Research

My research interests cover a broad array of topics ranging from biological physics to non-equilibrium statistical mechanics, the foundations of quantum mechanics and quantum field theory.

Biological Physics: our group is performing both experimental and theoretical work to uncover fundamental physical principles that underlie the formation of functional neuronal networks among neurons in the brain. One of the primary challenges in science today is to figure out how as many as 100 billion neurons are produced, grow, and organize themselves into the truly wonderful information-processing machine which is the brain. We combine high-resolution imaging techniques such as atomic force microscopy and fluorescence microscopy to measure mechanical properties of neurons and to correlate these properties with internal components of the cell. Our group is also using mathematical modeling to predict axonal dynamics and network formation. The aim of this work is twofold. On the one hand we are using tools and concepts from experimental and theoretical physics to understand biological processes. On the other hand, active biological processes in neuronal cells exhibit a wealth of fascinating phenomena such as pattern formation, collective behavior, non-equilibrium phase transitions and dynamics, and thus the insights learned from studying these biological systems broaden the intellectual range of physics. To capture the complexity of neuronal interactions we use theoretical methods from statistical mechanics, many-body physics and field theory such as: stochastic differential equations, Fokker-Planck formalism, Markov processes, effective energy landscape etc.

Non-equilibrium statistical mechanics and quantum mechanics: I am interested in the development of new theoretical methods that describe a wide range of complex phenomena in both biological physics and quantum mechanics, such as the formation of neuronal networks, evolution of regulatory genetic networks, protein dynamics and structure, evolution of strongly-coupled quantum systems etc. We build upon general methods used in the theory of stochastic processes (Chapman-Kolmogorov equation, Wiener-Levy and generalized Ornstein-Uhlenbeck processes) and on concepts from information theory (differential, conditional and joint entropy, Kullback-Leibler divergence etc.) to describe the dynamics of physical systems far from equilibrium. This line of research has (perhaps) surprising connections with constructive field theories (stochasticization of the basic field Lagrangian, renormalization and singular perturbations) as well as with the foundations of quantum mechanics (for e.g. Lindblad equation and the quantum Liouville equation). I am planning to include here a brief introduction to these fascinating topics. Meanwhile you can access some interesting papers here: http://www.ijqf.org. Non-equilibrium statistical mechanics and constructive quantum field theories rely upon advanced mathematical techniques: Ergodic theory, Operator Algebra, Functional Analysis, Algebraic topology etc. Over the years I have maintained a rather strong interest in these topics although they were not along my main line of research (at least as shown by the publication record).

Seminar on the Foundations of Quantum Mechanics: For the past few years I have been teaching a graduate level seminar on the Foundations of Quantum Mechanics at Tufts (Physics 0291). The focus of this seminar is to explore formulations of quantum mechanics that go beyond the standard Copenhagen interpretation of the subject. Topics include: Bohmian mechanics, Many Worlds interpretation, Lindblad Equation, Spontaneous Collapse Theories.

Condensed matter physics: My interests include both theoretical and experimental approaches to study quantum transport in nanoscale systems (carbon nanotubes, graphene, hybrid nanostructures), quantum many-body physics, topological insulators, biomaterials, and scanning probe microscopy. Some of my previous results are summarized below (see the list of publications for a full description).

Research Projects (click on the links below to learn more):
Geometry, topology and neuronal growth

Neuronal mechanics probed by atomic force microscopy

Neuronal growth and interconnectivity

Electrical and mechanical properties of nanomaterials

Some images from our research

Fluorescence image of a neuronal cell cultured on glass substrate. The fluorescence image was taken on the inverted stage of the MFP3D-Bio Atomic Force Microscope.

Left: AFM image of a Maltose Binding Protein patch nanografted on a Au/PEG substrate. Right: AFM image of collagen nanofibers on a glass substrate.

In the news: our paper on transport phenomena in reduced graphene oxide

In the area of experimental condensed matter/nanoscale physics and focused on developing new Scanning Probe Microscopies based on the Atomic Force Microscope for studying the local electronic properties of various nanoscale/molecular systems such as graphene, conducting polymers, and silicon nanowires. We are also interested in the interaction between these systems and various biomolecules such as enzymes and synthetic polymers. Besides its great importance for the understanding of the fundamental physics involved in nanoscale and molecular circuits, this research has a great potential for practical applications, ranging from molecular electronics to biodetection and chemical sensing. This research is done in collaboration with Prof. Sameer Sonkusale (Tufts, Electrical and Computer Engineering).
Left: Electrostatic Force Microscopy (EFM) image of carbon nanotubes on a silicon dioxide substrate. Right: EFM (phase) image of silicon nanowires on a silicon dioxide substrate. The phase shift shown by EFM is extremely sensitive to local electrostatic properties of the sample.