Principles of the Dynamics of Non-Equilibrium Systems

9 January to 30 June 2006

Report from the Organisers:
MR Evans (Edinburgh), S Franz (ICTP), C Godrèche (CEA, Saclay) and D Mukamel (Weizmann Institute)

S Wilkinson

MR Evans, D Mukamel, C Godrèche and S Franz

Scientific Background

The subject of collective phenomena in equilibrium systems is by now a mature one. Extensive studies over the last six decades have produced a clear understanding of the phenomenology as well as many rigorous mathematical results. On the other hand, systems that are not in thermal equilibrium are more poorly understood. Indeed, a general theoretical framework for the study of non-equilibrium collective phenomena is lacking and our understanding to date has relied on the study of specific models. By "non-equilibrium systems" we refer both to systems held far from thermal equilibrium by an external driving force and to the complementary situation of systems relaxing towards thermal equilibrium. Such systems display a broad range of phenomena, such as phase transitions and slow collective dynamics, which we would like to understand at a deeper level.

The study of non-equilibrium systems arises in many different contexts such as reaction–diffusion processes, interacting particle systems, driven diffusive systems, and the slow dynamics of both ordered and disordered glassy systems. It is a major research area which is represented in many different scientific communities throughout the world. In recent years the study of specific model systems has led to important breakthroughs in a variety of areas. Mathematical tools have been developed and some rigorous results derived pertaining to specific systems. These developments bring us closer to the point where we can ask questions of generality, both of techniques and results. This programme brought together different communities of physicists and mathematicians working in this diverse field.

Structure of the Programme

The programme was centred around three main themes:

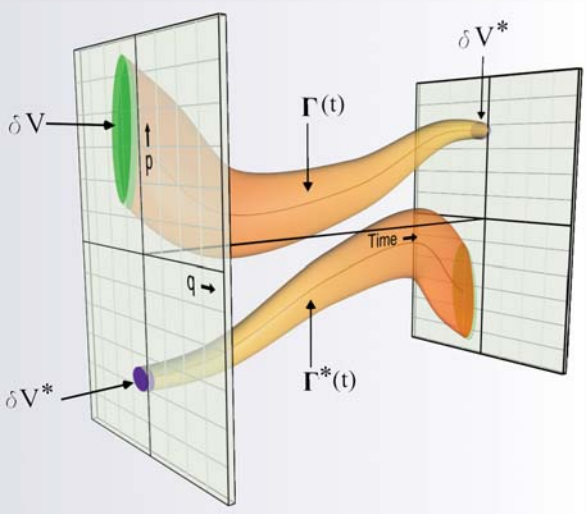
- Glassy constrained dynamics and ageing
- Driven diffusive systems and interacting particle systems
- Coarsening and persistence

Although these three themes are all concerned with systems governed by non-equilibrium dynamics, each explores a different aspect.

In the first, the systems are kept out of equilibrium not by external forces but rather as a result of a spontaneous failure of ergodicity. Glasses, either structural or spin glasses, are out of equilibrium due to the "rugged" character of the potential energy landscape, which traps them for long times in regions of the configuration space that have vanishing weight at equilibrium. In a wide variety of physical systems this results in a spectrum of long relaxation times.

In the second theme, the focus is on discrete models of non-equilibrium systems where the constituent elements (i.e., spins or particles) are driven by external forces and governed by dynamical rules that do not obey detailed balance or the equilibrium fluctuation-dissipation theorem. In driven diffusive systems a steady state held far from thermal equilibrium is eventually obtained and research has focussed on the novel properties of these non-equilibrium steady states.

D Evans and DM Carberry



An abstract (and highly schematic) representation of the time evolution of infinitesimal sets of phase space trajectories and their time reversed antitrajectories. The shrinkage and expansion of the cross-sectional area of these sets is associated with the loss and gain respectively of heat to a surrounding thermal reservoir. Understanding this diagram is key to understanding the proof of the Fluctuation Theorem

In the third theme, the approach to steady state is addressed. In many cases this approach takes place via a coarsening process where some spatial length grows unboundedly with time. There are time scales over which the local degrees of freedom remain unchanged during a coarsening process, and this results in persistence phenomena. Persistence phenomena in turn are closely related to the study of large deviations and extreme statistics in stochastic processes.

The programme's activities were organised around three workshops, each devoted to one of the themes. The first and last workshops each lasted a week and opened and closed the programme. The middle workshop was a two week long school forming a centrepiece for the programme. The activity of the programme naturally self-organised around these workshops, allowing the participants from various diverse communities to overlap and interact.

In total the programme had 60 long stay and 26 short stay visitors, with around 20 participants at any one time. We organised a seminar schedule of two seminars per week plus informal group discussions and expositions. Many participants gave seminars in other UK institutions including Bristol, Edinburgh, Heriot-Watt, Imperial, Manchester, Oxford and Warwick, as well as in various departments in Cambridge itself.

Workshops

Relaxation Dynamics of Macroscopic Systems

Workshop, 9–13 January 2006

Organisers: S Franz and J Kurchan

This workshop aimed to introduce the discussion on the dynamics of glassy and other relaxational systems out of equilibrium, which would be developed in the first two months of the programme.

The focus of the meeting was the off-equilibrium relaxational dynamics of systems with many degrees of freedom. The accent was on fundamental open problems in the theory of the dynamics of structural glasses, but also the dynamics of systems with non-equilibrium stationary states.

There were 25 seminars and 2 poster sessions. Among the seminars were a certain number of topical pedagogical reviews that served as introductions for students and young researchers: J-P Bouchaud presented an overview of the structural glass problem, with emphasis on phenomenological aspects and some theoretical scenarios; R Livi gave an introduction to the problem of heat conduction and the validity of the Fourier law in one-dimensional systems of interacting variables; C Godrèche discussed the dynamics of the zero-range process; and F Ritort discussed the application of recent off-equilibrium work theorems to compute free-energy differences between conformational states in biological systems.

The main topics that were discussed at the workshop were:

- Theoretical approaches to understanding the nature of the relaxation time in glasses, and its relationship with the growth of correlation scales
- Competing approaches based on kinetically constrained models and on spin glass theory
- Dynamical field theory for interacting particle systems on which some exciting new results have been reported by G Biroli
- Rigorous approaches to ageing dynamics presented by A Bovier, G Benarous and A Montanari

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Participants at the workshop on 'Non-Equilibrium Dynamics of Interacting Particle Systems'

Non-Equilibrium Dynamics of Interacting Particle Systems

School, 27 March–7 April 2006

Organisers: JL Cardy, MR Evans, D Mukamel and H Spohn

This school, sponsored by the EC, consisted of a programme of mini-courses of typically three hours' duration. Each course was pedagogical and aimed to bring young researchers from different backgrounds to the forefront of a broad and rapidly developing field. The school was an outstanding success attracting around 120 participants from 17 different countries.

Sixteen lecturers covered a variety of topics in the broad area of the title. Among the more prominent themes we would list fluctuations and large deviations in non-equilibrium systems; theoretical and experimental aspects of fluctuation and work theorems; mathematical models of self-organised criticality; the dynamics of granular media and traffic; a model of stochastic mass transport and condensation; and stochastic Loewner evolution. In addition to the lectures there were four contributed seminars on specific topics, which complemented the broad reviews of the lecture programme, and four timetabled poster sessions. The poster sessions attracted over 40 contributions and proved a popular forum for discussion, particularly for postgraduate students and postdoctoral researchers. The general atmosphere was very conducive to discussion and this allowed communication between the different communities that were represented at the school. The reaction of participants was overwhelmingly enthusiastic and some rated it the best scientific meeting they had ever attended.

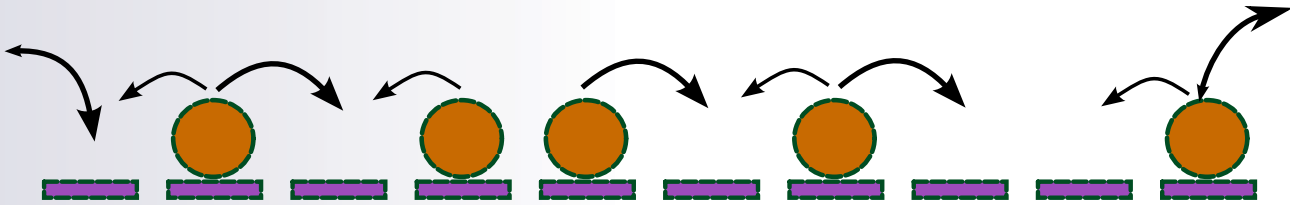
First-Passage and Extreme Value Problems in Random Processes

Workshop, 26–30 June 2006

Organisers: C Godrèche, S Majumdar and S Redner

This conference focussed on fundamental issues of first-passage processes and extreme value statistics, as well as on the applications of theory to granular matter, interfaces, biological processes, finance and the climate. It helped to develop connections between fundamental theoretical ideas and phenomenology by bringing together probability theorists, mathematicians and physicists. We anticipate that these interdisciplinary interactions will stimulate new collaborations and research initiatives in the near future.

On the theoretical side, a number of stimulating talks were given that provided a good snapshot of the current state of the art in the field. S Majumdar highlighted an unexpected relationship between first-passage properties of random walks in three dimensions and the maximum of a random walk in one dimension. A Comtet gave a stimulating and pedagogical talk that explained deep connections between the statistical properties of Brownian excursions, rooted trees and fluctuating interfaces. A Bray gave a comprehensive survey of first-passage phenomena in complex stochastic processes, such as random acceleration and random walks in shear flows. He also discussed first-passage properties of the persistence problem and various prototypical diffusion-controlled reactions. T Burkhardt gave a



The asymmetric exclusion process: a deceptively simple system of hopping particles which forms a fundamental non-equilibrium model

thorough discussion of some of the intriguing solved and unsolved problems in random acceleration processes, with applications to granular matter and polymers. Finally, C Godrèche discussed extensions of the Lévy arc-sine law for occupation time statistics in coarsening spin systems.

A wide range of applications of fundamental theory were presented by a complementary subset of the speakers. M Kearney outlined a number of basic problems in queuing theory that can be formulated as first-passage phenomena with exact solutions. O Benichou presented a novel approach for intermittent searching that combines two disparate components: a diffusive searching state and a ballistic-motion relocation state. Optimising a search that consists of these two components leads to novel scaling laws. J-P Bouchaud gave a nice overview of the role of long tails in microscopic distributions on the eigenvalue statistics of random matrices and in the statistical mechanics of disordered systems. Y Klafter discussed the application of Lévy flights and their influence on the first-passage statistics of biological processes, such as DNA translocation through pores, enzyme activity and dynamic force spectroscopy. Both Z Rácz and S Redner discussed the application of extremal ideas to understand the statistics of record temperature events in long-time climatological data.

C Dasgupta and H Taitelbaum highlighted how the theory of first-passage properties can be successfully employed in understanding experimental observations regarding the temporal behaviour of growing interfaces in fluctuating steps of crystals and growing droplets. These talks made a bridge between the theoretical and experimental studies of persistence and first-passage properties.

The overall atmosphere of the workshop was highly interactive and we believe that a variety of collaborations has been initiated as a direct result of the conference. There were also many young researchers and students in attendance and the conference provided these people with an invaluable introduction to the state of the art in the field. Finally, an important, but hard to quantify, element of the conference was its breadth, which afforded researchers the opportunity to learn about unexpected connections and applications of first-passage and extreme statistics problems.

Outcome and Achievements

The programme brought together researchers, students and postdoctoral workers from three main areas: glassy and constrained dynamics, driven diffusive systems, and coarsening dynamics and persistence. This mixture of people with different backgrounds and scientific interests resulted in many fruitful discussions and cross-fertilisation. The two workshops and one school, each centred around one of the main topics, served as focal points. This structure provided ample opportunities for interaction among the various groups. The school allowed students and young researchers to meet leading figures in this field and to be exposed to pedagogical reviews. The two workshops brought

S Wilkinson

Participants at the workshop on 'First-Passage and Extreme Value Problems in Random Processes'

their participants to the forefront of research in these areas, raising many open problems and suggesting new directions.

The programme, school and workshops were extremely productive and resulted in many new ideas and collaborations on a wide range of topics, which are now being pursued by the participants. Here, we mention briefly some of these directions.

In the field of glassy dynamics, topics include the development of new multi-point dynamic susceptibilities which are able to capture the dynamical behaviour of glassy materials near the glass transition; better understanding of the role of interface free energy of structural glass, which is a key ingredient in modelling these systems; the study of the structure and landscape of random functions; and progress in studies of models of diffusion in random potentials.

In the area of driven diffusive systems and interacting particle systems we have seen the development of traffic models in which, unlike most commonly studied models, jammed flow takes place via a phase transition; various generalisations of the zero-range process, a model that captures many generic features of driven systems far from thermal equilibrium; and the exact solution of the asymmetric exclusion process with many species of particle, another archetypal driven model, through the connection of an algebraic matrix-product approach with queueing theory.

In the realm of coarsening and persistence, interest was stimulated in curvature-driven coarsening; the statistics of records; and models of epidemic spread and disease diffusion.

Bringing together people working on the work and fluctuation theorems, a subject which has been hotly debated in recent years, resulted in better clarification of some of the subtle issues in this growing field. In addition, progress was made on fluctuation theorems in stochastic models and periodically pumped systems.

We hope that the sum of this activity and its current development will leave a lasting legacy.

Publications

The programme has fostered many new collaborations which have already resulted in some publications, but which should come fully to fruition over the next few years. A special issue of the *Journal of Statistical Mechanics: Theory and Experiment* is planned for 2007 containing invited papers representing the main themes and prominent directions that emerged during the programme.