)

3.3 PhD Dissertations

Antonio Carlos Costa (Supervisor: GJ Stephens Co-supervisor: TS Shimizu)
Thesis Title: Physics of behavior across scales: A dynamical systems approach to the representation and understanding of animal movement
Vrije Universiteit Amsterdam: https://research.vu.nl/en/publications/physics-of-behavior-across-scales-a-dynamical-systems-approach-to

4. Publications

4.1 Journals and Preprints

1. L Hebert, T Ahamed, A Carlos Costa, L O'Shaughnessy & GJ Stephens, WormPose: Image synthesis and convolutional networks for pose estimation in *C. elegans. PLOS Comp Bio* **17(4)**:e1008914 (2021); https://doi.org/10.1371/journal.pcbi.1008914

2. K Bozek, L Hebert Y Portugal, AS Mikheyev & GJ Stephens, Markerless tracking of an entire honey bee colony. *Nat Comm* **12,** 1733 (2021); https://doi.org/10.1038/s41467-021-21769-1

3. DM Nguyen, ML Iuzzolino, A Mankel, K Bozek, GJ Stephens & O Peleg, Flow-Mediated Olfactory Communication in Honey Bee Swarms. *Proc Nat Acad Sci (USA)* **118(13)**:e2011916118 (2021); https://doi.org/10.1073/pnas.2011916118

4. T Ahamed, A Carlos Costa & GJ Stephens, Capturing the continuous complexity of behavior in *C. elegans. Nat Phy*s https://doi.org/10.1038/s41567-020-01036-8. See also J Loveless & B Webb, Chaotic worms, *Nat Phys News & Views* (2020); https://doi.org/10.1038/s41567-020-01058-2

5. R Kok, L Hebert, G Huelsz-Prince, YJ Goos, X Zheng, K Bozek, GJ Stephens, S. Tans & JS van Zon, OrganoidTracker: efficient cell tracking using machine learning and manual error correction. *PLoS One* **5(10)**:e0240802 (2020); https://doi.org/10.1371/journal.pone.0240802

4.2 Books and other one-time publications

Nothing to report

4.3 Oral and Poster Presentations

1. K Bozek, L Hebert, Y Portugal & GJ Stephens, APS March Meeting, Nashville US (Mar 2021)
2. L O'Shaugnessy, T Izawa, JW Shaevitz & GJ Stephens, APS March Meeting, Nashville US (Mar 2021)
3. AC Costa, T Ahamed, D Jordan, GJ Stephens, APS March Meeting, Nashville US (Mar 2021)
4. J Loveless, APS March Meeting, Nashville US (Mar 2021)
5. GJ Stephens, Physics@Veldhoven, Veldhoven, NL (Jan 2021)
6. GJ Stephens, Imperial College, London UK (Dec 2020)
7. GJ Stephens, UvA, Amsterdam NL (Sep 2020)
8. GJ Stephens, Emory-TMLS Virtual Workshop (Sep 2020)

5. Intellectual Property Rights and Other Specific Achievements

Nothing to report

6. Meetings and Events

6.1 Emergent Regularities in Collective Behavior

- Date: April 8, 2020
- Venue: Online
- Speaker: Dr. Eddy Lee, Santa Fe Institute

6.2 LOOPER: Inferring computational algorithms enacted by neuronal population dynamics

- Date: May 1, 2020
- Venue: Online
- Speakers: Connor Brennan and Prof Alex Proekt, University of Pennsylvania

6.3 Periodic orbits in turbulent flows

- Date: May 7, 2020
- Venue: Online
- Speaker: Dr. Nazmi Budanur, IST Austria

6.4 Learning strange attractors from time series with autoencoders

- Date: September 15, 2020
- Venue: Online
- Speaker: Dr. William Gilpin, Harvard University

6.5 When flow meets fish: insights into aquatic locomotion

- Date: September 16, 2020
- Venue: Online
- Speaker: Prof. James Liao, University of Florida

6.6 Social Cognition-Shaped by Social Complexity or Coercion?

- Date: December 9, 2020
- Venue: Online
- Speaker: Prof. Molly Cummings, UT Austin

Travels, Meeting

- COVID-19 and related travel restrictions prevented professional travel for the entirity of FY2020.

7. Other

Nothing to report.