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Editors

The Mathematics of Movement

An Interdisciplinary Approach to Mutual Challenges in Animal Ecology and Cell Biology

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Preface

Quantifying and predicting the responses of biological entities to disturbances is key to the understanding of a vast array of processes occurring at all scales, from molecules and bacteria inside a microorganism, cells in a tissue, to humans and animals within an ecosystem. A natural metric used to infer such responses to perturbations is movement, which modern technology allows us to capture in great detail within cells, organs, tissues, and the environment. As the new generation of experimental probes and sensors is providing us with movement data of increasing resolution over extended periods of time and across multiple individuals simultaneously, we face the challenge of developing and integrating conceptual frameworks and methodologies to analyse and model the spatio-temporal dynamics of moving entities in a range of biological disciplines and beyond.

Given the ever-increasing level of sophistication required to interpret empirical observations, such challenges are customarily met by a continuous refinement and specialisation of the technical expertise within a discipline. But such advances, while certainly essential, bring with them the risk of siloed thinking, limiting the potential broader impact of knowledge transfer across disciplines. The set of mathematical tools to study movement is a paradigmatic example where such broader impact may be achieved, whereby progress from one area can be imported to the benefit of another area in a seemingly totally disconnected field. The reason that such possibilities arise is because the mathematical tools used to quantify movement processes, and their causes and consequences, constitute a language which, by its abstraction and generality, allows individuals from very distant disciplines to converse with one another. As illustrations of the similarities between applications in animal ecology and cell biology, one can think of the lessons learned in identifying the rules governing the spread of an infectious disease in an animal population that have guided quantitative studies on the growth of cancerous cells within a tissue, or the principles underlying cell chemotaxis that have helped quantify how environmental features influence animal migration. But cross-fertilisation has also occurred between biology and the engineering disciplines, e.g. the phenomenological laws explaining the collective murmuration of starlings and other birds have shaped the development of some of the path planning algorithms for robot swarms.

This book aims to disseminate the use of such a language, striving to facilitate a proliferation of techniques to quantify movement and enhance the reciprocal influence that seemingly unrelated fields of research may exert on each other. We thought it appropriate to coin the name *Mathematics of Movement* for such a language. It comprises the set of concepts, tools, and techniques that have been used across scientific domains to study movement in all its shapes and forms. Stochastic differential equations, partial differential equations, integro-differential equations, network theory, lattice and Brownian random walks, Monte Carlo methods, Bayesian statistics, and topological data analysis are all examples of quantitative approaches that form the backbone of the mathematics routinely used in the analysis and modelling of the movement of artificial objects and biological organisms. This book presents examples of some of these approaches with a focus on their application to animal ecology and cell biology.

It is within this philosophy of bridging disciplinary gaps that the idea of the book emerged. It came about following the 6-month research programme entitled "Mathematics of movement: an interdisciplinary approach to mutual challenges in animal ecology and cell biology", held in the second half of 2023 at the Isaac Newton Institute for Mathematical Sciences (INI) in Cambridge. The programme was organised and run by the present book editors in conjunction with Dr Guillermo Abramson from the Centro Atómico Bariloche and Instituto Balseiro, Bariloche, Argentina; Prof. Helen Byrne from the Mathematical Institute, University of Oxford, UK; Prof. Paul Kulesa from the Department of Biological Sciences, University of Notre Dame, USA; and Prof. Ran Nathan from the Department of Ecology, Evolution and Behaviour at the Hebrew University of Jerusalem, Israel. The programme saw the participation of around 200 scientists at different career stages, the majority of them being theoreticians but also with some experimentalists, from 24 countries across 5 continents for periods ranging from a few days to the entire duration of the programme. Participants came to present their research and discuss with other like-minded individuals interested in learning about other topics. It was precisely this strong interdisciplinary attitude that made the cross-fertilisation successful as evidenced by a survey conducted on 50 participants who overall indicated, as an outcome of their engagement with the programme, that they had initiated 44 new collaborations with scientists outside their own field.

As the book is the result of the many interactions that occurred at the INI, we first would like to thank all the programme participants for being the main source of inspiration. Our gratitude obviously does not stop here. As is customary with large endeavours, there are many other individuals and entities to thank starting from all the contributing authors, the referees who have helped maintain the high scientific standard of each chapter, the INI programme co-organisers, the administrative team at INI, the various colleagues that have encouraged us to complete the project, and the funding sources that supported the INI programme, which include the Engineering and Physical Sciences Research Council, the Development Assistance Committee, the Leverhulme Trust, the London Mathematical Society, the Newton Gateway, the Tuner Kirk Trust, the Rothschild Foundation, the Heilbronn Institute for Mathematical Research, and the University of Cambridge.

Finally, we conclude with a wish. And that is that the many scientists who already model and analyse movement phenomena across all application areas interact frequently, keep integrating their knowledge, and ultimately build a thriving interdisciplinary community, inching ever closer in making the mathematics of movement, for all intents and purposes, an interdisciplinary field of its own, advancing mathematics and science in tandem.

In memory of Paul Kulesa. On 15th March, 2025, our dear friend, colleague, and program co-organiser, Paul Kulesa passed away. Paul was a doctoral student of Professor James D. Murray FRS at the University of Washington, Seattle, where he received his doctorate in mathematical biology. Wishing to see model predictions being tested in the laboratory, he decided to become an experimentalist and trained under Professor Scott Fraser at the California Institute of Technology. He moved on to The Stowers Medical Center in Kansas to run his own laboratory, then to the University of Notre Dame, and most recently, to the Children's Mercy Hospital, Kansas City. Paul's work on neural crest has led to significant new findings in the field of collective cell movement, from the microscale genetic level right up to the macroscale tissue level. He was an excellent scientist who was always coming up with exciting, original ideas. He was warm, friendly, kind, highly supportive, and passionate about his science and had a wonderful sense of humour. He will be sorely missed by all who knew him. His work will live long into the future.

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