Second Sperlonga Summer School on Mechanics and Engineering Sciences

This is the second edition of the Sperlonga Summer School on Mechanics and Engineering Sciences, run jointly by the International Research Centre for the Mathematics and Mechanics of Complex Sys-tems (M&MoCS), the Foundation "Tullio Levi-Civita" and the Italian Association of Theoretical and Applied Mechanics (AIMETA), with the support of the town of Sperlonga—the permanent seat of the School.
The School will consist of four courses—of six hours each—and four one-hour seminars. The courses will be given by **Antonio Di Carlo** (Università Roma Tre), **Jordi García-Ojalvo** (Universitat Politècnica de Catalunya), **Davide Marenduzzo** (University of Edinburgh) and **Ignacio Pagonabarraga** (Universitat de Barcelona). The seminars will be given by **Antonio De Simone** (SISSA – International School for Advanced Studies), **Roberto Di Leonardo** (IPCF-CNR – Institute for Chemical-Physical Processes), **Laura Margheri** (The BioRobotics Institute, Scuola Superiore Sant'Anna) and **Simone Melchionna** (IPCF-CNR – Institute for Chemical-Physical Processes). Courses and seminars are organized with an interdisciplinary attitude, aiming to introduce young scientists to present-day developments in mechanics at the interface with mathematics, physics, materials science, biology, and engineering. The School will be visited by **Giovanni Ciccotti** (Sapienza – Università di Roma) and **Jean-Paul Ryckaert** (LPMM, Université libre de Bruxelles), who will participate as discussants in the closing session.

Course programmes

Ignacio Pagonabarraga (Universitat de Barcelona)

Soft active matter: from molecules to organisms

In these series of lectures, the common physical background underlying the physical properties of active matter at the cellular scale will be addressed. I will discuss the different ways in which activity imparts peculiar properties to living materials, quite distinct from their passive counterparts. By discussing the general properties of soft matter, I will analyse the specificities of active polymers, how they form gels with distinctive features and their mechanical implications. This description provides a general framework for understanding collective phenomena such as pattern formation or the onset of motility and cooperation. It will also allow for a discussion of the different levels at which active materials self-organize into emergent structures of various size and complexity.

Davide Marenduzzo (University of Edinburgh)

The nonequilibrium physics of active matter: from bacterial suspensions to cell motility

In this series of lectures I will give an introduction to the statistical physics of active matter, with emphasis on bacterial suspensions and cell motility as examples. We will first consider a system made up of a collection of self-propelled particles, and ask what collective dynamics this can lead to. We will analyse the Vicsek model, which is a paradigm for the physics of self-propelled particles, and then study generalisations. We will also see what happens when self-propelled particles and bacteria move around in complex geometries such as mazes, and consider what new physics emerges when active particles can reproduce as bacteria do. We will then introduce the problem of cell motility, and the outstanding questions in this field. We will review the ratchet models for motility, where motion is driven by the polymerisation of the cytoskeleton. Finally, we will introduce a continuum model which incorporates, on top of the cytoskeleton, also the molecular motors which interact with it, and show that they too may play a primary role in motility.

Jordi García-Ojalvo (Universitat Politècnica de Catalunya)

Gene, protein and population dynamics of cellular systems

Cellular populations are a form of active matter whose behaviour is governed by circuits of interacting genes and proteins. The structure and function of these cellular circuits are strongly dynamical. Ongoing experimental advances are allowing us to quantify cellular behaviour from the molecular level up, at different spatial and temporal scales. Experimental observations, combined with theoretical modelling based on concepts typical of statistical and nonlinear physics, are revealing nontrivial mechanisms of cellular processes such as decision making, differentiation, priming and pattern formation. This course will review the theoretical and experimental methods used to gain physical understanding of active biological matter by considering various model systems, including bacteria such as Escherichia coli and Bacillus subtilis and eukaryotic cells such as lymphocytes and embryonic stem cells.

Antonio Di Carlo (Università Roma Tre)

From molecular motors to a half-sarcomere: an exercise in mesoscopic modelling

Striated muscles are hierarchically structured, extremely sophisticated biochemical actuators. Each muscle fibre contains a bundle of myofibrils. Each myofibril is a long chain of sarcomeres. Each sarcomere, whose size is of the order of a few micrometres, is made up of two intercalated arrays of parallel filaments: thick filaments, composed of the protein myosin, and thin filaments, composed chiefly of the protein actin. At both ends of each sarcomere, thin filaments are held together by relatively stiff transverse structures (the so-called Z-disks). It is well established that muscle contraction is produced by the relative sliding between thick and thin filaments within each sarcomere. However, the underlying regulatory mechanisms are still poorly understood. In the last twenty years, experimental techniques have been developed to test biological tissues on very fine length scales, down to nanometres and beyond. Micromanipulation experiments are done with optical tweezers or microneedles on huge protein complexes, measuring nanometre displacements and piconewton forces. Theoretical models are required to help understanding the experimental data so obtained, and simplified models are especially well suited to this endeavour. Such models, purposefully discarding molecular details, may be characterized by a relatively small number of parameters, which can be calibrated by comparison with available experimental results. Moreover, the use of simplified models makes it possible to compute the evolution of large collective systems for physiologically significant time lapses. In these lectures I will discuss a mesoscopic approach to sarcomere modelling. The molecular motor myosin II, responsible for the muscular function at the nanoscale, is mimicked by a 1D Brownian ratchet model. The basic unit of muscle cells at the microscale, namely one half-sarcomere, is represented as a collective system of myosin motors arranged on a bundle of mock thick filaments, each of which interacts with a mock thin filament. All thin filaments are harmonically connected to the Z-disk, while the thick filaments are rigidly held together at the sarcomere centre (the so-called M-line). This model, properly implemented into a computer code, holds promise to produce a virtual lab where different assumptions on the activation-contraction coupling can be tested out.

Seminars

Antonio De Simone (SISSA – International School for Advanced Studies)

Motility at microscopic scales

We review recent results on the modelling of motility at microscopic scales. Starting from the study of swimming strategies of unicellular organisms, we discuss the geometric structure of the low Reynolds number swimming problem, its relation to geometric control theory, the implications on the crawling motility of biological organisms and cells, and the perspectives on mimicking these motility strategies with artificial, bio-inspired micro-devices.

Roberto Di Leonardo (IPCF-CNR – Inst. for Chemical-Physical Processes)

Hydrodynamic couplings between rotating propellers: swimming and synchronization

E. coli bacteria swim by rotating a helical flagellar bundle. The two phenomena that I will discuss are both related to the rotational flows generated by rotating propellers. The first example is about E. coli bacteria swimming in the proximity of a liquid-air interface. As opposed to swimming above a solid wall, we found bacteria swimming along anticlockwise circular trajectories. We quantitatively account for this through the hydrodynamic interaction of the bacterium with its own mirror image swimming on the opposite side of a perfect-slip boundary. In the second part of the talk I will discuss how swirling flows can couple nearby propellers, leading to phase locking. Using a combination of two-photon polymerization and holographic optical trapping we observe hydrodynamic synchronization in a number of micron-scale models based on light-driven rotators.

Laura Margheri (The BioRobotics Institute, Scuola Superiore Sant'Anna)

Characterization and modelling of the octopus as a biological model for the design of innovative soft robotics technologies

As a point of inspiration in the development of innovative technologies in soft robotics, the involvement of biology in engineering design has the potential to move toward components and systems that show better capabilities for smooth, soft interactions with the unknown physical environment. The octopus represents a paradigm of the tight relation between morphology and behaviour, and an "animal model" for soft robotics technologies. The seminar presents the study, measurement, and modelling the octopus arms' structural and mechanical characteristics to extract specifications for the design of innovative technological solutions which can be used for the development of a new generation of high-dexterous soft-bodied robots.

Simone Melchionna (IPCF-CNR – Inst. for Chemical-Physical Processes)

Pressure-driven and electrophoretic biological flows in nano- and micro-environments

Biological transport, involving cells, nutrients, biopolymers and so on, requires specific simulation techniques to reproduce the motion or suspended objects in complex flow conditions. In this endeavour, it is a crucial requirement to properly model the physical actions exerted on different suspended bodies, giving rise to body-specific migration forces. In this seminar, I will address a computational framework that allows to study biological flows ranging from blood flow to the translocation of charged molecules (such as DNA in nano-environments), by considering solvent-induced forces at the kinetic level, self-emerging at the macroscopic level as hydrodynamic interactions. Some applications will be presented showing how multiscale simulations allow discrimination between hydrodynamic, electrodynamic and entropic forces in diverse biofluidic systems.

Local Organizing Committee

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