Research in the Theory Department

Es gibt nichts Praktischeres als eine gute Theorie
Immanuel Kant

Structure of the Theory Department

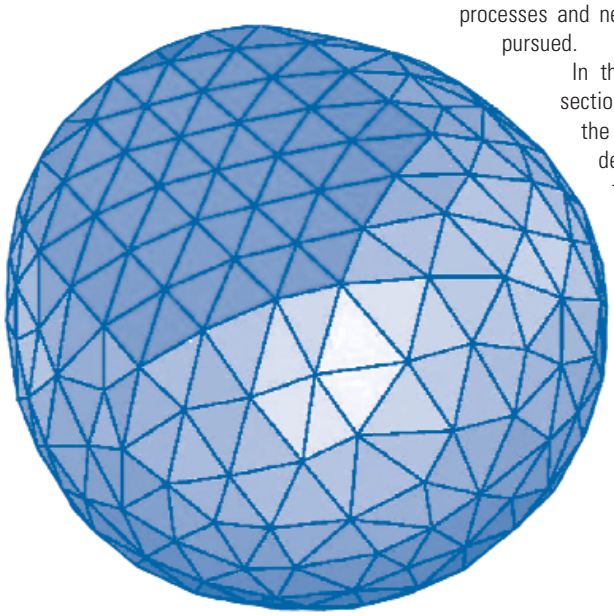
The researchers and doctoral students of the Theory Department form one experimental and seven theoretical research teams. Each of these teams consists of the team leader and several students. The team leaders are:

- Rumiana Dimova (experiment, membranes and vesicles).
- Thomas Gruhn (theory, membranes and vesicles);
- Jan Kierfeld (theory, polymers and filaments);
- Stefan Klumpp (theory, transport by molecular motors);
- Ulrich Schwarz (theory, membranes and cells) (until 2005);
- Christian Seidel (theory, polymers and polyelectrolytes);
- Julian Shillcock (theory, supramolecular modelling);
- Thomas Weikl (theory, proteins and membranes).

The Theory Department is responsible for the International Max Planck Research School and for the European Early Stage Training Network in which three departments of the MPI participate. The management of these networks is done by Angelo Valleriani.

Research in the Theory Department is focused on fundamental aspects of colloids and interfaces. In most cases, we study biomimetic model systems which are inspired by the nanostructures found in biological systems. Two examples are bilayer membranes with several components and active transport by molecular motors. In addition, some work has been done to directly address the complexity of biological systems. Two examples are the kinetics of protein folding and the elastic interactions of cells.

The conceptual framework for the understanding of these systems and their cooperative behavior is provided by *statistical physics* which includes thermodynamics, statistical mechanics, and stochastic processes. Some fundamental aspects of statistical physics such as irreversible processes and networks have also been pursued.



In the following three subsections, the research within the Theory Department is described in more detail in terms of the underlying systems which exhibit a hierarchy of structural levels, the generic phenomena found in these systems, and the methods used to study them.

Systems

First, one can emphasize the various systems which are studied in the department. If one looks at these systems bottom-up, i.e., from small to large scales, one can distinguish several levels of bionano systems as shown in **Fig. 1**.

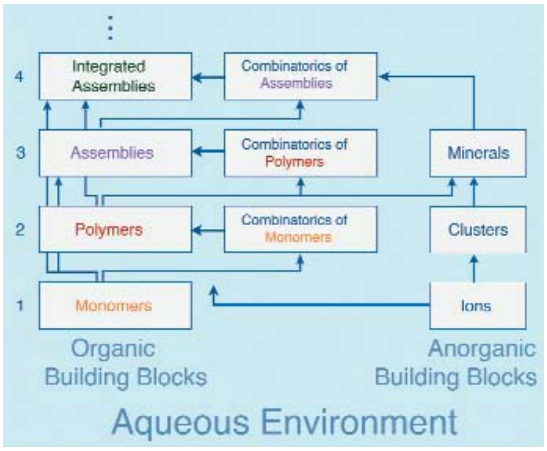


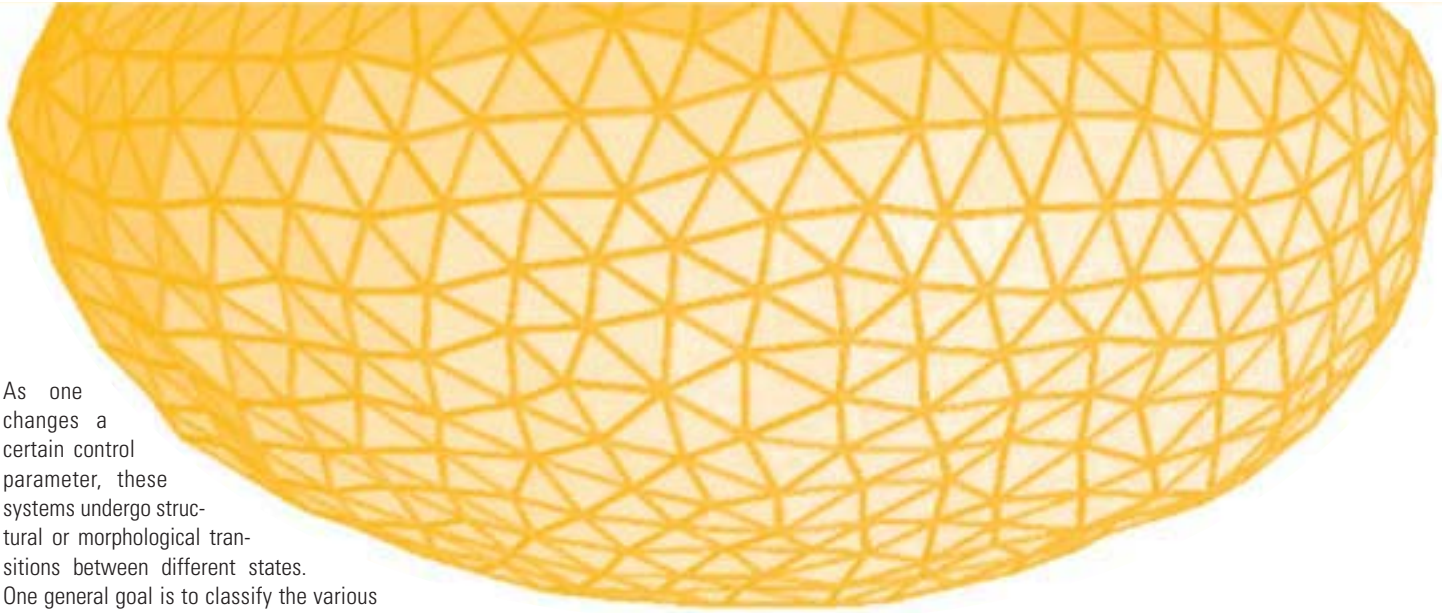
Fig. 1: Hierarchy of bionano systems, i.e., of biological and biomimetic systems in the colloidal regime between nanometers and micrometers. The assembly pathway on the left proceeds from small molecules or monomers to integrated assemblies, i.e., to 'assemblies of assemblies' that may differ in their architecture. The assembly pathway on the right leads to small mineral particles that are stabilized by adsorbed polymers.

During the last two years, research on biomimetic systems has been focussed on the levels of polymers (polyelectrolytes, semi-flexible polymers, mesoscopic rods), assemblies (cytoskeletal filaments, bilayer membranes), and integrated assemblies consisting, e.g., of filaments, motors, and cargo particles such as vesicles. Research on biological systems addressed the level of polymers in the context of protein folding and the level of whole cells which lies above those shown in **Fig. 1**.

If one looks at these systems top-down, i.e., from large to small scales, one encounters the problem of restricted geometries or confining walls and interfaces. One topic in this latter research area which has been studied in some detail were liquids at chemically and topographically structured surfaces.

Phenomena

At each level shown in **Fig. 1**, one encounters a variety of cooperative phenomena. These systems contain flexible or soft components that undergo thermally excited fluctuations corresponding to cooperative Brownian motion because the ambient temperature corresponds to liquid water. One would like to determine both, the typical states or morphologies attained by these systems and their fluctuation spectrum. In addition, these fluctuations lead to entropically induced forces which compete with the direct molecular forces.



As one changes a certain control parameter, these systems undergo structural or morphological transitions between different states. One general goal is to classify the various possible states and their transitions. This classification leads to "state", "morphology", or "phase" diagrams which describe the system's behavior in a global manner.

One structural transition which has been studied in the Theory Department during the last two years, both experimentally and theoretically, is the fusion of bilayer membranes and vesicles. In the experiments, the fusion was induced by the addition of multivalent ions which act to crosslink certain membrane-anchored molecules. In the simulations, the fusion was controlled by the initial tensions within the membranes. At present, the length scales accessible to experiments and simulations are still rather different whereas the time scales now begin to have some overlap.

Membrane fusion starts from an adhering state and is completed when the fusion pore has been formed. Such a fusion event represents an irreversible relaxation or "down-hill" process that proceeds from an initial state out of equilibrium towards another more stable state.
In order to reverse this process, one would need to involve a molecular motor that can break the neck of the fusion pore again. Such a motor must be able to couple the fission of the fusion pore, which represents an endergonic "uphill" process, to another process that represents an exergonic "down-hill" process. This type of coupling provides the basic mechanism for all active processes in biological systems.

Active biomimetic processes have now become a main focus of the Theory Department.

One important example is the transport by molecular motors. In this context, we have studied a variety of cooperative motor phenomena: build-up of traffic jams of motors; active structure formation leading to steady states with spatially non-uniform density and current patterns; and active phase transitions between different steady states far from equilibrium. A particularly simple active phase transition with spontaneous symmetry breaking is predicted to occur in systems with two species of motor particles which walk on the filaments in opposite directions.

Current projects on active processes include: effect of disordered filaments and regulatory proteins on motor transport; active force generation by polymerization; cooperative behavior of filaments on motor covered substrates; adhesion of membranes with active stickers.

In addition, the Theory Department coordinates a new European network (STREP) on "Active Biomimetic Systems".

Methods

The theoretical work starts with the definition of a certain model which (i) is amenable to systematic theoretical analysis and (ii) captures the essential features of the real system and its behavior. New models which have been introduced in the Theory Department include: semi-flexible harmonic chains for filaments; coarse-grained molecular models for bilayer membranes; lattice models for membranes with adhesion molecules; geometric models for membranes with lateral domains; and lattice models for transport by molecular motors.

These theoretical models are then studied using the analytical tools of theoretical physics and a variety of numerical algorithms. The analytical tools include dimensional analysis, scaling arguments, molecular field or self-consistent theories, perturbation theories, and field-theoretic methods such as renormalization. The numerical methods include the application of mathematical software packages such as Mathematica or Maple as well as special algorithms such as, e.g., the Surface Evolver for the calculation of constant mean curvature surfaces.

Three types of computer simulations are applied and further developed: Molecular Dynamics, Dissipative Particle Dynamics, and Monte Carlo methods. Molecular Dynamics is applied to particle based models of supramolecular assemblies; Dissipative Particle Dynamics, which is a relatively new simulation algorithm, is useful in order to extend the Molecular Dynamics Studies towards much larger systems and longer time scales; Monte Carlo methods are used in order to simulate even larger mesoscopic systems such as filaments and membranes up to a linear size of hundreds of nanometers.

The experimental work is carried out in our membrane lab which is equipped with calorimetry, optical microscopy, micropipettes, and optical tweezers. An advanced confocal microscope is currently installed that will be available to all four departments of the MPI.

Additional information about research in the Theory Department is avalaible at *www.mpikg.mpg.de/th/*.

Reinhard Lipowsky
Director of the Theory Department