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Edited by Pierluigi Contucci , Cristian Giardinà
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ADVANCES IN DISORDERED SYSTEMS, RANDOM PROCESSES AND SOME APPLICATIONS

A unified perspective on the study of complex systems is offered to scholars of various disciplines including mathematics, physics, computer science, biology, economics and social science.

The contributions, written by leading scientists, cover a broad set of topics: new approaches to data science, the connection between scaling limits and conformal field theories, new ideas on the Legendre duality approach in statistical mechanics of disordered systems. The volume moreover explores results on extreme values of correlated random variables and their connection with the Riemann zeta functions, the relation between diffusion phenomena and complex systems and the Brownian web, which appears as the universal scaling limit of several probabilistic models. Written for researchers from a broad range of scientific fields, this text examines a selection of recent developments in complex systems from a rigorous perspective.

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Preface

Modern science is witnessing a peak of intense activity toward the study of complex systems. This new topic is a very heterogeneous variety of approaches, methods and perspectives that share the common attempt to understand the collective behavior of a very large number of units correlated by simple competitive and cooperative interactions. These types of investigations have indeed appeared several times in the past. Recently though, the availability of large databases and the advent of unprecedented computer facilities have created a fertile ground for the current boost. Moreover, the progress made in the studies of non-homogenous, disordered systems of the last two decades has produced new promising approaches and technical tools for applied research topics. The analysis of such objects has led to a fruitful dialog involving mathematics and physics as founding and guiding disciplines, with an increasingly growing contribution of specific problems from the socio-economic, biological and other sciences. The present book is a collection of selected contributions by leading world experts toward the process of building up a rigorous conceptual framework within these new ideas that have irrigated the exact sciences, revealing a host of new questions, strategies and solutions.

The volume opens with the contribution by Mario Rasetti and Emanuela Merelli that focuses on a new approach to Data Science that challenges the traditional ones. The authors, after a broad introduction that encompasses motivational arguments and epistemological reasonings, build up a general framework identifying it with a topological field theory of data. The theoretical physics scheme of field theory is proposed as a guide where the relevant information is encoded into topological features as it happens, for instance, in general relativity and its geometrical curvature theory. The content is grounded on a rich and articulated scientific culture and presents a wide set of novel and brilliant ideas. The strategy and vision introduced have the potential to widely impact the field by providing a unified, pre-axiomatic framework, that is able to guide instances and specific case studies.

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The contribution by Elena Agliari deals with stochastic processes for diffusion phenomena and statistical mechanics techniques for complex systems, showing the strong analogies between the two theories from a methodological point of view. In particular, after diffusion is initially analyzed and approached from different perspectives, the author provides the basic elements of the theory of random walks on graphs as paradigmatic models of diffusion phenomena. The quantum analogue of classical random walk is also addressed. The description of basic statistical mechanics models defined on infinite graphs is briefly reviewed in the third chapter in order to show that the main concepts characterizing random walks, such as recurrence, transience and spectral dimension, also determine the properties of these models. Finally, taking the Curie-Weiss model as an example, the problem of the explicit evaluation of its free energy is mapped into a random walk framework. This dictionary allows exploitation of some of the methodologies originally used in one field to apply them efficiently to the other. The clear and well organized exposition make this work a suitable starting point for scholars wanting to investigate topics at the interplay between diffusion phenomena and statistical mechanics.

The contribution by Francesco Guerra is, as typical of the author, towards a quest for a mathematically simple and physically deep understanding of the mean field spin glass phase. It starts with a brief summary of the classical Legendre dual (energy-entropy) structure that occupies a central role in the study of statistical mechanics models. The author therefore introduces a new kind of Legendre duality that occurs in disordered models. The latter is inspired by the interpolation methods and convexity arguments, of which the author is inventor and master, successfully used in the analysis of mean field disordered models (REM, GREM, SK and p-spin). The main features of this new Legendre duality are the facts that it appears as an inequality in the opposite direction with respect to the usual one and involves the covariance of the random interaction instead of the energy. Taking as a pedagogical example the REM model, the author shows how to construct in an explicit way the Legendre functional considering a variational problem involving the square of the Hamiltonian function. The author suggests moreover that this procedure works also in other cases and may provide a general framework to investigate the properties of disordered models from a new perspective. The general concepts introduced in this work, despite their deep meaning and consequences, are developed in a simple and clear way and can be useful to obtain new insights in the field.

The contribution by Louis-Pierre Arguin also finds its roots in the field of disordered systems. The work deals with the extreme value of correlated random variables, such as the energy levels of a spin glass model. The topic of Arguin's contribution is to show general arguments for obtaining the leading

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order behavior of the extrema of log-correlated random variables, as well as subleading corrections and fluctuations. The main ideas that Arguin emphasizes are the three steps that lead to the results: multiscale decomposition, dichotomy of scales and self-similarity of scales. He introduces the ideas with the Gaussian branching random walk for pedagogical reasons. But he also shows some key ideas of how to apply it to the two-dimensional Gaussian free field. Potential applications to seemingly unrelated problems are also discussed. For instance, the relation between the maxima of the characteristic polynomials of random matrices and the maxima of the Riemann zeta function on an interval of the critical line is analyzed.

The main topic of the contribution by Federico Camia is the continuum scaling limit of planar lattice models. This topic is at the interface between statistical physics and Euclidean field theory. The link between the two areas emerges via the scaling limit that turns a lattice model into a continuum model as the mesh of the lattice is sent to zero. The author chooses to focus on a concrete example, namely the random walk loop soup, that plays the role of the ideal gas (being made of non-interacting lattice loops) and that is also related to the discrete Gaussian free field. In the scaling limit the Brownian loop soup emerges, which is a model already appearing within the Schramm-Loewner Evolution (SLE) context. The model is also used to explain the deep connection between scaling limits and conformal field theory of two-dimensional critical systems.

The volume closes with the contribution by Emmanuel Schertzer, Rongfeng Sun and Jan Swart on the Brownian web and the Brownian net. The Brownian web is formally a collection of one-dimensional coalescing Brownian motions starting from everywhere in space and time, and the Brownian net is one in which the above is also branching. Brownian web and net arise as the diffusive scaling limit of many one-dimensional interacting particle systems with branching and coalescence. Here the authors focus on coalescing random walks and random walks in i.i.d. space-time random environments. The prominent role of Brownian web/net is due to their appearance as universal scaling limits of several other models. The authors argue why this is the case by considering several models: the biased voter model, true self-avoiding walks, true self-repelling motion, drainage networks and others. This contribution is clearly a great source of the current state of research on Brownian web and Brownian net, and will prove to be very handy for researchers who wish to be introduced to the area and work on it.

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