Journal of Statistical Physics, Vol. 128, Nos. 1/2, July 2007 (© 2007)
DOI: 10.1007/s10955-007-9331-z

Introduction

Mark Alber[1], Erwin Frey[1] and Ray Goldstein[1]

Published Online: May 9, 2007

This special Issue on Statistical Physics in Biology stems from the workshop "Applications of Methods of Stochastic Systems and Statistical Physics in Biology" held from October 28–30, 2005, at the University of Notre Dame. The workshop was co-organized by the Interdisciplinary Center for the Study of Biocomplexity at the University of Notre Dame and Los Alamos National Laboratory, in cooperation with SIAM and supported by the NSF and DOE.

The workshop consisted of a public lecture by Alan Perelson, Los Alamos National Laboratory, a Keynote Address by Dennis Bray, Cambridge University, a Miller Lecture in Biophysics by Albert Libchaber, Rockefeller University, four sessions of talks, a poster session and a panel discussion on future directions in biomedical modeling.

The workshop brought together researchers in many disciplines (including mathematical biology, statistical physics, experimental and theoretical biology, biophysics, engineering, and computer science) to discuss current and future applications of methods of stochastic systems and statistical physics to problems ranging from individual molecules to HIV immunology, cardiac electrophysiology and ecology.

The data available from genome projects and high-throughput experiments pose grand challenges on developing complex large-scale models of stochastic systems with many interacting variables. The complex nature of current biological and biochemical data makes interpretation and modeling particularly difficult without advanced and novel mathematical and statistical techniques.

The theory of stochastic processes provides a huge arsenal of methods suitable for analyzing the influence of noise on a wide range of systems. Noise-induced,

[1] Departments of Mathematics and Physics, Interdisciplinary Center for the Study of Biocomplexity, University of Notre Dame.

noise-supported or noise enhanced effects may offer an explanation for as yet open problems (information transmission in the nervous system and information processing in the brain, processes at the cell level, enzymatic reactions, etc.), and pave the way to novel technological applications. Noise can play a prominent role in structure formation in biology, e.g. in the complex dynamics of the heart, brain, or ecosystems.

In what follows we mention a few papers from the 23 contributions just to give an idea of the broadness of the topics discussed in this issue.

Protein motors play a central role in many cellular functions. Due to their small size their motion is dominated by high viscous friction and large thermal fluctuations. Elston and Wang describe a mathematical framework for an intermediate level of description in which the major conformational changes of the motor protein are treated as continuous motions and changes in the chemical state of the motor are modeled as discrete Markov transitions.

Reactions in the intracellular medium occur in a highly organized and heterogenous environment. This makes modeling approaches based on the law of mass action or its stochastic counter-part largely invalid. This has led to the recent development of a variety of stochastic microscopic approaches based on lattice-gas automata or Brownian dynamics. Grima et al. propose to use a mesoscopic method which permits the efficient simulation of reactions occurring in the complex geometries typical of intracellular environments. This approach is used to model the transport of a substrate through a pore in a semi-permeable membrane, in which its Michaelis-Menten enzyme is embedded.

Drasdo et al. demonstrate that models in which cells, despite their complexity, are represented as simple particles, which are parameterized mainly by their physical properties, can explain many collective phenomena in multi-cellular systems. They illustrate general approach by a number of examples such as unstructured cell populations growing in cell culture and growing cell layers in early animal development.

Modeling studies in cardiac electrophysiology cover a wide range of phenomena from the sub cellular and cellular levels to the tissue and whole organ level. Currently most stochastic modeling in this area is performed on the sub cellular and cellular level, and includes stochastic models of individual ionic channels and Markov-chain state models of ionic currents and cardiac cells. Glass et al. show that, in the neighborhood of bifurcation points, the fluctuations induced by the stochastic opening and closing of individual ion channels in the cell membrane, resulting in membrane noise, may lead to randomness in the observed dynamics.

Starruss et al. provide indications that the specific cell shape of myxobacteria might play an important role in the morphogenesis during the life cycle. A Cellular Potts Model (CPM) that captures the rod cell shape, cell stiffness and active motion of myxobacteria is presented. By means of numerical simulations of model cell populations where cells interact via volume exclusion, they provide evidence of a purely mechanical swarm formation mechanism that is controlled by the cells' aspect ratio.

A paper by Komarova studies stochastic dynamics of the two most common patterns in cancer initiation and progression: loss-of-function and gain-of-function mutations. She describes three constant-population stochastic models: a mass-action model, a spatial model and a hierarchical model and demonstrates that hierarchical tissue organization lowers the risk of cancerous transformations.

Mobilia et al. study the general properties of stochastic two-species models for predator-prey competition and coexistence with Lotka—Volterra type interactions defined on a d-dimensional lattice.

Pathogen-mediated competition, through which an invasive species carrying and transmitting a pathogen can be a superior competitor to a more vulnerable resident species, is one of the principle driving forces influencing biodiversity in nature. Joo et al. investigate the effects of stochastic fluctuations on bacterial invasion facilitated by bacteriophage, and examine the validity of the deterministic approach.

This issue also contains several review papers describing areas which could potentially benefit from applying methods of stochastic analysis and statistical physics. For example, Keldermann et al. review recent results on studying dynamics of different excitation patterns organized by pacemakers that occur in the medium as a result of deformation. They also consider the interaction of several pacemakers with each other and the effects of pacemakers in the presence of a heterogeneous medium.