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Helsinki University of Technology, Finland

Fluctuations and Scaling in Materials

&

Stochasticity and Non-Linearity in Material Response

StatPhys 23 Satellite Meeting

ESF activity

4th – 7th July 2007

Todi, Italy

TEKNILLINEN KORKEAKOULU
TEKNISKA HÖGSKOLAN
HELSINKI UNIVERSITY OF TECHNOLOGY

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Istituto dei Sistemi Complessi - CNR, Italy

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Book of Abstracts

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About the meeting

Statistical physics is a fundamental tool necessary to understand the behaviour of matter, and is becoming ever more important in the modern world of carefully engineered materials. The presence of disorder and heterogeneities creates spatial and temporal fluctuations at all scales and often a sample is manifestly out of equilibrium necessitating the tools of non-equilibrium statistical mechanics. These phenomena are intractable with textbook engineering-oriented methods or classical thermodynamics. Interactions can amplify the fluctuations and lead to the emergence of non-trivial size effects and instabilities.

The aim of this satellite meeting to StatPhys 23 is to bring together theorists and experimentalists working in phenomena of relevance for the statistical mechanics community, having their roots in materials science. Aspects of primary focus for the conference range from the noise phenomena present in a system responding to external (mechanical, magnetic, electric) perturbations to theories of critical phenomena applied in this field, to experiments looking for novel signatures of statistical behaviour, to scaling phenomena in material-related problems. These include the mechanical behaviour of materials - fracture and plasticity, Barkhausen noise in magnetic materials, electromigration, vortex noise in superconductors, martensitic transformations and much more....

The conference program includes, as a special session, the workshop "Stochasticity and Non-Linearity in Material Response" as part of the ESF activity "Stochastic Dynamics: Fundamentals and Applications".

CONTENTS

INVITED CONTRIBUTIONS

Scaling Properties of Fracture Surfaces and Implications on Crack Growth Models

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Failure of heterogeneous materials continues to pose significant challenges: stress enhancements in the vicinity of cracks indeed makes classical homogenization methods irrelevant to relate their toughness or lifetime to the fracture processes occurring at the microstructure scale. Crack surface roughening is a consequence of these local processes. We showed recently that fracture surfaces exhibit anisotropic scaling features, reminiscent of interface growth problems, characterized by two independent critical exponents, the roughness exponents measured along and perpendicular to the direction of crack growth respectively. Different materials were investigated. Different sets of critical exponents were measured whether the surfaces are examined at scale below or above the size of the damaged zone. In this latter case, model of crack growth derived from linear elasticity theory succeeds to account for the experimental observations. In this model, the onset of crack propagation can be interpreted as a dynamic phase transition, which will be briefly discussed.

A Lattice Gas Approach to Studying Fluctuations in a Sheared Granular Medium

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Granular materials distribute external loading through a heterogeneous pattern of filamentary contact forces i.e. they exhibit spatial fluctuations in the distribution of force. Observations of sheared experimental systems have revealed that the largest contact forces, i.e. those greater than the mean, are exponentially distributed. Molecular dynamics can be applied to simulate the shear of granular particle systems, where particle-particle interactions are described by detailed repulsive elastic forces subject to dissipation. An alternative statistical approach will be presented, an adaptation of a Granular Lattice Gas, in which particles are entities of unit mass and velocity that interact through elastic and inelastic collisions upon a hexagonal lattice. Force chains are identified as the continuous paths of contacting stationary particles between the top and bottom shearing plates, excluding non force bearing loops and dangling-ends. The description of static force in the system is crude and is measured by taking the number of force chain particles present at an instant in time. The model is dynamic and temporal fluctuations in the force chains can also be studied. The condition for granular rearrangement or slip is also crude with a force chain breaking at any point with an equal probability that depends on the shearing rate. Given such simplicity, it is remarkable that the exponential distribution of contact forces described above is recovered from this lattice gas model. In addition, our results reveal in agreement with experiment that the onset of the force chains in a sheared granular medium can be identified with a continuous transition in static force as the granular density is increased.

Crackling Noise: From Magnets to Earthquakes

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Models suggest that the earth and magnets crackle alike! We show how recent studies on Barkhausen Noise in magnets driven by a slowly increasing magnetic field shed light on modelling the statistics of earthquakes in inhomogeneous fault zones, and motivate new ways to analyse seismic data. In particular we focus on the universal, i.e. detail independent, effects of disorder in both cases. The studies draw on methods from the theory of phase transitions. Applications to other crackling systems are also discussed.

Barkhausen Noise in Soft Magnetic Materials

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We review the statistical properties of the magnetization noise produced by the jerky motion of domain walls in magnetic materials, known as Barkhausen noise. We show how the scaling properties of the Barkhausen signal can be understood in terms of depinning transition of the walls, with critical exponents corresponding to two different universality classes. In addition, we present the most recent results on the time asymmetries of the signal which reveal subtle properties of the magnetization dynamics, as the existence of an equivalent negative mass for domain walls due to the eddy current's counterfield.

Fluctuations and Scaling of Steps on Crystal Surfaces: Revelations from Random Matrix Theory

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Fluctuations of steps on surfaces are analysed by analogy to Brownian motion of strings or to worldlines of fermions in 1D. The former, well-studied perspective gives insight on the novel fluctuations of facet edges. The latter leads from a simple mean-field solution for the step-spacing distribution to the Calogero-Sutherland model, random matrix theory, and a sophisticated but still simple expression generalizing the Wigner distribution. We applied the approach to numerical and experimental data. Going beyond equilibrium, we derived a Fokker-Planck equation to describe relaxation from arbitrary initial configurations and applied the Wigner expression to the distribution of capture zones in island growth, deducing from the exponent the critical-nucleus size and the dimensionality.

Work supported by NSF-MRSEC, done in collaboration with A. Pimpinelli, E.D. Williams, M. Giesen, and H. Ibach, and many in our groups.

The Dynamics of Precursors to Frictional Sliding

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The dynamics of frictional motion are governed by the nature of the interface separating two sliding materials. We report that the spatial profile of the contact-area along an interface is a dynamic quantity which evolves via a discrete sequence of rapid crack-like precursors to overall motion. These precursors, which are generated at stress levels much lower than the critical stress for sliding, significantly modify the initially uniform contact area profile. Thus, when overall sliding finally occurs, the contact area is highly non-uniform in space. These results suggest a fundamentally new view of the processes leading to frictional motion with ramifications to earthquake dynamics and material failure.

Universal Domain Wall Dynamics in Disordered Ferroic Materials

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The dynamics of driven domain walls (DWs) is studied in disordered uniaxial ferroics like periodically poled ferroelectric $KTiOPO_4$, quantum ferroelectric $SrTi_{18}O_3$, relaxor ferroelectric $Sr_{0.61}Ba_{0.39}Nb_2O_6$, ultrathin ferromagnetic multilayers Pt/Co/Pt, and discontinuous magnetic metal-insulator multilayers $(Co_{80}Fe_{20}/Al_2O_3)_{10}$ with ac susceptibility and domain imaging. Sideways "creep" and "slide" motion - well-known from dc excitation - is mapped onto characteristic dynamic modes in the susceptibility spectra in Cole-Cole presentation. They are complemented by "switching" at high field amplitudes and by "DW segmental relaxation" at high frequencies, respectively. Scaling theory helps to understand the dynamic "relaxation-to-creep" transition, while the crossover between the modes "creep", "slide" and "switching" is numerically modelled by use of the Edwards-Wilkinson equation of DW motion.

Ultra Slow Motion of an Interface Pinned by Impurities

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Many experimental systems can be modelled as interfaces pulled by a force on a disordered landscape. In all these systems the physical properties are drastically modified by the existence of impurities in the material on which the interface pins. While for large forces the interface simply slides, for small forces it is pinned by the impurities. Motion is still possible thanks to thermal kicks, but becomes exceedingly slow. The relevance for applications of this regime has motivated a continuous research activity during the last two decades. In spite of these efforts, the slow motion of the interface has remained numerically inaccessible. We have developed a new technique that allows to overcome this problem and to get the important physical quantities characterizing the steady state ultra-slow motion. In my talk I will explain this technique, describe the different characteristic lengths involved in the motion and discuss the nature of the so-called depinning transition.

Dynamical Noise and Avalanches in Quasi-Static Plastic Flow of Amorphous Solids

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We will review recent results on amorphous systems subjected to simple shear in the athermal, quasistatic limit. The athermal quasistatic trajectories are shown to separate into smooth, reversible elastic branches which are intermittently broken by discrete catastrophic plastic events. Atomistic computer simulations indicate that these events present a broad distribution of sizes, and can be seen as self-induced avalanches of local elementary rearrangements. Strikingly, data obtained using differing interaction potentials can be brought into quantitative agreement after a simple rescaling, emphasizing the insensitivity of the emergent plastic behavior in these disordered systems to the precise details of the underlying interactions: the results should be relevant to understanding plastic behavior in systems such as colloidal or metallic glasses well below their glass temperature, soft glassy systems (such as dense emulsions), or compressed granular materials. A mean-field model of plasticity is then analysed, based on the dynamics of an ensemble of shear transformation zones, interacting only via intrinsic dynamical noise generated by the flips themselves. The model captures the emergence of avalanches, yet with scaling properties which are highly sensitive to the description of elastic couplings.

Spontaneous Shear Localization in a Model Brittle Solid

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To date, the most studied statistical models of brittle materials have been so-called “random fuse” models. Such models are well-suited to studies of tensile fracture, but lack excluded volume interactions which, in shear fracture, carry significant shear stress and prevent interpenetration of damaged surfaces. To account for these effects, we modify a 2D amorphous Lennard-Jones (LJ) model. LJ bonds that form during deformation are assigned a reduced interaction strength relative to initial bonds; this accounts for loss of cohesion via damage (in the same spirit as the fuse models) while maintaining hard-core repulsion to prevent interpenetration of opposing sides of damaged surfaces. We will compare and contrast various aspects of the brittle response of this model with a standard LJ model which responds in a ductile way.

Intermittent Subgrain Dynamics During Plastic Deformation Monitored by High-Angular 3DXRD

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By means of high angular 3-Dimensional X-ray diffraction (3DXRD), individual subgrains can be identified within a single grain in the bulk of a polycrystalline, macroscopic specimen. The observed broadened reflection constitute of individual sharp peaks superimposed on a broad cloud of enhanced intensity. Their sharpness in all directions of reciprocal space and their integrated intensity allows their identification with almost dislocation-free subgrains. In this manner, the evolution of the dislocation structure can be monitored during in-situ loading. The dynamics of individual subgrains during in-situ tension displayed unexpected intermittent dynamics with subgrains emerging and disappearing in the course of deformation, indicating that the dislocation structure is more volatile than commonly assumed. Interpretation of these findings and more recent results from other loading conditions are discussed.

Colloidal Crystals and Glasses: Tools for a Multiscale Analysis in Plasticity?

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Micrometer-size colloidal particles form phases (gas, liquid, glass, crystal) similar to those formed by atoms in different states of matter. Due to the large length- and time scales, colloidal particles can be studied by optical microscopy, making colloidal systems powerful models to study dynamical processes in condensed matter at the “atomic” scale.

We investigate the formation of defects in crystals, and the mechanism of strain relaxation in glasses. We observe that strained colloidal crystals exhibit dislocations that show remarkable similarities to dislocations in atomic crystals. Using a laser diffraction microscopy setup and confocal microscopy, we visualize the nucleation, motion and topology of these defects on a range of length scales down to the particle scale. Confocal microscopy allows us to determine the positions of the individual particles in the solid phases in three dimensions, and to determine the local strain field associated with the particle displacements. We apply this technique to visualize the three-dimensional strain distribution in strained glasses, enabling us to obtain fundamental insight into the mechanism of flow in these materials. I will elucidate the interplay between applied and local strain, and thermal fluctuations that determines macroscopic flow.

Failure of Snow and Dry-Snow Slab Avalanche Release

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Snow is a sintered material at high homologous temperature under terrestrial conditions. This high temperature, and the consequently high vapour pressure, lead to rapid changes in shape and bonding properties, called metamorphism. Under shear loading snow shows a strain softening behaviour indicating that during shear deformation leading to failure, two processes with different characteristic times compete: bond breaking and bond formation (re-bonding or sintering). The different characteristic times explain the strong rate-dependence of snow strength. Recent measurements of fracture energy (GII = 0.02 J m^{-2}) suggest that snow is one of the most brittle earth materials (even if considering that the mode I fracture energy is about 10 times larger). Various scale issues impede direct application of experimental laboratory results to the snow avalanche problem. The release of a dry-snow slab avalanche is essentially a fracture process. Below a cohesive slab along an extended plane of weakness a fracture spreads from a local failure with the result that high tensile stress and tensile fracture develops up-slope – and eventually the whole slab releases. Spatial variations in snowpack properties strongly affect the avalanche formation process. The relation between the scale of variation and the critical crack length in the fracture process (which is estimated to be about 0.5 m) seems to be crucial. Numerical modelling across scales – taking into account the variations in material properties – is needed to achieve useful results for avalanche mitigation purposes.

Driven Disordered Periodic Media with an Underlying Structural Phase Transition.

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We study the non-equilibrium steady states of a crystal whose ground state can be tuned through a square-triangle transition, driven across quenched random background. We obtain a complex sequence of novel dynamical states: plastic, anisotropic hexatic, dynamically stabilized triangle and square phases and intermediate regimes of phase coexistence with anomalously slow dynamics. Finite size scaling arguments and defect structure analysis establish the reality of the hexatic phase, indicative of a KT type freezing transition. We suggest analogy of our continuum model with XY model in magnetic field. Noise studies in coexistence phase show highly correlated motion with 1/f noise and breakdown of Koshelev-Vinokur proposal of shaking temperature. Our study reveals dynamic nucleation under external fields. Such states, as we obtain, should be observable in transport experiments on mixed phases of several superconductors and on adsorbed colloid monolayer.

Slow Crack Growth: Brittleness, Plasticity and Disorder

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We present experimental studies of slow crack growth in various sheets. In paper sheets, crack growth is intermittent. The average behaviour as well as the intermittent statistics are compared to a model of thermally activated rupture in brittle materials, with or without disorder. The comparison suggests elementary rupture events occur at a nanometer scale. In polycarbonate sheets, we evidence the effect of visco-plasticity on crack dynamics. The crack growth is clearly correlated to the elasto-plastic transition dynamics that follows an Eyring-Arrhenius law. However, a full description of the crack dynamics requires an additional term, the same one that was needed to describe growth in paper.

Hysteresis and Metastability in Martensitic Transitions

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Martensitic materials are an example of ferroic materials displaying a first-order phase transition which, in many cases, occurs in athermal conditions [1]. The order parameter that displays the discontinuous character is the deformation or strain and the conjugated force is the applied stress. The transitions show many features parallel to those observed in ferromagnetic systems: metastable evolution, rate independent hysteresis and avalanches [2]. Some of the basic features of this behaviour can be studied by the paradigmatic model for athermal first-order phase transition in disordered system: the T=0 RFIM driven by an external field with metastable dynamics.

[1] F. J. Pérez-Reche et al., PRL 87, 195701 (2001).
[2] E.Vives et al. PRL 72, 1694 (1994).

Crackling Plasticity: Why this was not Discovered Earlier?

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Using two independent experimental methods, acoustic emission and high-resolution extensometry, to probe the collective dislocation dynamics in various metallic single crystals, we show that the jerky character of plastic deformation, revealed several years ago on ice single crystals, appears as a rule rather than an exception. This crackling plasticity is observed in single- as well as multi-slip situations, and is not significantly influenced by forest hardening. Strain bursts are however limited in size by a non-trivial finite size effect resulting from a strongly anisotropic spreading of dislocation avalanches over lamellar structures. This explains why macroscopic strain curves are smooth and why crackling plasticity was not discovered earlier.

Small is Ugly: Microcrystals, Dislocation Avalanches and the Limits of Formability.

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The stress-strain curves of plastically deformed microcrystals display widely distributed jumps (strain bursts) which result from the collective avalanche dynamics of the interacting lattice dislocations. By combining 3D dislocation dynamics simulations with statistical analysis, we demonstrate that these bursts exhibit a universal size distribution (a truncated power law) which does not depend on material parameters or deformation geometry. A simple scaling relation which relates the cut-off to the system size and driving mode.

At small specimen sizes, the localized strain increments produced by the bursts are so large that formability may be lost completely. The combined effects of burst-like deformation and strain localization are illustrated for the bending deformation of thin monocrystalline wires, where they result in ever more ugly shapes as the wire diameter decreases to the sub-micron range.

Role of Disorder in the Size-Scaling of Material Strength

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Understanding the specimen size dependence of materials strength has been a fundamental scientific problem for centuries with important practical implications. Here, we report the results of numerical simulations of a disordered lattice model for fracture which allow us to understand the crossover between a disorder-induced statistical regime and a stress-concentration controlled regime ruled by fracture mechanics. The numerical results are described by a scaling law, accounting for the presence of a statistical fracture process zone which we quantify by averaging over several disordered configurations of the model. The theoretical fracture strength scaling law exhibits an excellent agreement with experimental results obtained from notched paper samples.

CONTRIBUTED TALKS

Fluctuations in Fluid Invasion into Disordered Media

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Interfaces moving in a disordered medium exhibit stochastic velocity fluctuations obeying universal scaling relations related to the presence or absence of conservation laws. For fluid invasion of porous media, we show that the fluctuations of the velocity are governed by a geometry-dependent length scale arising from fluid conservation. This result is compared to the statistics resulting from a non-equilibrium (depinning) transition between a moving interface and a stationary, pinned one.

Modelling Size Effects in Plasticity

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Strong yield stress fluctuations and size effects are observed in plastically deformed micron size samples [1]. The problem can be analysed in the framework of the yielding transition proposed for the dynamics of interacting dislocations [2]. Here we discuss the numerical results of a cellular automaton model of dislocation dynamics including long-range stresses, dislocation annihilation and multiplication. We compute the yield stress distribution and its dependence on the sample size. The numerical results are compared with experiments [1].

[1] M. D. Uchic et al., Science 305, 986 (2004).
[2] M. Zaiser and P. Moretti, JSTAT, P08004 (2005).

Fluctuations in Media with Slowly Varying Parameters

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A generalization of the fluctuation-dissipation formula for systems with slowly varying parameters is given using the Langevin approach [1], momentum method [2] and the time multi-scale technique. It is shown that spectral function of the fluctuations in these systems is determined not only by the dissipation but also by the time and space derivations of the dispersion. The non Joule dispersion contribution is characterized by a new non-local effect originating from an additional phase shift between the force and response of the system. That phase shift results from the parametric control to the system. The general formalism is illustrated for an oscillating electrical circuit. It is shown that in that system the dispersive contributions strongly affect the quality factor.

[1] V. V. Belyi, Phys. Rev. Lett., 88, 255001, (2002).
[2] V. V. Belyi, Phys. Rev. E, 69, 017104, (2004).

Entropy of Microstructure

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In materials with random structure energy is not determined uniquely by any finite set of microstructure characteristics. Therefore, the question arises how could one properly formulate the constitutive equations if energy is not defined uniquely. The key point of this talk is that there is a “missing” parameter in thermodynamic description of microstructure, entropy of microstructure. It can be experimentally measured via Einstein's type relation. To the author's knowledge, the necessity to introduce entropy of microstructure was first recognized in connection to modelling of plasticity in samples of micron sizes [1]. It is clear now that this parameter is essential in any modelling of random structures. In the talk the basic features of entropy of microstructure will be discussed, its explicit computation will be given for several random structures and the closed thermodynamic relations for entropy of microstructure will be derived.

[1] V. Berdichevsky, J. Mech. Physics of Solids, 53, 2457-2469, 2005

Thermal Rounding of the Depinning of a Driven Elastic String in a Random Medium

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We present a numerical study of a driven elastic string in a two-dimensional random medium. The abrupt zero-temperature depinning transition, characterized by a sample-dependent critical force F_c, is rounded at finite temperature, where the velocity is non-zero for any finite force. We have obtained the critical exponent Ψ describing the decrease of the string velocity with decreasing temperature at the critical force, $V(F_c) \sim T^{\Psi}$. Using finite size scaling we could identify how the divergence of the depinning correlation length depends on temperature. This analysis allows us to obtain the velocity-force universal function at low temperatures and around the critical force. Our results are compared with recent experiments on magnetic domain-wall motion in ultra-thin films.

Deriving the Burridge-Knopoff Model and Exploring the Dependence of its Dynamics on Friction.

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The Burridge-Knopoff (BK) model is a model of an earthquake system that can exhibit fluctuations with characteristics consistent with real earthquake data. However, the model was not rigorously derived and the constraints on certain model parameters often seem arbitrary. Here the theoretical link between the earthquake system and the BK model is established. The BK system undergoes a critical transition between small and large events by varying the rate of velocity weakening of the Carlson & Langer (CL) law. The BK system's dynamics are further explored using the more realistic Dieterich rock-friction, of which the CL law is a limiting case. A transition surface in the three dimensional parameter space is observed along with a range of power law exponents spanning that observed in nature.

Crackling Noise in Ferromagnetic Materials: Barkhausen Effect and Asymmetry in the Pulse Shape

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The Barkhausen effect is due to the jerky motion of domain walls in disordered magnetic materials, and is one example of "crackling noise" in condensed matter physics. The application of an external field acts as a pressure on domain walls, but because of the presence of defects, as inclusions and dislocations, the motion proceeds in avalanches. These avalanches show interesting statistical properties that encode important information on the magnetization reversal process on a microscopic scale. A microscopic theory based on a Langevin equation for the elastic domain walls describes with great accuracy most experimental results. However it does not account for the lack of symmetry in the average pulse shape. This can be explained by taking into account the contribution from Eddy currents, which results in a negative effective mass associated with the wall.

Variation of Shear Force Fluctuations in a Granular Material

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We investigate the force required to shear a granular medium in an annular geometry. Previous work has indicated that, as the velocity increases, the distribution of the torque narrows (*i.e.* there are less fluctuations) [1]. We argue that this is a signature of the fluidisation of the medium; the “smoothing” of the fluctuations results from the decorrelation of collisions in the fluid state. A stochastic description of the system reveals similarities with the motion of magnetic domain walls in ferromagnets this is the well known Barkhausen noise [2].

We report further on the response of the system to changes in the normal load and its inertial mass. We find that increasing the inertia seems to increase fluidity, as one might expect, though leaves the torque distribution as wide as before. The normal load has a more complex effect: fluctuations increase while the load is increasing, but decrease otherwise.

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Scaling and Universality in Rock Fracture

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We present a detailed statistical analysis of acoustic emission time series from laboratory rock fracture obtained from different experiments on different materials including acoustic emission controlled tri-axial fracture and punch-through tests [1]. In all considered cases, the waiting time distribution can be described by a unique scaling function indicating its universality. This scaling function is even indistinguishable from that for earthquakes suggesting its general validity for fracture processes independent of time, space and magnitude scales.

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Statistical Properties of Microcracking in Heterogeneous Materials

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In order to predict failure time of materials, fracture can be viewed as a critical phenomenon: a clustering of microcracks, for instance. We focus on polyurethane foams and monitor acoustic emission signatures of the microfractures which occur during mechanical tests. We highlighted diffuse microcrack nucleation and progressive localization into a dominating crack. Acoustic energy distributions follow a power law with an exponent independent of the material density, the loading mode, or the behaviour law. Time intervals between two damaging events seem to be power law distributed only if the stress remains nearly constant for the most part of the test. A critical region where the cumulative energy could be described by a power law appears only for creep tests.

Non-equilibrium Dynamics of Elastic Lines in Random Media and Vortices in Superconductors

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We will show simulation results of the relaxational dynamics of elastic lines in random media. We study the non-equilibrium dynamics of single lines in a random quenched potential in three dimensions. We find aging in the two-times density-density correlation and mean-squared-displacement correlation functions. They can be scaled with a multiplicative law similar to the one found in directed polymers in 2d. The linear responses also ages in the same way and we study the fluctuation-dissipation relation where an effective temperature characterizing the dynamics of the slow modes can be defined. We also analyse the case of interacting elastic lines, corresponding to flux lines in disordered superconductors (the vortex glass) and compare the obtained results with case of the non-interacting single lines.

The Linear Response Domain in Glassy Systems

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Molecular dynamics simulations are performed on a realistic glass forming model system. The linear and non-linear response domains are explored numerically for the case where one of the particles interacts with a constant external force. As the temperature is lowered towards the glass transition, we find that the range of fields over which the response is linear, shrinks towards zero. We show that the time required for convergence of the Steady State Fluctuation Theorem becomes very large as the glass transition is approached. This in turn implies that the domain over which linear response can be observed becomes progressively smaller as the glass transition is approached.

Characterization of Microcracked Solids with a Given Statistical Orientation of Cracks

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The macroscopic degradation of brittle materials is governed by the generation of cracks and by their mutual interactions. The overall mechanical behaviour depends upon the positional and orientational distribution of an assembly of cracks. We considered an arbitrary two dimensional distribution of slit-cracks. Then, we demonstrated that the statistical angular distribution of cracks can be described by a sole order parameter, which takes into account all of the microscopic features reflected macroscopically. Moreover, by developing an iterated homogenization procedure, we showed that the Young modulus of such a solid exponentially decays with the density of cracks.

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Dynamic metastability of the two-dimensional Potts model

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We investigate [1] the dynamics of the q-color Potts model on a 2D square lattice after a quench below the critical point, for q = 8, 12, 24. A metastable phase is observed in the numerical simulation when the quenched is above a certain temperature T_{sp}, at which the relaxation and nucleation times of the fluid become of the same order. T_{sp} is observed to decrease for increasing q and fixed size. However, it seems to converge to the critical temperature for increasing sizes and fixed q, therefore suggesting that no metastability exists in the thermodynamic limit, in agreement with the droplet expansion performed for the 2D Potts model [2].

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Influence of the Driving Mechanism on First-Order Phase Transitions

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Both ferromagnetic and martensitic systems display a first-order phase transition which usually occurs in athermal conditions [1]. These systems can be driven either by the intensive variable or by the extensive variable [2]. We present two lattice models based on the random-field Ising model (RFIM) with the aim of understanding the basic features of the two different driving mechanisms. Both models reproduce the re-entrance in the hysteresis loop and the fluctuations of the measured field when the system is magnetization driven [3, 4].

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Microscopic Process of the Fatigue Fracture of Heterogeneous Materials

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One of the most important scaling laws of time dependent fracture is Basquin's law of fatigue, namely, that the lifetime of the system increases as a power law with decreasing external load amplitude, $t_f \sim \sigma_0^{-\alpha}$. We show that in spite of the broad scatter of the Basquin exponent α, the fatigue fracture of heterogeneous materials exhibits intriguing universal features. Based on stochastic fracture models we propose a generic scaling form for the macroscopic deformation and show that at the fatigue limit the system undergoes a continuous phase transition when changing the external load. On the microlevel, the fatigue fracture proceeds in bursts triggered by damage sequences. We demonstrate that the bursting activity is characterized by universal power law distributions, and that the non-universality of the Basquin exponent at the macrolevel solely reflects the specific damage accumulation mechanism of the material.

Discrete Dislocation Dynamics with Dynamic Strain Aging

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We consider a model of discrete dislocation dynamics where a simple mechanism to mimic dynamic strain ageing (DSA) due to dislocation-solute atom interaction has been included. DSA is modelled by a time-dependent pinning force acting on a dislocation, which increases in magnitude as long as the dislocation remains immobile (up to a saturation value). We demonstrate that the inclusion of DSA in this way renders the “jamming” transition between a moving and a jammed phase discontinuous. When the system is driven with a constant velocity, we observe strain localization and serrated stress-time curves reminiscent of the Portevin-Le Châtelier effect. We interpret the deformation bands as nucleation events associated with the underlying discontinuous jamming transition.

Statistical Properties of Plasticity and Transport in Vortex Lattices

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We investigate the effects that plasticity of vortex lattices has on current transport in disordered Type II superconductors. Vortex lattices are often encountered in a polycrystalline metastable state, where topological defects such as dislocations arrange into large grain boundaries, due to their long-range interactions.

We analyse the dynamics of disordered vortex polycrystals in the framework of collective transport theories. We conclude that the grain structure appears less prone to deformation, adjusting more effectively to the disordered environment. In order to substantiate this global picture, we perform a numerical analysis of current transport, by investigating the role of relevant variables such as magnetic field, pinning strength and defect density. We recover phenomena of critical current enhancement and I-V curve hysteresis, which are commonly observed in field-cooling experiments.

Path to Criticality in Martensites

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Experiments in martensites reveal intermittent behaviour with power-law statistics only attained after a cyclic process through the transformation (training). Within materials science, criticality has been recognized in the last years as a key factor in crystal plasticity, brittle fracture and damage. Our work extends the paradigm of criticality also to martensitic transformations. We show that the attainment of criticality is due to the interplay between the reversible phase change and the irreversible development of an optimal amount of plastic deformation. Our method is based on the systematic reduction of a continuum theory of martensitic transformations to a self-organizing "spin" model. This approach is remarkably successful, as it reproduces all the essential experimental observations in thermally cycled martensites, including training-induced scale-free behaviour and hysteresis shakedown.

Depinning Model for Amorphous Plasticity Applied on a Hierarchical Lattice

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Plastic deformation of amorphous materials is assumed to consist of consecutive localized plastic deformation events. Based on this assumption we present a simple depinning model for the shear stress plasticity in 2d. The essence of this model is to introduce a local plastic threshold. Each plastic deformation gives rise to a long range elastic field which modifies the effective threshold values. At each time step the "weakest" region is deformed. As the simulation evolves the stress required to overcome the threshold of the weakest region reaches a stationary value corresponding to the critical stress. We estimate the corresponding critical exponents and analyse the spatio-temporal correlations by implementing the model on a hierarchical lattice [1] allowing us to speed-up a single update step from $O(N)$ of the conventional square lattice to $O(\log(N))$.

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Ageing in Disordered Magnets

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The aging of ferromagnetic models with disorder quenched to below the critical point is studied through two-time space- and time-dependent correlation and response functions. The corresponding ageing exponents are determined. The forms of the scaling functions of the integrated responses are well described by the theory of local scale-invariance. For the autocorrelation, the existence of large finite-time corrections to the leading behaviour is revealed.

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Roughness of Fracture Surfaces: A Tool to Probe the Mechanical Heterogeneous Properties of Brittle Materials

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Recently, a model of crack propagation within ideal elastic disordered materials has been proposed [1]: This approach furnishes a path equation of the crack front involving various mechanical parameters of the material (Poisson's ratio, typical size of heterogeneities, their typical “strength” compared to the mean properties of the material, etc.). We will show that, using this equation, it is possible to estimate these parameters from the statistical analysis of fracture roughness. In fact, a map of the material disorder can be obtained within a cut plane of its 3D structure. The method will be validated on fracture surfaces of synthetic brittle glass ceramics the micro-structure of which is known a priori [2]. Its possible application to quasi-brittle materials will be then discussed.

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From Granular Stress to Server Breakdown: a Random Neighbours Yielding Model

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Stress propagation in granular matter and satisfactory client service both involve random redistribution of loads when some unit breaks down. We introduce random demand redistribution in a parallel set of servers with finite capacity, showing that such redistributions gives rise to an exponential distribution of loads in the system.

We then investigate the endurance of the system as function of the redistribution rule and find that the system obeys precise scaling laws. In particular, the average capacity, load, and size of the system at the ultimate breakdown are power functions of the number of absorbing units.

A New Method to Derive One-Time-Direction Evolution of a Classical System from Microscopic Analysis of Particles Collisions and Origin of Fluctuations

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One-time-direction macroscopic evolution of a classical system of two interacting gases A and B having different temperatures is derived from microscopic analysis of the collisions underlying the process of energy exchange. Assumed is a spatial symmetry, S1, for input velocities. If the collisions are hard-sphere-like ones, the output velocities satisfy another kind of spatial symmetry, S2. We show that the symmetries S1 and S2 are sufficient conditions for the one-time-direction heat transition between the gasses A and B. From the developed equations follows that one can define the fluctuations possible for the considered process in terms breakdown of the symmetries S1 and S2. An experiment with an alternating current flowing in presence of acoustic wave is proposed to verify the theory.

Creep Dynamics in Paper

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We study experimentally global and local deformation during paper creep. We discuss the connection between numerical dislocation models and the creep fracture in paper. The local deformation field of paper during a creep experiment can be obtained by using digital image correlation methods. We present experimental local deformation fields and study deformation field fluctuations.

We observe Andrade creep in experiments during primary creep: $\varepsilon_t \sim t^{-0.7}$. The standard deviation of the relative strain rate decreases during the primary creep: fluctuations in the local deformation decrease at a lower rate than global strain: $s(\varepsilon_t) \sim t^{-1/2}$. In the discrete dislocation dynamics simulation model the dislocation movement rate and standard deviation of local movement rates coincide with experiments.

Crackling Noise During Interfacial Rupture

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We study the slow growth of a crack line along a weak heterogeneous plane of a transparent Plexiglas block. We follow the slow interfacial propagation using a high resolution and fast camera. We show that the fracture dynamics is governed by local and irregular avalanches with very large size and velocity fluctuations. This intermittent dynamics (local pinnings and depinnings of the crack front which trigger a rich burst activity) is characterized by measuring both the acoustic emission and the local waiting time fluctuations along the crack front during its propagation.

Levy Walk Scaling Behavior of Inhomogeneous Plastic Deformation

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The scaling behaviour of the Portevin-Le Chatelier effect was studied by deforming a substitutional Al-2.5%Mg alloy and an interstitial alloy, low carbon steel for a wide range of strain rates. To reveal the exact scaling nature, the time series data of true stress vs. time, obtained during deformation, were analysed by two complementary methods: the finite variance scaling method and the diffusion entropy analysis. From these analyses we could establish that in the entire span of strain rates, PLC effect showed Levy scaling behaviour [1, 2]. The Levy walk behaviour of the PLC effect is further supported by analysing the dislocation band movement in the continuous time random walk framework [3]. In this paper, we present a complete description of the scaling behaviour of the PLC effect.

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The Bubble Formation Under a Sound Wave Perturbation and the Arnold Circle Maps

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We studied the bubble formation generated in a viscous fluid under the perturbation of a sound wave of frequency f_s. By varying the air flow Q, the time between successive bubble $T_n = t_{n+1} - t_n$ decays as Q^β, and the β value depends on the size and geometry of nozzle. We applied the integrate-and-fire model $t_{n+1} f_s = t_n f_s + \Omega(Q) + \varepsilon(Q)\sin(2tn)$, for fixed values of the sound amplitude, with a sinusoidal baseline and constant threshold established by the sound wave. The model is a deterministic one-dimensional system that predicts the instant of a bubble detachment as a function of the previous one. The changes in the dynamics as the air flow varies can be predicted by a curve in the parameter space of the so called Arnold family of circle maps.

Microscale Patterning of Plastic Deformation: Self Affine Surfaces and Scale Free Statistics of Deformation-Induced Surface Steps

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We use atomic force microscopy and scanning white light interferometry to investigate the spatial intermittency of plastic flow in crystalline materials. To this end we analyse one-dimensional surface profiles obtained from surface maps of alkali halide single crystals deformed in uni-axial compression. The profiles of samples deforming in dual slip show self-affine behaviour over many orders of magnitude. For the special case of single slip a different behaviour is observed. In this case, height distributions of surface steps extracted from the profiles show scale-free behaviour, similar to the strain bursts observed in compression of micron sized samples and in dislocation dynamics simulations. We extend our experimental investigation to micron sized Cu-bending beams for which simulations indicate a similar behaviour.

Fluctuations and Scaling in Interface Roughening Dynamics of Mercury-Silver Reactive-Wetting in Room Temperature

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We study the interfacial characteristics of reactive-wetting of small mercury droplets (150 microns in diameter) spreading on thin silver films (2000 – 4000 Å) in room temperature. The process is studied using an optical microscope, and the propagating interface is analysed in order to determine its roughness and growth scaling exponents. When a finite number of interfaces is involved, temporal width fluctuations show up. This fluctuative behaviour is shown to contain information on the growth process of each specific interface. We define a new measure of the temporal interface width fluctuations in order to extract the lateral correlation length of the interface from the fluctuating data. We demonstrate the generality of the new method in a wide range of growing interfaces in diverse time and length scales, and show how the fluctuations result from the competing physical mechanisms (normal growth and surface tension) in such processes.

Mesoscopic Model for Plasticity in Amorphous Materials

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Since plastic deformation in amorphous and disordered materials cannot be explained in terms of dislocations, a common assumption consists of describing it as deriving from a succession of localized reorganizations at some microscopic scale. Such local deformations induce internal stresses corresponding to the effect of a local plastic shear in a small inclusion surrounded by an elastic matrix. We discuss mesoscopic models for amorphous plasticity defined by the data of a local random plastic threshold and an elastic stress redistribution. These 2D depinning models are developed in the case of anti-plane and plane geometry. We give here a comparison of the critical behaviour and spatio-temporal correlations in the two geometries.

Path Independent Integrals to Identify 2D Localized Amorphous Plastic Reorganizations

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Plasticity of amorphous materials has motivated an increasing amount of studies in recent years. In the absence of underlying crystalline lattice in materials such as foams, suspensions or structural glasses, it is generally accepted that plastic deformation corresponds to a succession of localized structural reorganizations. These local events induce long range elastic fields which can be decomposed onto a multipolar basis. Independently of the material details, it is possible to extract singular scale free dominant terms which can be associated to pure deviatoric or pure volumetric local transformations. We propose an analytic and numerical method to identify from the displacement field the location and the amplitude associated to such singular events.

POSTERS

A Sum Rule Approach to Detect Complex Correlation in Time Series

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A basic problem in the analysis of time series consists in unveiling and characterizing correlations among the variables at different times. In practice inmost cases this consists in considering the two point correlations over a long time series. Often complex properties are related to the long time behavior of these correlations. However, in many systems, like for example financial time series, simple correlations are intrinsically excluded by the arbitrage hypothesis. This leaves space for subtle complex correlations which are clearly difficult to detect. The usual approach is to focus on the pair correlations for grouped variables like in the problem of volatility clustering. Also in this case the availability of long time series is fundamental. This poses another problem because the stationarity hypothesis is not always appropriate. Inspired by these problems we introduce a new method to detect complex correlations in time series of finite size. The method comes from the Spitzers identity which controls the extremal values for sums of random variables. The basic idea is that a deviation from this identity is a sign of correlations in the variables and it corresponds to a sort of sum rule for correlations of any extension also in non stationary processes. We have tested the method which has only four point correlations. The application to real financial data shows that the method is a practical tool to detect correlations of any type even in finite time series. This is usually not possible with the standard statistical tools.

Non-Maxwell Relaxation and Fractional Order Relaxation Equations

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As well known the charge relaxation in homogeneous isotropic systems has the Maxwell exponential character. In the case of inhomogeneous media it seems that it Maxwell is conserved with replacement of medium conductivity for its effective value. But strict study shows that it is not so. In this report it was shown that there are two physical mechanisms of non-Maxwell relaxation in disordered systems. The new fractional order relaxation equations are deduced.

Classical Hall Transition and Large Linear Magnetoresistance in Strongly Inhomogeneous Planar Systems

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The magneto-transport properties of planar strongly inhomogeneous self-dual two-phase systems are investigated, using the exact dual transformation [1]. The explicit expressions for the effective conductivities/resistivities at arbitrary concentrations and magnetic fields are obtained for three different models [2, 3]. They show unambiguously an existence of the large linear magneto-resistance effect [2] and the sharp transition between partial Hall constants [3] for strongly inhomogeneous systems at high magnetic fields. The obtained results show a remarkable similarity with the existing experimental data. Both these effects and a strong correlation between them are a consequence of the exact duality [3]. The possible physical explanation and application of these effects are proposed.

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Intermittent Flow in the Uniaxial Compression of Colloidal Crystals

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Cooperative dislocation dynamics, intermittency and power-law distributed plastic events had been repeatedly reported in recent experiments [1-3] of crystal plasticity, emphasizing the importance of stress and strain fluctuations at small scales in contrast with the ideal smooth plastic flow paradigm that prevails at large scales. Here we report results from numerical simulations of the over-damped dynamics of small colloidal crystals submitted to strain and/or load controlled uniaxial compression tests. Even at small sizes, where only a few dislocations mediate the process, burst like events are present and appear to be power-law distributed. The size dependence of the strain and stress values at the onset of plasticity and the analogies and differences of the underlying deformation mechanisms are also analysed in both deformation protocols.

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Flow of Autonomous Traffic on a Single Multi-Lane Street

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We investigate the behaviour of an original traffic model. The model considers a single multi-lane street, populated by autonomous vehicles directed from either end to the other. Lanes have no intrinsic directionality, and the vehicles are inserted at random at either end and in any lane. Collision avoidance is fully automatic and, to enhance the transport capacity of the street, vehicles form *trains* in which they may travel at high speed quite close to the vehicle in front.

The insertion of a simple “keep left” rule for vehicles is not necessarily obeyed, particularly at high density, due to the complex interactions of many vehicles. We also discuss the changes in direction that occur to the lanes under the “keep left” and “random” rules. Under some conditions these changes form particularly interesting highly polarized and stable *alternating processes*.

Mean-Field Theory for Solid-on-Solid Models for Surface Growth

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A mean-field approach is used to study lattice models for surface growth with wetting and roughening transitions. Two types of mean-field approximations are used to get the properties of restricted solid-on-solid models which display a pinned as well as a moving phase. The equations for the simple mean-field approximations are solved exactly and give the expected growth exponent. The equations for the pair mean-field approximation are solved numerically and predict the correct growing surface with constant velocity at the moving phase and show a better agreement with numerical simulations. We show also that when detailed balance is fulfilled the pair approximation becomes the exact solution for the pinned phase.

Application of the Confined Quantum Field Theory in the Statistical Physics

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Confined Quantum Field Theory (CQFT) solves some fundamental problems in physics like the conflict between the theory of the relativity and the quantum field theory. Concerning statistical physics is its simple description of superconductivity and super fluidity, which is a transition from disorder to order movement of the conducting electrons and helium's respectively. CQFT establishes a relation between the metric of the quantum domain and the energy density. Therefore the energy of the quantum system dictates the radius of the confinement. The elements of the superconductivity are conducting electron with radius of confinement coincide with some number of the period of the bulk. Electrons in such energy state can move in the bulk without resistance. We show in fact that the Boltzmann equation can be used to describe the transition.

Crack Velocity in 2d Lattice Spring Systems

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We study fracture dynamics in 2d lattice systems, and we find the crack velocity as a function of the applied strain. We work in mode I and III for square and triangular lattices, also in the presence of anharmonicities. Analytical results in limiting cases are obtained for mode III, explaining the behaviour when the material strengthens or becomes softer at large deformations. In the first case the crack becomes supersonic, and propagation is driven by solitons; softening of the material effectively reduces the velocity compared to the harmonic case.

In mode I we find that the velocity in harmonic lattices is limited by the Rayleigh velocity no matter the applied strain. In the presence of non-linearities the behaviour is qualitatively similar to mode III. The non-linear region can be an arbitrarily small neighbourhood of the crack tip, but it has a crucial effect on the crack velocity.

Grain Boundary Diffusion in a Peierls-Nabarro Potential

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Understanding interface kinetics is an important theoretical and practical problem, since this process influences the materials microstructure, such as the grain size, the texture, and the interface type. Here we study the evolution of grain boundaries (GB) in a crystalline material, considering the role of the Peierls-Nabarro (PN) potential. The GB is schematized as an array of dislocations that interact with each other through long-range stress fields and with the crystalline PN potential. We analyse the dynamics of the centre of mass of the GB and its spatio-temporal fluctuations integrating the corresponding Langevin equation.

Critical Fluctuations of Dynamical Events in Random Media

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Many-body systems with disorder exhibit various interesting dynamical behaviours such as slow relaxation, hysteresis and pinning. Recently, critical fluctuations of dynamical events have been studied extensively in glassy systems. Stimulated by these studies, we investigate avalanches observed in random media from the viewpoint of fluctuations of dynamical events.

Acoustic Emission Scaling in Fracture

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Acoustic emission (AE) is one of the most helpful ways to extract information from fracture experiments but a simple connection between experimental results and fracture models is still lacking. Here we examine the energy released during the fracture of 2D systems within the framework of the random fuse model. In our study, the system is slowly driven by an external voltage (equivalent to an increasing strain in an experimental setup) that induces avalanches of failure events. The scaling behaviour of avalanche damage and energy is analysed defining the last one as the electric energy dissipated by the fuses involved. Other possible approximations to acoustic energy are also contemplated as well as its dependence on system size and lattice type looking for evidences of universal behaviour in fracture.

Stochastic Resonance in One Dimensional Ising Models with Antiferromagnetic (AF) Exchange Coupling: Application to Co- and Rare-Earth-Based Single Chain Magnets

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We study the effect of AF exchange on the single spin-flip Glauber dynamics of Ising chains subject to an oscillating magnetic field. For a nearest neighbour Ising AF chain, the master equation is solved within a linear field approximation and a long time limit. Resonant behaviour of the magnetization as a function of temperature is found at low frequency when spins on opposite sub-lattices are uncompensated owing to different gyromagnetic factors. For an axial next-nearest neighbour Ising (ANNNI) chain an extra decoupling approximation is required, and the dynamic critical exponent z is found to be in a different universality class than that of the unfrustrated Ising chain. The investigated models are pertinent to Co- and Rare-Earth-based single chain magnets showing slow relaxation of the magnetization at low temperature.

Stochastic Analysis of Metal Cutting Acoustic Emissions

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We analyse some acoustic emission time series obtained from a lathe machining process. Considering the dynamic evolution of the process we apply two classes of stationary stochastic time series models. We apply a preliminarly RMS transformation followed by an ARMA analysis; results thereof are mainly related to the explanation of the background part of the signal. Analyses of acoustic emissions may also be performed with the scope of understanding the evolution of the ageing process that causes the degradation of the working tools. Once the importance of the discrete part of the acoustic emission signals (i.e. isolated amplitude bursts) in the ageing process is understood, we apply a stochastic analysis based on point processes to model the waiting times between bursts and to identify a parameter with which to characterise the wear level of the working tool. A Weibull distribution seems to adequately describe the waiting times distribution.

Correlation Functions of a Nematic Liquid Crystal in Non-Equilibrium Steady States

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A fluctuating hydrodynamic approach is used to show that the strong couplings between the fluctuating velocity and orientation fields of a nematic generate long-ranged fluctuations in equilibrium and non-equilibrium steady states induced by a thermal gradient. The fluctuating hydrodynamic equations are established by using a time-scale perturbation analysis and from them the temperature, velocity, orientation and crossed correlation functions are calculated analytically. The thermal gradient introduces an asymmetry in the light scattering spectrum and shifts its maximum by an amount of the order of 7% and its width at half height may decrease by 10%. The temperature auto-correlation becomes generically long-ranged by two different physical mechanisms: the absence of spatial homogeneity due to the thermal gradient and the coupling of hydrodynamic modes. We compare both mechanisms and find that the latter is the dominant.

Quantum Annealing in the Random Field Ising Model

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We have investigated the performance of quantum annealing (QA) applied to the random field Ising model (RFIM) [1]. The RFIM presents an interesting test problem, being exactly solvable in polynomial time with combinatorial optimization graph algorithms, but yet it has a highly non-trivial energy landscape at zero temperature. QA is based on searching for the ground-state of a classical Hamiltonian by adiabatically switching off an appropriate source of quantum fluctuations [2].

Our main focus is on the decay rate of the residual energy, defined as the energy excess from the ground state. This is found to be $e_{res} \sim \log(N)^{-\zeta}$, with the ζ in the range 2...6, depending on the strength of the random field and the dimension of the problem [1].

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Zero Temperature Random Field Ising Model: Exact Results and Simulations

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Dynamical critical behaviour of the mean-field zero-temperature random-field Ising model is analysed. Based on the probability of finding a given sequence in the response signal, which has the form of a Markov chain with Poisson transition probabilities, an exact description of the avalanche duration distribution, the absolute probabilities of signal values, and the signal time-autocorrelation function is given. The overall behaviour of these quantities depends on their characteristic lengths, which all diverge near the critical point $z = 1$ as $\sim 1/|\ln(z)|$, where z is a control parameter of the underlying dynamics. Analytical findings are supplemented by the results of extensive simulations of mean-field and finite-dimensional model systems.

A Thermodynamical Fibre Bundle Model for the Fracture of Disordered Materials

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We introduce disorder [1] in a thermodynamic fibre bundle model proposed by Selinger et al. a few years ago [2]. The model displays new features and, for simple forms of disorder, is analytically tractable. It is found in particular that, to the same values of some macroscopic quantities such as stress and strain, may correspond different microscopic configurations. This fact can be of relevance for determining the thermal activation time of the fracture. We show that this behaviour can be characterized by an experimentally accessible analogue of the Edwards–Anderson parameter which is in relation with a non-monotonic increase of the fraction of broken fibres as a function of temperature at either constant stress or constant strain. At zero temperature the model reduces to the classical, irreversible, fibre bundle model.

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Effect of Diffusion of Monomers on Nanocluster Nucleation

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The thermo-fluctuation approach assumes that forming clusters do not disturb the supersaturated solution and the absorption probability depends on the average monomer concentration in the system.

We will consider a more general case, when the difference between the absorption and desorption rates coincides with the value of the diffusion current at the cluster interface. This current can be determined from the solution of the diffusion problem in the vicinity of the selected cluster. Absorption by other clusters forms the boundary conditions for this problem. Thus, the absorption/desorption mechanisms couple the kinetics of impurity atoms at the cluster interface with impurity diffusion which depends on monomer annihilation at other clusters. We demonstrate that such coupling can result in deviation of the forms of parameters governing clusterization from those predicted by the thermo-fluctuation approach.

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