BROWNIAN RATCHETS

Illustrating the development of Brownian ratchets, from their foundations, to their role in the description of life at the molecular scale and in the design of artificial nano-machinery, this text will appeal to both advanced graduates and researchers entering the field. Providing a self-contained introduction to Brownian ratchets, devices that rectify microscopic fluctuations, Part I avoids technicalities and sets out the broad range of physical systems where the concept of ratchets is relevant. Part II supplies a single source for a complete and modern theoretical analysis of ratchets in regimes such as classical vs. quantum and stochastic vs. deterministic, and in Part III readers are guided through experimental developments in different physical systems, each highlighting a specific unique feature of ratchets. The thorough and systematic approach to the topic ensures that this book provides a complete guide to Brownian ratchets for newcomers and established researchers in physics, biology and biochemistry.

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From Statistical Physics to Bio and Nano-motors

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To our families

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Preface

This book is about Brownian ratchets, devices that rectify microscopic fluctuations. It was written with two purposes in mind. First, to introduce new readers to the field. To this is devoted the first part of the book, which treats, with as few technicalities as possible, the general ideas as well as set the broad range of physical systems where the concept of ratchets may be of relevance. The second purpose of the book is to address researchers already active in the field, by providing them with a single source for a general and detailed theoretical analysis of ratchets in the different regimes (classical vs. quantum, stochastic vs. deterministic) as well as with a coverage of experimental realizations with different physical systems, each highlighting a specific unique feature of ratchets.

No attempt has been made to provide the reader with an exhaustive list of references. There are excellent review papers, cited in the book, that already serve this purpose. We limit our reference list to the material we used the most, and to some historically important references which, despite their age, are still irreplaceable.

The book is divided into three parts. Part I covers, at an informal level, much of the material that will then be examined in depth in the rest of the book. As such, it can be used by the reader with a broad interest in the topic, but no specific need to go any deeper. This part starts with a historical overview of the Brownian ratchets. Definitions, basic ideas and fundamental concepts are introduced: from the very definition of Brownian ratchet, to the fundamental limitations imposed by the second law of thermodynamics. The historically important Brillouin paradox and Feynman ratchets are reviewed, and used to highlight the main ideas behind the concept of ratchets. This part continues by examining three fundamental models of ratchet devices, used to illustrate the general operation of a Brownian ratchet, and how directed motion is related to two fundamental requirements: out-of-equilibrium settings and symmetry breaking. This part concludes with an overview of the general relevance of the concept of ratchets. It is shown that the concept applies to very diverse fields, from biological systems to game theory.

Part II offers a detailed theoretical anlysis of ratchets. The relationship between symmetry and transport is examined in detail, thus formalizing a necessary condition, symmetry breaking, for the generation of directed motion. The concept of ratchets is also extended beyond the initial formulation in terms of rectification of Brownian motion. Noiseless (deterministic) ratchets are considered, as well as systems where Brownian (white) noise is replaced by Lévy noise. Quantum ratchets, both in the Hamiltonian and in the dissipative regime, are discussed and their unique features highlighted. Finally, a quantitative analysis of the operation of a ratchet is provided in terms of efficiency and coherency.

Part III examines experimental realizations of the ratchet effect in a variety of systems. Ratchets for colloidal particles, cold atom ratchets and solid-state ratchets are discussed. The aim is not to produce a complete list of experiments, already available in review articles. Instead, we tried to report on the different unique features of ratchets, which were highlighted by experiments with different systems. This part is concluded with a discussion of bio-inspired molecular motors. The relationship of ratchets with biological systems is an interesting one. On the one hand, ratchet mechanisms explain some intriguing dynamics at the molecular level. On the other hand, observed biological mechanisms have inspired the design of *artificial* Brownian motors.

In the last few years the authors were fortunate to have the opportunity to speak with many pioneers of the field. We thank all of them for all that we learnt from them, and in particular: Sergej Flach, Peter Hänggi and Fabio Marchesoni.

One author (FR) would like to express a special thank you to his first two PhD students, Michele Schiavoni and Ralf Gommers, with whom he started his long journey in the world of Brownian ratchets. He is also grateful to Sergey Denisov for being always available for many endless discussions on everything to do with ratchets and chaos. The list of people deserving a special thank you would not be complete without Eric Lutz, whose infinite passion for Lévy distributions was a constant source of inspiration.

Another author (DC) would like to thank Jesús Casado Pascual, for introducing him to the fascinating world of ratchets and rectifiers.

Last but not least, a big thank you to our children Marco Cubero, and Caterina Kukua and Ruggero Kwesi Renzoni, who managed to cheer us up every time we realized that everything we wrote had to be rewritten.