Advanced Study Group 2015
Statistical Physics and Anomalous Dynamics of Foraging

(Convenor: Rainer Klages, Queen Mary University of London)

1 Background

Our Advanced Study Group (ASG) was motivated by cross-disciplinary research generating the new field of *Movement Ecology*, which aims at understanding patterns, mechanisms, causes and consequences of organismal movement. Recent advances in animal tracking technology and environmental monitoring yield data sets of higher spatio-temporal resolution and increasing size. In parallel, the theory of anomalous stochastic processes has made huge progress. Here anomalous refers to a mean squared displacement that grows nonlinearly in the long time limit hence characterizing stochastic processes that are more non-trivial than Brownian motion.

The focus of our ASG was to study foraging of biological organisms by bringing together the very different disciplines of nonequilibrium statistical physics and anomalous stochastic processes with the ones of mathematical biology and ecology of animal movements. A key topic was to assess the validity of the *Lévy Flight Hypothesis* (LFH), which stipulates that under certain conditions Lévy motion is optimal to find randomly distributed targets. Along these lines we aimed to shed light onto the ecologically and biologically relevant conditions and constraints to model and understand foraging.

2 People and activities

The ASG team members were chosen to represent the above fields of research: F.Bartumeus (CEAB-CSIC Blanes, Spain), theoretical ecology and data analysis of animal movements; D.Boyer (UNAM, Mexico), stochastic modeling of animal movements; A.V.Chechkin (NAS, Kharkov, Ukraine); anomalous stochastic processes; L.Giuggioli (U. of Bristol, UK), statistical physics of animal movement and interaction; R.Klages (QMUL London, UK), nonequilibrium statistical physics and anomalous diffusion; J.Pitchford (U. of York, UK), mathematical biology and data analysis of foraging. Our ASG was supported by a grant from the *Office of Naval Research Global*, which enabled us to host a 6-month project student and to externally collaborate with N.Watkins (Potsdam, D and Warwick, UK).

Our ASG started in July 2016 and ended in December 2016. It was perhaps the longest activity of this type in Movement Ecology so far. The basis of our approach was to inititiate a sound communication between experimental biologists and ecologists, and theorists in statistical physics and anomalous stochastic processes. Traces of such a communication can be found in literature on the LFH, however, exactly this debate reflects a lot of misunderstandings that needed to be resolved. For this purpose we invited 20 visitors, most of them clustered during two focus weeks. The first focus week included talks by five PKS members (V.Zaburdaev, H.Kantz, E.Altmann, B.Friedrich, S.Gupta); some further visitors were invited jointly with these PKS groups later on. Our ASG activities were thus very well embedded into research at PKS, and we very much benefitted from each other. Our second focus week featured a lecture series consisting of three talks by V.Mendez, F.Bartumeus and D.Campos, based on their recent textbook [1]. Over the 6 month period of the ASG, team members gave seven conference and nine external seminar talks or colloquia covering research related to ASG activities. Twelve articles and book chapters are accepted or got published already, seven more are submitted. Our ASG has both initiated and supported about fourteen ongoing projects. One project student was trained successfully.

3 Scientific results

Anomalous diffusion in movement ecology. The most important result of our ASG is a consensus between all team members about the status of the LFH. Our discussions converged onto the scenario of analyzing movement data summarized by Fig. 1. In this figure one version of the LFH (the Lévy Environmental Hypothesis) is represented by the top picture in the middle column, where the environment generates (Lévy) motion for a forager represented by a point particle that samples the environmental complexity. Our figure shows a way beyond the LFH by highlighting the importance to understand the precise interplay between extracting movement ecology data from real world measurements, and analyzing this data by advanced methods of statistical physics and (anomalous) stochastic processes in order to construct a mathematical model that can be verified by experiments. A position paper will summarize this point of view [2]. Related to this theme, ASG members published a Comment [3], a News and Views article [4], a Nature perspective article [5] and a book chapter review [6].

Figure 1 not yet publicly available; to be published as part of a paper by:
F.Bartumeus, D.Boyer, A.V.Chechkin, L.Giuggioli, R.Klages, J.Pitchford, N.W.Watkins (2016)

A toolbox for analyzing foraging data from an anomalous dynamics perspective. Motivated by our key result above, the need emerged to create a toolbox of important methods, well known to theorists, that experimental biologists and ecologists might apply in order to better analyze movement data. Guided by the LFH scientists have mainly focused on extracting probability distributions from movement data by testing them for power laws. This is insufficient if one includes the possibility of more complicated stochastic models beyond Lévy motion, which require more advanced statistical data analysis. Here extracting correlation functions, comparing time with ensemble averages in view of weak ergodicity breaking, and being aware of possible non-stationarity like ageing is a promising way forward. A joint paper on this topic is in preparation [7]. Related to this point, ASG members published a number of articles in which they study anomalous stochastic processes by sharpening the tools of mathematical modeling and methods of analysis: quantifying both non-ergodicity [8] and the tails of probability distributions [9], studying slow [10], spatially [11] and temporally modulated Lévy flights [12], and analyzing distributed-order diffusion equations [13]. Five articles are submitted, three further are in preparation.

Statistical analysis and stochastic modeling of biological movements Conversely, the ASG supported and triggered a number of projects that started from statistical data analysis of experimental movement data by aiming at constructing a mathematical model of the biological movement, cf. Fig.1. ASG members published an article on the problem of how to test for Lévy walks in movement data [14], another article on space use and search tradeoffs is submitted, three further articles on analyzing movements of penguins, cells and worms are in preparation.

First passage and first arrival times. An important topic is to study efficiency, optimality and reliability of foraging strategies. Mathematically this can be done by calculating first arrival and first passage time distributions as well as respective averages of first passage and arrival times. Multiscale random walks were analyzed along these lines in Ref. [15], another article on assessing intermittent Lévy-Brownian motion is under review [16]. The 6-month student project consisted of computing first arrival and first passage times for Lévy walks and flights. It was finished successfully by yielding a long report; a corresponding article will be submitted.

Resetting, reinforcement and memory. The talk by S.Gupta (PKS) during the first focus week injected the new concept of resetting from stochastic theory into ASG activities: After times drawn randomly from some probability distribution a point particle jumps back to a location where it started or came from previously. Biologically this may model home range behavior, where a foraging animal returns to a shelter. Along the same lines one can model reinforcement, where an animal returns to food sources it has found before. This requires to successively include memory into a stochastic process. Studying resetting is already a hot topic in stochastic theory. Our ASG triggered applications to animal foraging, which defines a completely new line of research in movement ecology. Four articles on home range models, Lévy flights with resetting, foraging with and localization by memory are in preparation.

4 Summary and outlook

Our ASG triggered a large number of new projects bringing together experimental biologists and ecologists with statistical physicists and stochastic theorists. Most importantly, it initiated a very fruitful exchange of ideas between these very different scientific communities by widening the scope beyond the LFH. Our activities created awareness for the different approaches used in the different disciplines by generating an important transfer of ideas in both directions. This was a big success but may only be considered as a first step. Our endeavour needs to be continued by organizing a larger international conference. This should bring together more scientists in order to establish a broad, sound basis for future work. Publishing a book that summarizes the state of the art in this new field might help to achieve this next important goal.

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