Physics of Complexity @ ISC - Sapienza

Rome, 2014-2015

institute
for complex
systems

National Research Council of Italy

Physics of Complexity @ ISC - Sapienza

The **Institute of Complex System** (*ISC*) of the National Research Council (*CNR*) was created on February 2010.

The **Unit Sapienza** of ISC has been built upon researchers previously involved with the National Institute of Material Physics (*INFM*) within the **Department of Physics**. For this reason, since the very beginning, their research has been deeply interconnected with the activities of the Department of Physics.

Since 2010 the Unit has grown and its interests expanded in several directions, while the basic mission remained unchanged: the understanding of all those systems where the mutual interactions between a large number of components cannot be reduced to an effective single-element scheme. The resulting complexity manifests itself in a wide variety of emerging phenomena occurring in different contexts, ranging from social networks to granular materials, from (soft) colloids to (hard) electronic systems, from collective motions of animal groups to non-linear systems.

In this booklet each staff member of the Unit presents some of his/her activities, with the aim to give an overview of the research carried out presently at ISC-Sapienza.

Rome, November 2014

For further information please visit our web sites:

www.isc.cnr.it

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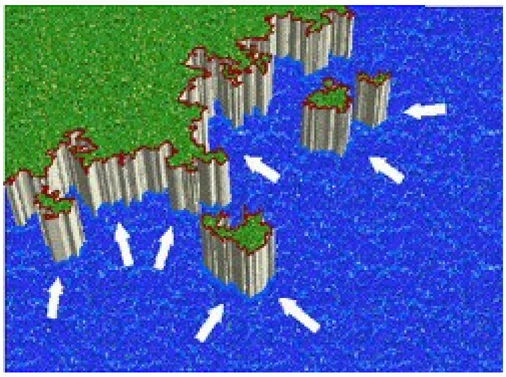
keywords

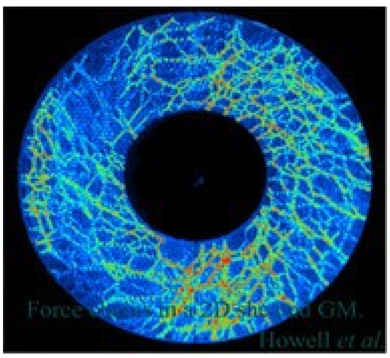
- *Percolation*
- *Granular materials*
- *Stochastic processes*

Rocky coast erosion and percolation theory

As shown by a minimal numerical model, percolation theory can be used as a guide to decipher the physics of rocky coast erosion and could provide precise predictions to the statistics of cliff collapses. I'm interested in possible applications of percolation theory in geomorphology, as revealed by irregular geometries or anomalous statistics.



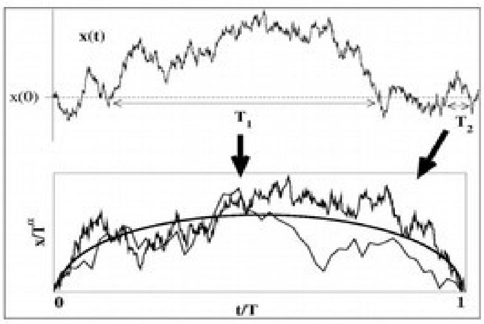
Friction in granular materials



Friction is a very old, but still open field of research, relevant from the physics at nano-scale to earthquakes. The friction response of a granular material could be very fluctuating, due to the anomalous stress propagation in the material. This systems represent an interesting laboratory, both experimentally and theoretically, for the introduction of new models and concepts.

Avalanche dynamics and crackling noise

Irregular, bursty dynamics can be modeled via simple stochastic processes, revealing unexpected connections between different physical systems (crackling noise).



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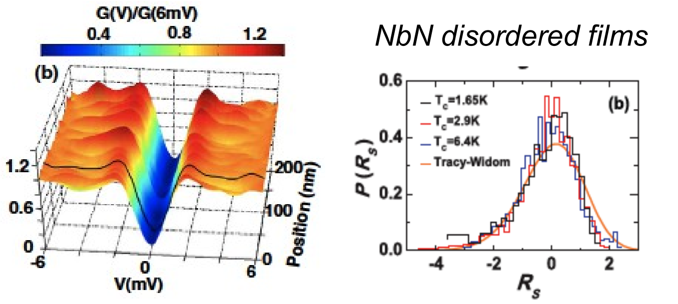
keywords

- *Theory of Many-Body Systems*
- *Superconductivity in low dimensions*
- *Materials with Novel Electronic Properties*

The understanding of the electronic properties of **complex solid-state systems**, where one observes the **competitio**n between different phenomena, requires to develop and implement a modern quantum-field theory approach. This includes several analytical techniques, ranging from a conventional perturbative expansion to the derivation of the quantum functionals for the collective degrees of freedom

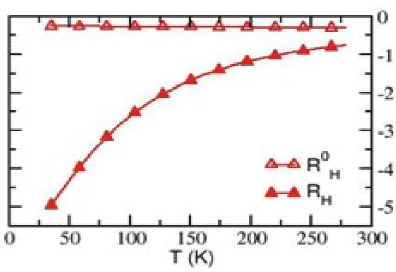


The inhomogeneous local DOS measured by STM shows an universal probability distribution of the local SC order parameter when properly rescaled

A typical example of competing states is provided by **strongly disordered superconductors**: here disorder tends to order the charge, by localizing the electrons, and pairing tends to order the global electronic phase, i.e. to form the superconducting state. As a compromise, the system develops an intrinsic inhomogeneous phase with unusual glassy properties.

G.Seibold et al. Phys.Rev.Lett.108, 207004 (2012).
G. Lemarie et al. Phys. Rev. B 87, 184509 (2013).

The competition and interplay between two different phenomena, i.e. magnetism and superconductivity, is also the key issue for the understanding of the new generation of **iron-based** high-temperature **superconductors.** In these materials the multiband structure and the interband nature of the pairing lead to a plethora of new phenomena, unexpected in other multiband superconductors. In addition the electron pairing in these materials turns out to be very robust against disorder, a still unexplained phenomenon that represent nowadays a promising root for future applications.



Unconventional Hall effect in pnictides

L. Fanfarillo et al. PRL 109,096402 (2012).

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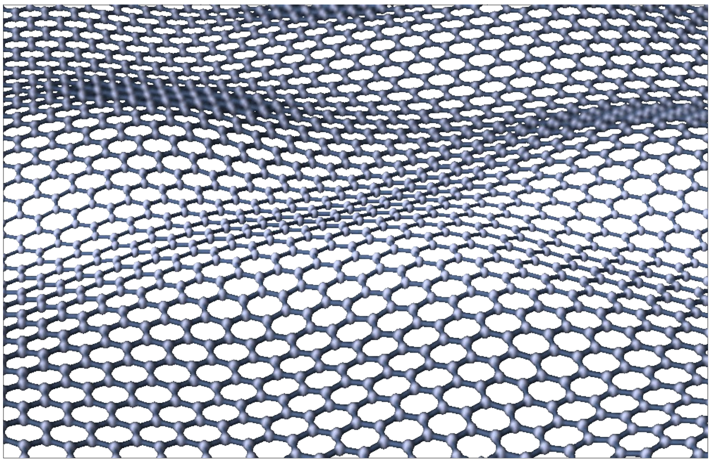
keywords

- *Many-Body Interactions and Theoretical Physics in Condensed Matter*
- *Superconductivity and collective phenomena*
- *Graphene and low-dimensional systems*

My research activity investigates the appearance of many-body phenomena of fundamental physics in a variety of specific condensed matter systems.
Examples of open research lines where Master theses are available:

Graphene and post-graphene compounds
Theoretical modelling of electronic, lattice, thermodynamical, optical, and magnetic properties of two-dimensional materials (graphene, dichalcogenides,...).

Interactions and Pairing in Iron-based Superconductors
Microscopical description of the scattering and pairing mechanisms in the normal state (transport, optical properties) and in the superconducting state (gap symmetry).



Lattice/spin polarons and Interplay between electron-lattice and magnetic interactions
Mechanisms and properties of complex objects (*polarons*) where different degrees of freedom (electron, lattice deformation, spin) are entangled at a local scale. Itinerant vs. trapped states.

Spontaneous broken-symmetry phases in layered compounds
Nematic, charge and bond-density-waves driven by Hubbard-Hund interactions in layered two-dimensional materials.

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keywords

- *Interdisciplinary applications of statistical physics*
- *Complex networks*
- *Dynamics of social systems*

Statistical physics approach to social dynamics

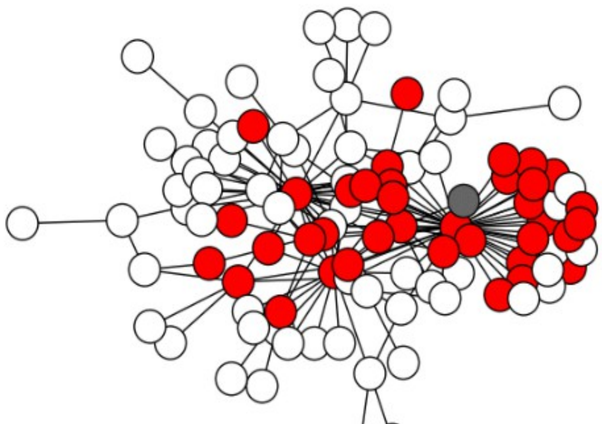
In recent years it has become widely recognized that many large-scale phenomena observed in social systems are the "macroscopic" emergent effect of the "microscopic" behavior of a large number of interacting agents. This has led to the introduction of elementary models of social behavior (opinion dynamics, cultural and scientific evolution, language change). Many of these models are relatives of models that are studied in modern statistical physics, and it is natural to approach them using the same concepts and tools successfully applied in physics.

C. Castellano et al., “Statistical physics of social dynamics”, Rev. Mod. Phys. 81, 591 (2009)

F. Colaiori et al., “A general three-state model with biased population replacement: analytical solution and application to language dynamics”, Phys. Rev. E (to appear).

Spreading processes on complex networks

Dynamical processes have been studied for decades on regular lattices and their behavior is generally well understood. When such processes take place on a complex topology, what is the effect of the disordered interaction pattern on their phenomenology? In recent years I have been in particular involved in the investigation of the behavior of spreading processes, which range from infectious disease epidemics to “social contagion”, i.e., information diffusion or meme propagation. Complex networks topology has a very strong impact on epidemic processes, facilitating spreading and increasing the risk of pandemics. Nontrivial effects are responsible for this vulnerability and their understanding challenges established theoretical approaches.



The study of epidemic-like spreading processes in the social domain, spurred by that the “big data” revolution is a very active and promising field for future research.

C. Castellano and R. Pastor-Satorras, “Threshold for epidemic spreading in networks”, Phys. Rev. Lett. 105, 218701 (2010).

M. Boguna' et al., “Nature of the Epidemic Threshold for the Susceptible-Infected-Susceptible Dynamics in Networks”, Phys. Rev. Lett. 111, 068701 (2013).

R. Pastor-Satorras et al., “Epidemic spreading in networks”, arXiv: 1408.2701 (2014).

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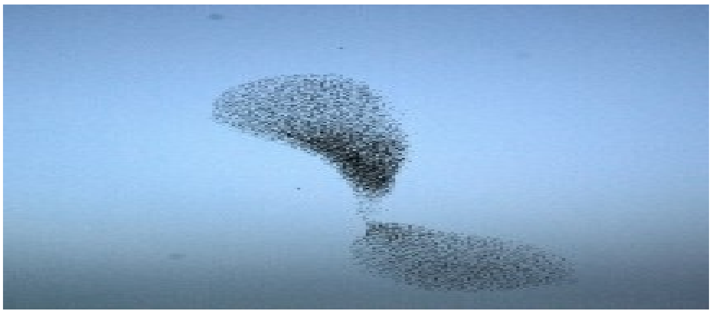
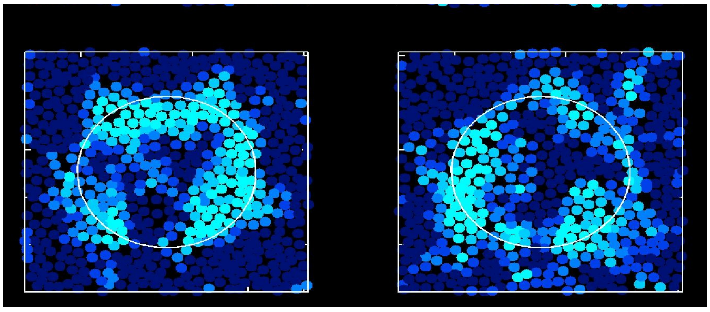
keywords

- *Collective Behavior in Biological Systems*
- *(Non-Equilibrium) Statistical Mechanics*
- *Inference, Modeling & Simulations*





Collective Behavior in Biological Systems

The basis of our overall methodology is linking the experimental data (observed behaviour) with the theories explaining the interactions rules governing large animal groups. This broad mandate requires an interdisciplinary approach ranging from field experiments, to computer vision, to statistical physics. In general, we have split our focus in two areas: i) experimental data gathering and processing; ii) data analysis and theory. Our experimental work is carried out in the natural habitat of the animal we are studying. We use multiple synchronized high speed cameras to capture image sequences of the aggregation. By using novel computer vision algorithm, we are then able to reconstruct the 3D trajectories of each individual in the group. Our data analysis follows a theoretical approach inspired by the principles of statistical physics.

Supercooled liquids and the glass transition

I am working on devising new methods to detect a growing static correlation length in deeply supercooled liquids. By using amorphous boundary conditions we measured for the first time a thermodynamic correlation length. In so doing we test the validity of different theoretical frameworks of the glass transition, namely the Adam-Gibbs theory and the Mosaic (aka Random First Order) theory. We are also trying to measure the surface tension between different amorphous phases in deeply supercooled liquids and to establish a link between static relaxation and dynamic heterogeneities through the concept of surface tension. Check my pedagogical reviews on spin-glasses and supercooled liquids, Spin-Glass Theory for Pedestrians [J. Stat. Mech. (2005) P05012] and Supercooled Liquids for Pedestrians, Physics Reports 476, (2009), P51

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keywords

- *Transport of biopolymers in nanopores*
- *Statistical mechanics of complex systems*
- *Nonlinear Physics and Chaos*

Transport of proteins

Nanopore technology is the “art” of retrieving chemical and physical information about biomolecules through their transport behavior across nanopores (nanoscale “holes”) FigB. This field is considered the new frontier of single-molecule manipulation and sequencing with relevant applications to biology and medicine. Experiments are becoming very accurate and produce a countless number of facts and data which the theory is called to explain.
Main theoretical tools: Stochastic Processes, Modelling and Simulations, Statistical Mechanics.

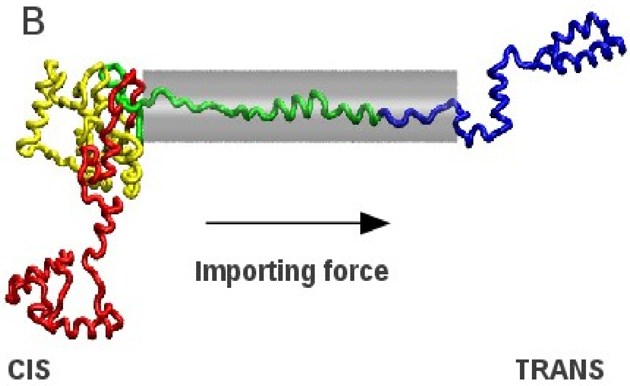
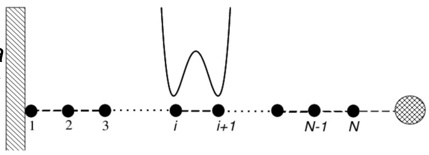


Fig. Transport of a protein by a pulling force

Statistical mechanics of complex systems

Understanding complex phenomena like the emergence of collective or auto-organized dynamics in many-body systems requires to master advanced concepts and methods of statistical mechanics and stochastic process theory. Particular important is the modeling of complex systems which finds several applications *e.g.* to biology, material science, economic or social phenomena. We are interested to study complex behaviors in granular materials and transport processes.

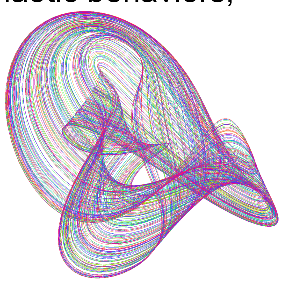
Fig. Chain of nonlinear oscillators considered a paradigm of a complex system.



Nonlinear Physics and Chaos

Nonlinearity is a general element of natural phenomena and Chaos theory is the systematic study of the “unexpected” effects produced by nonlinearities. In particular, two initial conditions differing for an infinitesimal error, which according to Newton's physics would yield similar results, can led to vastly different outcomes (Butterfly effect). The discovery that unpredictable behaviors are consistent with deterministic laws changed the way we perceive the world around us. Non-linear physics is the interdisciplinary field that develops mathematical tools and concepts to classify and characterize: chaotic behaviors, strange attractors and the related fractal structures.

Fig. A strange attractor showing a fractal structure.



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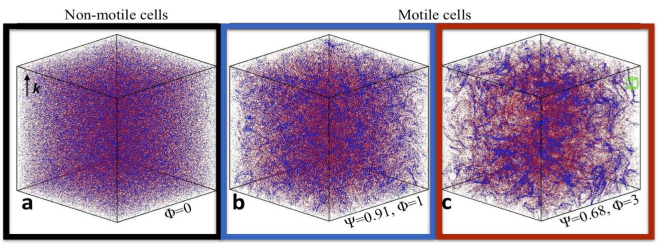
keywords

- *Turbulence and transport of fields and particles in turbulent flows*
- *Chaos and dynamical systems*
- *Population dynamics*

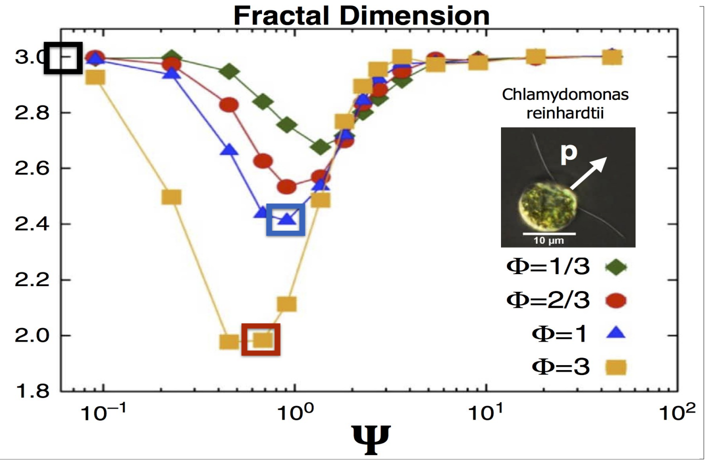
Transport of swimming microorganisms in turbulence

Typically turbulence is very effective in mixing transported substances so that quickly they distribute uniformly in the container (imagine stirring milk into coffee). What does happen to **microorganisms transported by a turbulent flow**? Microorganisms are typically very small and have the same density of the fluid so that are expected to follow the fluid elements and thus to mix very efficiently. However, **if they can swim**, as bacteria or some species of algae, something **counterintuitive** can happen, namely **they can unmix forming fractal aggregates**. This is because swimming allows cell to escape from fluid trajectories, inducing a sort of effective compressibility. This phenomenon has been studied experimentally, in a vortical flow, and numerically, in a turbulent flow, for gyrotactic microalgae (such as, e.g., Chlamydomonas).



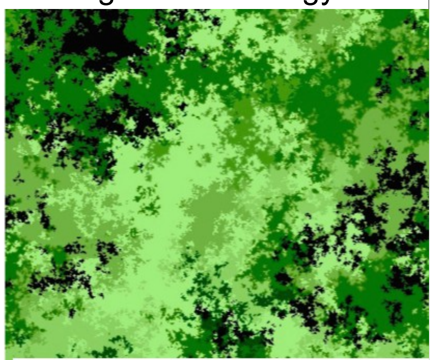
W. M. Durham, E. Climent, M. Barry, F. De Lillo, G. Boffetta, M. Cencini, R. Stocker Nature Comm. **4**, 2148 (2013)

F. De Lillo, M. Cencini, W. M. Durham, M. Barry, R. Stocker, E. Climent, G. Boffetta, Phys. Rev. Lett. **112**, 044502 (2014)



Neutral biodiversity models

Species abundance distributions and how the number of species changes with the area (**Species Area Relationships**) can be captured by simple neutral models, with a flat "fitness" landscape. Efficient algorithms have been developed to study nontrivial regimes of small speciation rate and large local population sizes, relevant to microorganisms ecology. We found that **large local populations give rise to shallower SAR, in accord with field observations.**



M. Cencini, M. A. Munoz and S. Pigolotti *PLoS ONE* **7**(6), e38232 (2012)

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keywords

- *Network Science*
- *Quantitative Linguistics*
- *Biophysics*

Interdisciplinary research
Physics as a tool

typical problems

Structure of Social Networks

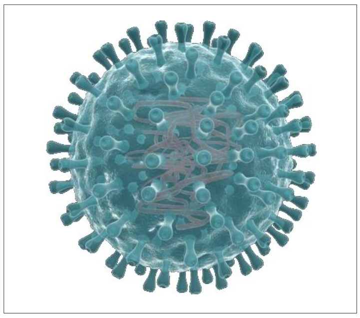
Social networks have empirically been found to be *assortative* (i.e., the degrees of neighboring nodes are positively correlated), while other networks (e.g., technological, biological) show the opposite pattern (*disassortative*). Why is that so?
How do these patterns change in *signed networks*, where relations indicate trust/distrust, friendship/enmity? Do individuals who dislike many others tend to dislike each other, or do they dislike those who dislike only very few others?

Credit: Illustration / Jonathan Saragosti

Rules and Exceptions in Language Dynamics

In all languages, rules have exceptions in the form of irregularities. Since rules make a language efficient, the persistence of irregularity is an anomaly. How do language systems become rule governed? How and why do they sustain exceptions to rules? Frequent words are unlikely to change over time (e.g., frequent verbs tend to maintain an irregular past tense form). What is the role of frequency in maintaining exceptions to rules?

Dynamics of Virus-Host interaction



In the case of fast mutating viruses (e.g., Influenza virus), the virus-host interaction is driven by *cross-immunity*: after being infected by a strain, the host acquires immunity to a set of other strains *antigenically similar* to the infecting one (i.e., triggering the same host immune response). The evolutionary dynamics of viruses is then ruled by their relative *antigenic distance*. Can we understand the nontrivial relation between antigenic and genetic distance?

methods

Tools from statistical physics, modeling, analytical approach (whenever possible), simulations, data analysis, web-based experiments.

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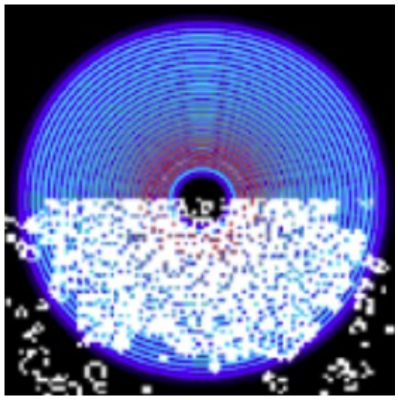
keywords

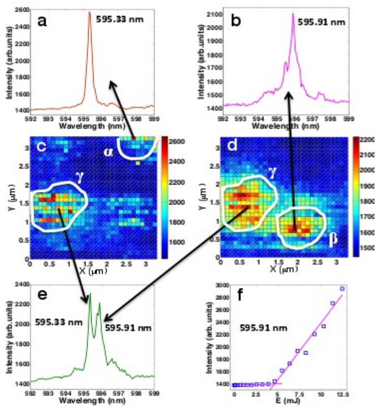
- *Photonics and nonlinear optics, experiments and theory*
- *High performance computing*
- *Theoretical physics*

The enlightened game of life

Is complexity linked with light? We decide if something is complex or not by observing its structure and hence interacting with electromagnetic waves. Is this fact more fundamental than that? We want to develop theoretical models for assessing the link between light and complexity, starting from the simplest one: the Conway's Game of Life



Random lasers, experimental activity



Complexity arises when there is disorder and nonlinearity. Photonics is full of examples in which highly nonlinear regimes occur in the presence of disorder. The case of light-matter interaction in random systems is specifically important for a novel class of devices named random lasers. In our laboratory we study random lasers in bio-templated materials and other complex systems.

Quantum gravity simulation

Highly nonlinear regimes in optics are formally identically to quantum gravity enhanced quantum mechanics, including a generalized uncertainty principle. Can we simulate quantum gravity in the lab?

$$\Delta X \Delta P \geq \frac{\hbar}{2}(1 + \beta \Delta P^2)$$

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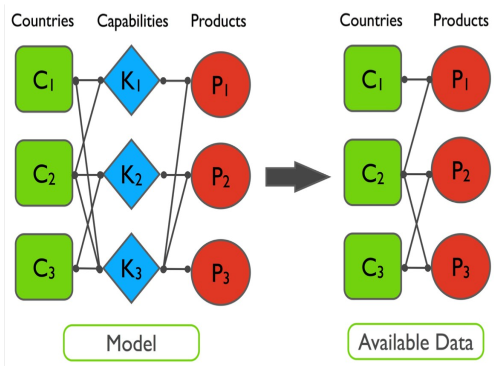
keywords

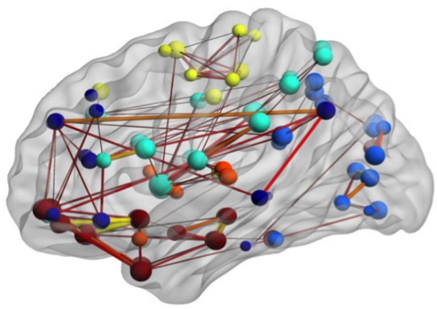
- *Stochastic processes and networks for interdisciplinary applications*
- *Networks and complex structures in brain science*
- *Long range interacting systems*

Economic complexity: If we study how different countries produce different products, we find data which look in contrast with standard economic theories: differentiation of production appears much more important than specialization for advanced economies. Studying the network structure of world production through a non-linear *pagerank-like* approach permits to uncover the hidden potential of growth of countries and to classify the technological complexity of products.



Complex structures in brain and NMR

Human brain is one of the most complex object of study in science and it is characterized by a spatio-temporal multiscale and multilevel structures. Nuclear Magnetic Resonance is the best *in vivo* tool to study both its 3-d disordered structure and its complex behavior. With this experimental technique, supported by the generalized diffusion theory, we can study the diffusion of water molecules in each cell (i.e. voxel) of a 3-d grid to get 3-d brain mages (DNMR). The same technique is used to analyze the temporal coordination between different regions of the brain during its functioning (fMRI). Network theory then permits to determine the topological properties of this functional network and characterize in the best way the functional connectivity and coordinated behavior of different brain regions.



Quasi-stationary states in long range interacting systems

Particle systems with long range interactions (e.g. self-gravitating gas) present a peculiar behavior which differs strongly from standard short range interacting systems both at equilibrium (e.g. ensemble inequivalence, negative specific heat) and far from it. In particular their out of equilibrium dynamics is characterized by the presence of *quasi-stationary states* in which the system gets trapped. They are due to the prevalence of collective motion on the two-body collision dynamics which in general drives the system at equilibrium. Its study is still an open issue.

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keywords

- *Granular Materials*
- *Brownian Motors*

Granular Materials

Granular materials are studied and used to test various fascinating theories in the field of non equilibrium statistical physics.

Many different experiments have been realized in the Granular Dynamics Laboratory in the Fermi Building, ground floor, Room 012. In our experiments grains are made of steel or plastic beads of various size, in the 1 – 4 mm range. The beads are kept in movement by a shaker and various different regimes are realized (granular gas and liquid) in various different setups (3d, 2d and also 1d). The dynamic of the grains is studied by high speed cameras and/or probed by intruders.

Brownian Motors

Brownian motors are a class of devices that extract useful work from noise. Such an extraction, which is impossible in the classical equilibrium thermodynamic framework, is made possible through the use of granulars that are, by definition, in non equilibrium conditions. The rectification of fluctuations is challenging from the experimental point of view and the final direction of motion is not easily predicted without a suitable theoretical model.

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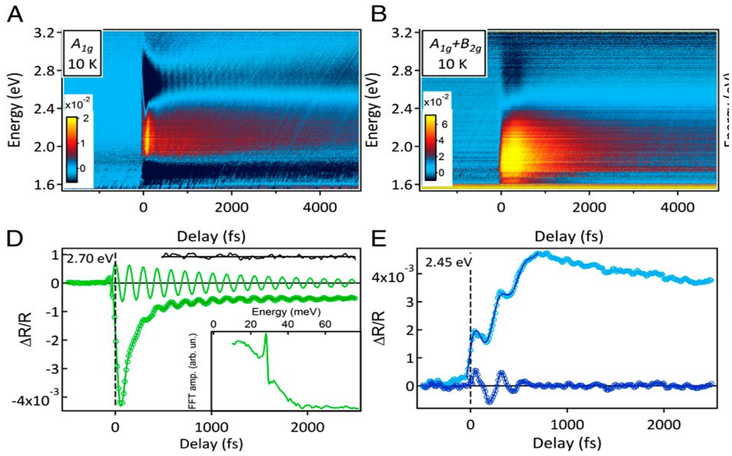
keywords

- *Theory of Many-Body Systems*
- *Superconductivity*
- *Emerging materials*

Complex Solids

My main interest are complex solids intended as materials in which different phases compete producing interesting collective behavior. Competition arise because interactions and the kinetic energy contribute similarly to the energy, therefore complex solids are nor in the weak nor in the strong coupling regime which makes them difficult to treat with conventional perturbative approaches. Competition between phases often leads to gigantic responses to external perturbations which makes complex solids interesting for applications. I use many-body numerical and analytical techniques to model the behavior of system with fascinating properties as high temperature superconductors and multiferroics (materials which have ferroelectric and magnetic order coupled). My work is often close to concrete experiments performed by partner groups and in the last years have been focused on time-dependent phenomena as collective modes of superconductors (including the possibility to observe the analogous of the Higgs boson in condensed matter), generation of magnetic responses with an electric pulse or vice versa and understand the physics of many-body quantum systems out of equilibrium.



Many-body physics in real time

In the last years dramatic technical progress have enable experiments where quantum matter is perturbed and its evolution is monitored in the femtosecond time scale. The figure shows experiments by our partners at Laussane [Mansart et al. PNAS, 110, 4539 (2013)] where the reflectivity as a function of energy is monitored as a function of time delay after an impulsive perturbation. Ultrafast time resolution allows to see lattice vibrations (A and D) and also electronic oscillations (B and E). The material is a high temperature superconductor and the electronic oscillations are attributed to the superconducting condensate. Modeling these and related experiments can help to understand the mechanism of superconductivity in these materials, one of the main open problems in physics.

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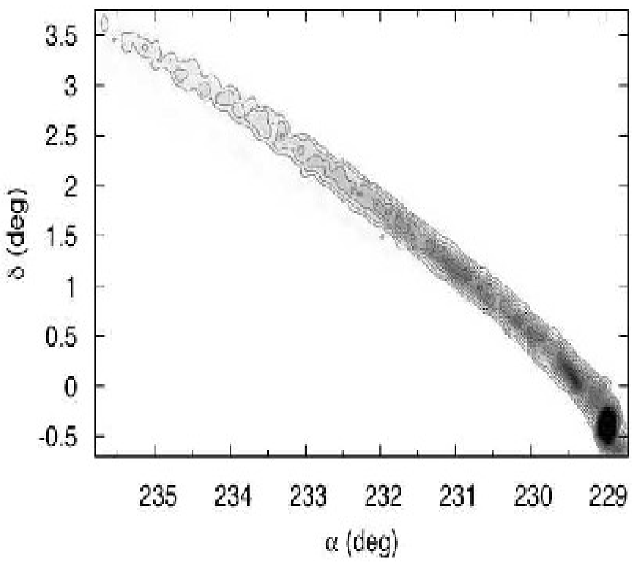
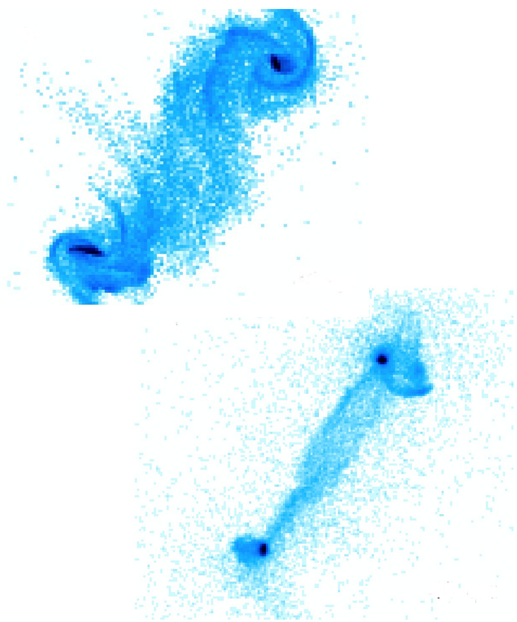
keywords

- *Globular Clusters dynamics*
- *Galaxy interactions*

Globular Cluster dynamics

Globular Clusters (GCs) are old star clusters in the galaxy and cornerstone for our understanding of the formation, structure and dynamics of Milky Way. Last decade has seen the discovery of tidal tails emanating of GC.Tails are a new probe of the potential of the galaxy and its time evolution. Through numerical simulation and observational comparison we can explore the features of dark halo and its dynamics





Galaxy interactions

Galaxies are recognized as the product of evolution lasting nearly 14 billion years. It is clear that many galaxies interact with neighboring ones and galaxy interactions are believed to be the key evolutionary mechanism, in particular for the early-type. We are studying models and numerical simulations to understand which are the dominant physical processes which drives their evolution and produce the richness we observe in the universe

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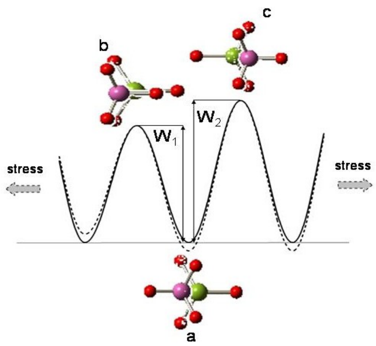
keywords

- *Spectroscopies*
- *Innovative materials for energy storage*
- *Phase transitions*

Materials for hydrogen storage

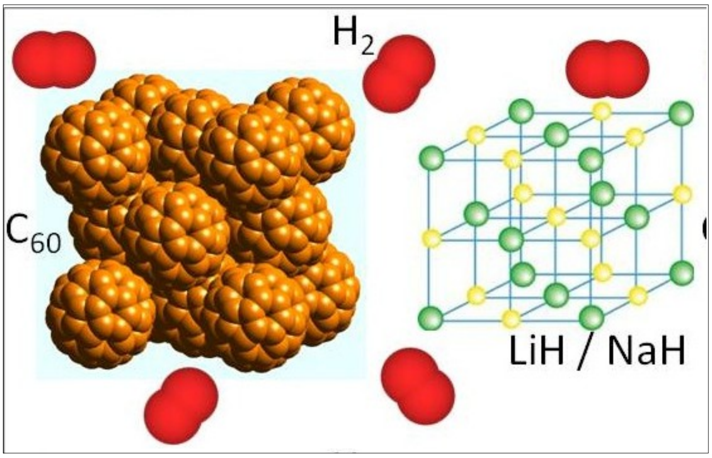
The most promising way to store hydrogen is the solid state storage, but at present a lot of fundamental research is still needed to make such solid state tanks satisfactorily compatible with the targets of current applications.
Best candidates are metal hydrides and complex hydrides. A big role in increasing their capacity and enhancing the hydriding and dehydriding kinetics is played by the artificial manipulation, like nanostructuring of the powders, their mechanical alloying and catalysing. We study the hydrogenation and dehydrogenation fundamental mechanisms of such novel materials by means of mechanical and infrared spectroscopies, thermal analysis and ab initio simulation.



A. Paolone, F. Teocoli, S. Sanna. O. Palumbo and T. Autrey, J. Phys. Chem. C **117** 129-134 (2013).

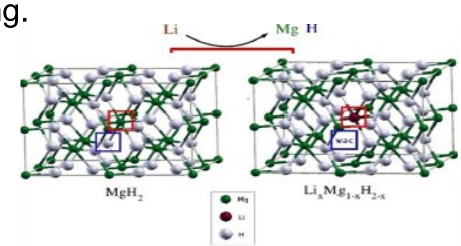
A. Paolone, F. Vico, F. Teocoli, S. Sanna. O. Palumbo, R. Cantelli, D.A. Knight, J. Trepovich and R. Zidan, J. Phys. Chem. C **116** 16365-16370 (2012).

A. Paolone, O. Palumbo, P. Rispoli, R. Cantelli, T. Autrey, A. Karkamkar, J. Phys. Chem. C Lett. **113** 10319-10321 (2009).



Hydrides as new anodes for lithium batteries

The incorporation of lithium by hydrides through an electrochemical conversion reaction is a promising alternative to Li intercalation into graphite for next-generation Li-ion cells.
This reaction has been proved only for a couple of metal hydrides. We are currently studying the applicability of complex hydrides and possible improvements of the hydrides performances in the cells by means of artificial nanostructuring.



D. Meggiolaro, G. Gigli, A. Paolone, F. Vitucci, S. Brutti, J. Phys. Chem. C **117** 22467-22477 (2013).

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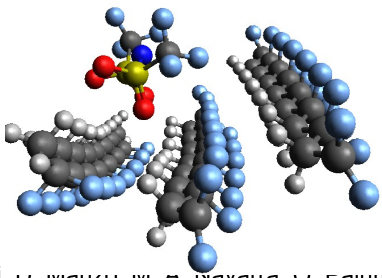
keywords

- *Spectroscopies*
- *Innovative materials for energy storage*
- *Phase transitions*

Ionic liquids and their interactions with membranes

Ionic liquids (ILs), which are inorganic salts with melting point below 100°C are environmentally friendly solvents with useful properties. Moreover their attractive properties can be tuned by variation of the cation and anion. Our research is focused to achieve a better physical understanding of the ions interactions and dynamics within the liquids by means of infrared and mechanical spectroscopies, thermal analysis and ab initio simulation.
The occurrence of phase transitions and their kinetics is studied too.
In particular, it is showed that in the composite systems usually used for applications, the interaction with the swelling membrane modifies the physical properties of ILs.



F. M. Vitucci, D. Manzo, M. A. Navarra, O. Palumbo, F. Trequattrini, S. Panero, P.Bruni, F. Croce, A. Paolone, J. Phys. Chem. C **118** 5749-5755 (2014).

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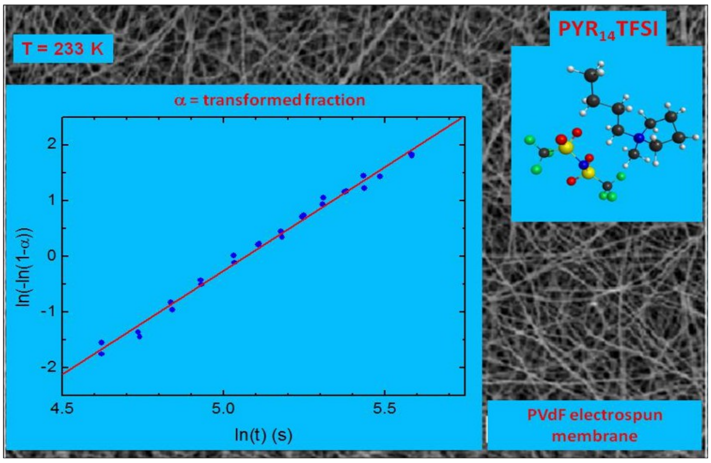

New materials for lithium batteries

We investigate the fundamental properties of new materials considered as promising as high energy density electrodes for lithium batteries, such as $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO) or $LiCoPO_4$ (LCPO). We studied the disorder of LNMO by means of EXAFS, the vacancy dynamics in LNMO by anelastic spectroscopy and the infrared phonon spectrum of LCPO.

G. Greco, S. Brutti, F. M. Vitucci, L. Lombardo, M. Koentje, A. Savoini, A. Paolone, S. Panero, J. Phys. Chem. C doi:10.1021./jp5063622.

F. M. Vitucci, O. Palumbo, A. Paolone, R. Cantelli, S. Brutti, S. Panero, J. Alloys Compds. **604** 83-86 (2014).

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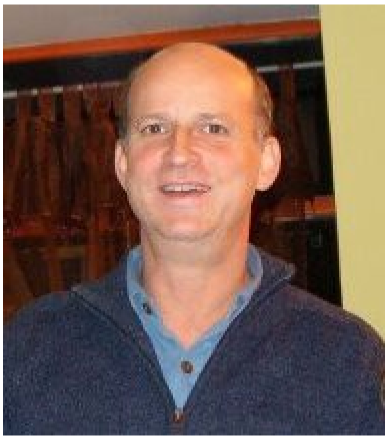

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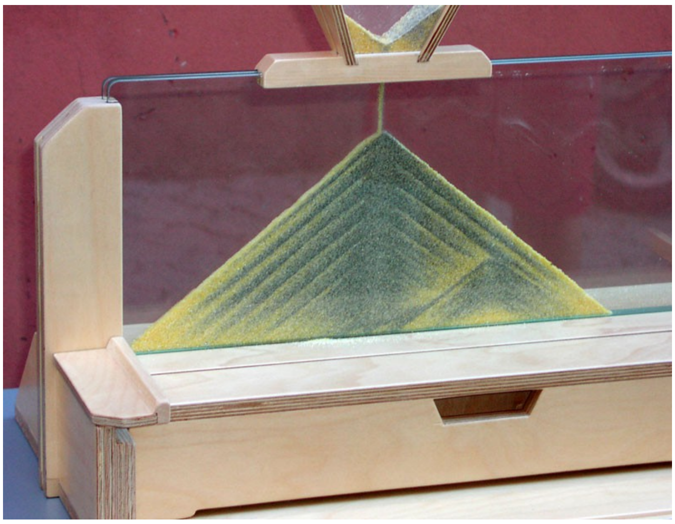
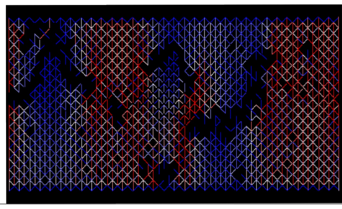
keywords

- *Dynamics of granular matter*
- *Disordered materials*
- *Complexity in society, biology and economics*

Topic 1
In our world, granular matter is more ubiquitous than crystals, however its dynamics is much less understood. Grains also provide a laboratory model for earthquakes and dissipative processes. We try to improve our understanding of the collective dynamics of grains performing laboratory experiments and numerical simulations, and try to describe it by means of stochastic processes.



Topic 2
Structural phenomena occurring in disordered materials often bring the features of criticality, i.e. long range correlations and self similar patterns, like for example in the pattern of a propagating crack. Despite their complexity, it is often possible to understand and describe these phenomena by means of simple models like cellular automata and lattice gas.



Topic 3
Understanding the dynamics underlying human and biological activities is difficult. However the now available large amount of data provides lot of information. We are presently investigating the mutual import-export relations of world-wide countries, pointing out analogies with some ecological systems.

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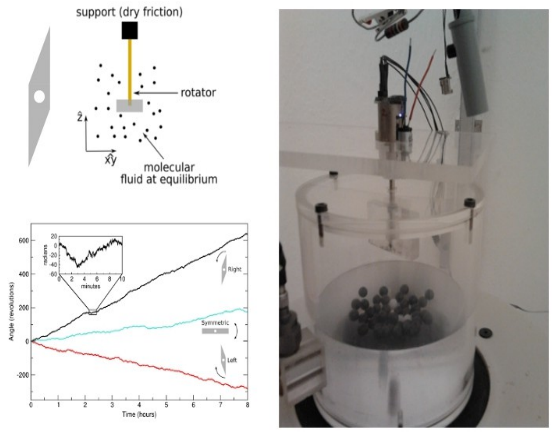
keywords

- *Granular materials*
- *Out-of-equilibrium statistical physics*
- *Brownian motors*

Granular materials
Granular media are systems made of many “grains” (particles from 0.1mm or larger) which lose energy when interacting. They are a fascinating testground for many recent theories in out-of-equilibrium statistical physics (see below). Here we study those systems by numerical simulations, kinetic theories and experiments. You can have a look to our lab at the ground floor of Fermi Building, Room 012.

Out-of-equilibrium statistical physics
Equilibrium statistical physics fails in many systems where currents and dissipation appear (turbulence, forced fluidodynamics, aggregate of self-propelled particles, open systems, etc.). Many alternative approaches exist, such as hydrodynamics and kinetic theory, e.g. the Boltzmann equation.



Sometimes these systems are also “small” and for this reason fluctuations can be very large: the theories of probability, stochastic processes, and large deviations, become – therefore - essential tools.

Brownian motors
They are small objects that “rectifies” fluctuations, obtaining work from heat. We study models and experimental examples, showing in which (non-equilibrium) conditions such a rectification may be optimized.

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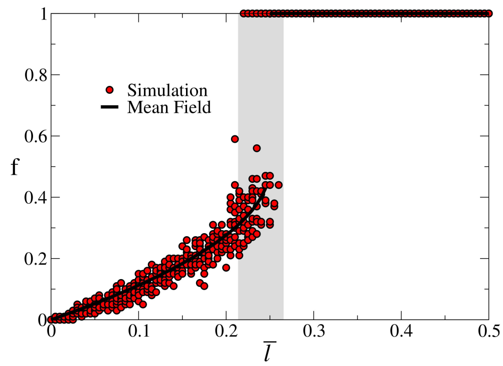
keywords

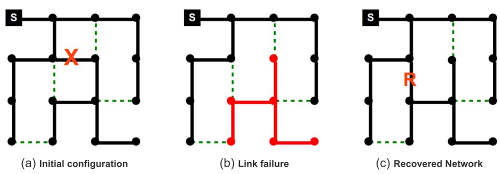
- *Complex Networks: Critical Infrastructures, Social Networks*
- *Statistical Mechanics: Energy Landscapes, Soft Matter*
- *Computational Physics: Hard body simulations, Monte Carlo*

Complex Networks and Power Grids



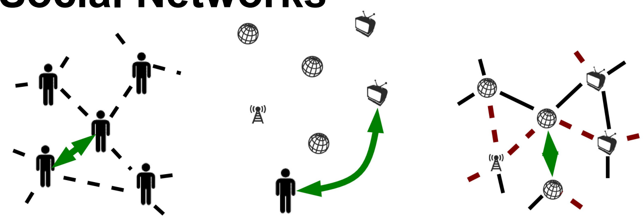
Electric power-systems are one of the most important critical infrastructures. We apply statistical mechanics to understand emerging phenomena in power grids

Self Healing Networks



We study self-healing models of complex networks modelling. Obvious applications are to infrastructural networks like gas, power, water, oil distribution.

Social Networks



We focus on data-driven computational models of complex socio-cognitive systems: spread of information and opinions, social human behavior, evolution of social networks. We aim to develop innovative mathematical models and computational tools to better understand, anticipate and control massive social phenomena with a complex systems approach.

publications

- **Abruptness of Cascade Failures in Power Grids**
  Scientific Reports 4, 3694
- **Self-Healing Networks: Redundancy and Structure**
  DOI: 10.1371/journal.pone.0087986
- **Opinion dynamics on interacting networks: media competition and social influence**
  Scientific Reports 4, 4938

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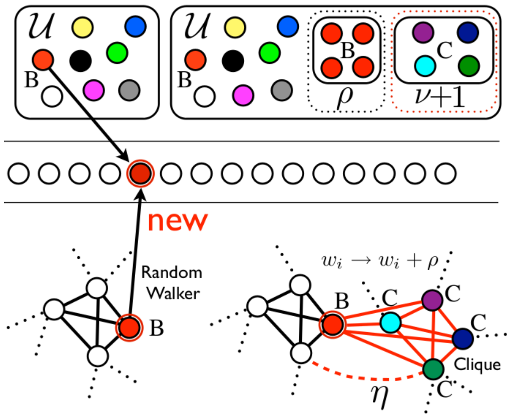
keywords

- *Opinion Dynamics, Quantitative Linguistics*
- *Citizen Science and Human Computation*
- *Learning Dynamics*

The dynamics of correlated novelties

Novelties are commonplace in daily life. They are also fundamental to the evolution of biological systems, human society, and technology. By opening new possibilities, one novelty can pave the way for others in a process that Kauffman has called "expanding the adjacent possible".

F. Tria et al., Sci.Rep. 4, 5890 (2014)



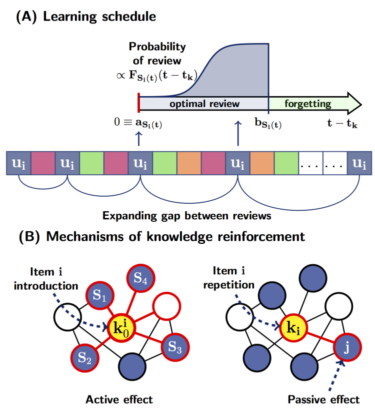
Web-based social computation

The Web has progressively acquired the status of an infrastructure for social computation allowing researchers to coordinate the cognitive abilities of human agents by steering the collective user activity towards predefined goals. This general trend is triggering the adoption of web-games as a very interesting laboratory to run experiments whenever the contribution of human beings is crucially required for research purposes.

http://www.xtribe.eu

Statistical modeling of learning paths

Each sphere of knowledge could be depicted as a network of correlated items. By properly exploiting these connections, innovative and more efficient learning strategies could be defined, possibly leading to a faster learning process and an enduring retention of information.



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keywords

- ***Collective Behavior in Biological Systems***
- ***(Non-Equilibrium) Statistical Mechanics***
- ***Inference, Modeling & Simulations***

From bird flocks to fish schools, from insect swarms to cell colonies, collective behaviour is a very widespread phenomenon in many biological systems.
It is hard to define, but easy to recognize.
What are the mechanisms regulating collective behaviour in biological systems?

The aim of my work is to understand the collective behaviour exhibited by flocks of starlings (Sturnus vulgaris) and swarms of non-biting midges (Chironomidae) through the analysis of synchronized high speed image sequences from three cameras.
Using stereo matching and other computer vision techniques, we are able to reconstruct, in three dimensions, the trajectories of individual animals within the aggregation.
Further analysis of the trajectories should lead to a better understanding of the fundamental interaction rules between individuals.

- *Information transfer and behavioural inertia in starling flocks*
  Nature Physics 10 (9), 691-696

- *Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study*
  Proceedings of the National Academy of Sciences
  105 (4), 1232-1237

- *Collective Behaviour without Collective Order in Wild Swarms of Midges*
  PloS Computational Biology 10 (7), e1003697

Experiments find coherent information transfer through biological groups on length and time scales distinctly below those on which asymptotically correct hydrodynamic theories apply.

We need a new continuum theory of collective motion coupling the velocity and density fields to the inertial spin field recently introduced to describe information propagation in natural flocks of birds.

- *Silent Flocks*
  arXiv:1410.2868

Which is the "recipe" that exactly reproduces the real biological systems? Which are the hypotheses cut by the "Occam's Razor" for which "entities must not be multiplied beyond necessity"?

Biological data have hidden information to be gathered: we have to solve the "Inverse Problem".
We can try to take advantage of the critical aspects of biological systems because in physics this is synonymous of phase transition and scale invariance.
A deeper statistical mechanics insight allows us to "rescale" biological data from different events and obtain more robust and meaningful answers.
It is required a complex and interdisciplinary line of research that includes:

- Deep theoretical expertise on statistical physics of complex systems ;
- Bayesian inference on biological data;
- Optimization – Simulations - Modeling ;

- *Scale-free correlations in starling flocks*
  Proceedings of the National Academy of Sciences
  107 (26), 11865-11870

- *Statistical mechanics for natural flocks of birds*
  Proceedings of the National Academy of Sciences
  109 (13), 4786-4791

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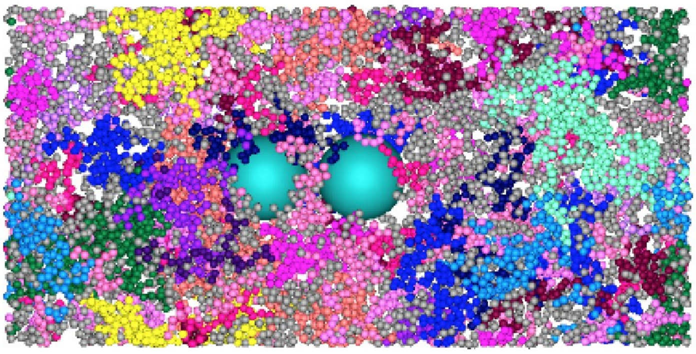
keywords

- *Simulation and theory of soft matter systems*
- *Gel and glass transitions*
- *Complex effective interactions: novel phases and anomalous dynamics*

Complex effective interactions

Colloidal particles can be treated as super-atoms moving in a continuum (solvent) in the framework of statistical mechanics. They interact with *effective potentials* that can be tuned arbitrarily by changing the properties of the particle (e.g. shape, architecture, heterogenous surface) or by varying externally the conditions of the solutions in which they are suspended. In this way, they experience interactions and show phenomena that are not found in atomic or molecular systems.

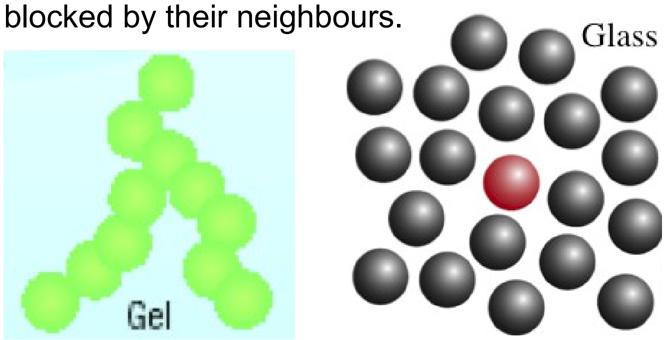


The simplest way to control the interactions between colloids is to add smaller particles (cosolute) in the solution, which originate so-called depletion interactions. By tuning the properties of the co-solutes, novel effects can be found. For example a co-solute close to its percolation transition induces so-called Casimir-like forces on the colloids.

N.Gnan, E. Zaccarelli, F.Sciortino *Nature Communications* 5, 3267 (2014)

Gels and Glasses

By tuning effective interactions, we find not only new thermodynamic phases (e.g. crystals with unconventional lattice spacings) but also different types of disordered arrested states: **Gels** where particles are organized into networks and **Glasses** where particles are blocked by their neighbours.



Recent Results:
in collaboration with B. Ruzicka and R. Angelini (CNR) we studied colloidal clays, which form *equilibrium gels* (Nat. Mater. 10, 56 2011) and *orientational glasses* (Nat. Comm. 5, 3267 2014);

in collaboration with P. Schurtenberger (Univ. Lund, Sweden), we study microgel polymeric particles, which swell upon increasing temperature, and can be studied at ultra-high densities (Soft Matter 9, 3000 2013).

in collaboration with U. Edinburgh and Madrid we study the interplay between crystals and glasses in hard spheres (PNAS 111, 75 2014).