

Biological Physics/Physics of Living Systems: A Decadal Survey

Committee

William Bialek

Chair

Dr. Bialek is the John Archibald Wheeler/Battelle Professor in Physics at Princeton University. He also is a member of the multidisciplinary Lewis-Sigler Institute. In addition to his responsibilities at Princeton, he is Visiting Presidential Professor of Physics at the Graduate Center of the City University of New York, where is helping to launch an Initiative for the Theoretical Sciences. Born in 1960 and educated in the San Francisco public schools. He attended the University of California at Berkeley, receiving the AB (1979) and Ph.D. (1983) degrees in biophysics. After postdoctoral appointments at the Rijksuniversiteit Groningen in the Netherlands and at the Institute for Theoretical Physics in Santa Barbara, he returned to Berkeley to join the faculty in 1986. In late 1990 he moved to the newly formed NEC Research Institute (now the NEC Laboratories) in Princeton, where he eventually became an Institute Fellow. Dr. Bialek's research interests have ranged over a wide variety of theoretical problems at the interface of physics and biology, from the dynamics of individual biological molecules to learning and cognition. Best known for contributions to our understanding of coding and computation in the brain, Dr. Bialek and collaborators have shown that aspects of brain function can be described as essentially optimal strategies for adapting to the complex dynamics of the world, making the most of the available signals in the face of fundamental physical constraints and limitations. More recently, he has followed these ideas of optimization into the early events of embryonic development and the processes by which all cells make decisions about when to read out the information stored in their genes. Throughout his career Dr. Bialek has been involved both in helping to establish biophysics as a sub-discipline within physics and in helping biology to absorb the quantitative intellectual tradition of the physical sciences. For more than twenty years Dr. Bialek has participated in summer courses at the Marine Biological Laboratory in Woods Hole, Massachusetts, serving as co-director of the computational neuroscience course in the summers of 1998 through 2002. Currently, he is involved in a major educational experiment at Princeton to create a truly integrated and mathematically sophisticated introduction to the natural sciences for first year college students.

Bridget Carragher

Member

Dr. Carragher is the co-director of Simons Electron Microscopy Center, at the New York Structural Biology Center and an Adjunct Professor in of Biochemistry and Molecular Biophysics at Columbia University. She received her Ph.D. in biophysics from the University of Chicago in 1987. She worked in a variety of positions, both in industry and academia until moving to the Scripps Research Institute in 2001. Since 2002 she has served, together with Clint Potter, as the Director of the National Resource for Automated Molecular Microscopy (NRAMM), an NIH funded national biotechnology research resource. The focus of NRAMM is the development of automated imaging techniques for solving three-dimensional structures of macromolecular complexes using cryo-transmission electron microscopy (cryoEM). The overall goal is to develop new methods to improve the entire process, from specimen preparation to the generation of the final three-dimensional map. In 2007 Bridget co-founded a new company, Nanolmaging Services, Inc., whose goal is to provide cryoEM and other microscopy services to the biopharmaceutical and biotechnology industry. She serves as Chief Technology Officer of Nanolmaging Services. In 2015 Bridget and Clint moved their academic lab from The Scripps Research Institute to the New York Structural Biology Center where they serve as co-directors of the Simons Electron Microscopy Center. In May 2018 they were awarded a U24 grant to build the National Center for CryoEM Access and Training (NCCAT).

Ibrahim Cisse

Member

Dr. Cissé is currently the Class of 1922 Career Development Assistant Professor in the Department of Physics at MIT. He came to MIT in January 2014 after working at HHMI's Janelia Farm Research Campus where he was in the Transcription Imaging Consortium since January 2013. Prior to this, he was in Paris from January 2010 to December 2012, at Ecole Normale Supérieure de Paris, jointly in the Departments of Physics and Biology, as a Pierre Gilles de Gennes Fellow and a European Molecular Biology Organization long-term fellow. He received his Ph.D. from the Physics Department at the University of Illinois at Urbana-Champaign in December 2009. His graduate research in single-molecule biophysics was done in the lab of Taekjip Ha, focusing on weak and transient interactions in vitro. He received his B.S. in physics in 2004 from North Carolina Central University, and during that time he was investigating packing of ellipsoids using M&M candies with Paul M. Chaikin. Dr. Cissé is native of Niger, where he lived before moving to the U.S. for college. His current research work uses physical techniques to visualize weak and transient biological interactions. These are used to study emergent phenomena in live cells with single molecule sensitivity. Of particular interest to his research group are collective behaviors that emerge from weak and transient biological interactions in living cells. For instance, in high order organisms like humans, very little is understood of how transcription, the first step in the central dogma of biology is carried out at the cellular level. Complex behaviors involving transient spatiotemporal clustering of molecular enzymes control genome regulation in ways that his lab is working to visualize. The lab's approach is to develop and use highly sensitive experimental techniques capable of detecting and quantifying in a meaningful manner weak and transient biomolecular interactions. They have developed biophysical tools to measure weak and transient interactions both among isolated biomolecules (in vitro), and directly inside individual living cells with single-molecule sensitivity. Currently, they set out to understand what roles weak and transient interactions play in regulating genomic processes and nuclear organization at the single-cell level.

Michael Desai

Member

Dr. Desai is a professor of organismic and evolutionary biology at Harvard. He holds appointments in the Department of Organismic and Evolutionary Biology, the Department of Physics, and the FAS Center for Systems Biology. Prior to this, Dr. Desai received a B.A. in physics from Princeton University and a Ph.D. in physics from Harvard University. He then worked as a fellow at the Lewis-Singler Center for Integrative Genomics and Princeton University. He currently studies natural selection and other evolutionary forces. His group uses a combination of theoretical and experimental approaches to study how genetic variation created by natural selection and other evolutionary forces, is created and maintained. They also develop methods to infer the evolutionary history of populations from the variation observed in sequence data. Their focus is primarily on the dynamics and population genetics of natural selection in asexual populations such as microbes and viruses, which are often dominated by the random fluctuations in when and where rare mutational events occur. They are developing new approaches to population genetic theory to better understand the structure of genetic variation in these populations. To complement this theoretical work, the lab has developed high-throughput techniques which allow them to directly observe the evolution of thousands of experimental budding yeast populations simultaneously, tracking changes in fitness and other phenotypic characteristics and correlating these with the evolution of genetic variation within and between populations.

Olga Dudko

Member

Dr. Dudko is currently a professor in the Department of Physics at UC-San Diego. Prior to this, she received her Ph.D. in theoretical physics at the B. Verkin Institute for Low Temperature Physics & Engineering in Kharkov, Ukraine, followed by postdoctoral appointments at Tel Aviv University in Israel, and the National Institutes of Health. Her current lab searches for general principles that unify seemingly very different and often formidably complex biological systems. They try to capture these principles in the form of physical theories that are reasonably simple and abstract, yet are capable of generating concrete, experimentally testable predictions.

Daniel Goldman

Member

Dr. Goldman is a Dunn Family Professor in the School of Physics at the Georgia Institute of Technology, where he holds a Dunn Family Professorship. He received his B.S. in physics at the Massachusetts Institute of Technology in 1994. He received his Ph.D. in 2002 from the University of Texas at Austin, studying nonlinear dynamics and granular media. He did postdoctoral work in locomotion biomechanics at the University of California at Berkeley. He became a faculty member at Georgia Tech in January 2007 and is an adjunct member of the School of Biology and a member of the Bioengineering Graduate Program. Dr. Goldman is a Georgia Power Professor of Excellence, a fellow of the American Physical Society (2014), and has received an NSF CAREER/PECASE Award, a DARPA Young Faculty Award, a Sigma Xi Young Faculty Award, and a Burroughs Wellcome Fund Career Award at the Scientific Interface. His research integrates work in complex fluids and granular media and the biomechanics of locomotion of organisms and robots to address problems in non-equilibrium systems that involve interaction of matter with complex media. This work answers questions such as how organisms like lizards, crabs, and cockroaches cope with locomotion on complex terrestrial substrates (e.g. sand, bark, leaves, and grass). His lab seeks to discover how biological locomotion on challenging terrain results from the nonlinear, many degree of freedom interaction of the musculoskeletal and nervous systems of organisms with materials with complex physical behavior. The study of novel biological and physical interactions with complex media can lead to the discovery of principles that govern the physics of the media. His approach is to integrate laboratory and field studies of organism biomechanics with systematic laboratory studies of physics of the substrates, as well as to create mathematical and physical (robot) models of both organism and substrate. Discovery of the principles of locomotion on such materials are expected enhance robot agility on such substrates.

Jané Kondev

Member

Dr. Kondev is the William R. Kenan, Jr. Professor of Physics at Brandeis University. He works primarily on problems in molecular and cell biology. He earned his Ph.D. in physics from Cornell University in 1995. Dr. Kondev's research in the physical biology of the cell focuses on three distinct areas: regulation of gene expression, structure of chromosomes and their function, and dynamics of the cytoskeleton. He employs a combination of theory and experimentation on single molecules and single cells. Kondev established the Quantitative Biology Research Community (QBReC) that consists of undergraduate researchers who, while majoring in different fields of science, conduct collaborative research on specific biological problems and function as a single interdisciplinary research group. The QBReC program includes a freshman year lab and lecture course, which introduces students to science in an integrated fashion, combining physics, chemistry, biology, and mathematics, and collaborative research and mentorship opportunities.

Peter B. Littlewood

Member

Dr. Littlewood is a Professor of Physics at the University of Chicago, who was previously director of Argonne National Laboratory, and before that a Professor of Physics at the University of Cambridge and head of the Cavendish Laboratory. He is the founding executive chair of the Faraday Institution, UK's independent centre for electrochemical energy storage science and technology, supporting research, training, and analysis. He began his career with almost 20 years at Bell Laboratories, ultimately serving for five years as head of Theoretical Physics Research. His research interests include superconductivity and superfluids, strongly correlated electronic materials, collective dynamics of glasses, density waves in solids, neuroscience, and applications of materials for energy and sustainability. He is a fellow of the Royal Society of London, the Institute of Physics, the American Physical Society, and TWAS (The World Academy of Sciences). He serves on advisory boards of research and education institutions and other scientific organizations worldwide. He holds a bachelor's degree in Natural Sciences (physics) and a doctorate in physics, both from the University of Cambridge.

Andrea J. Liu

Member

Dr. Liu is the Hepburn Professor of Physics in the University of Pennsylvania Department of Physics and Astronomy. Prior to becoming a professor, she received her Ph.D. in physics from Cornell University, followed by being a postdoctoral fellow at the Exxon Research and Engineering Company, and then a postdoctoral appointment at UC-Santa Barbara. She then worked as a faculty member at UCLA before moving to the University of Pennsylvania. Her research group uses a combination of analytical theory and numerical simulation to study problems in soft matter physics ranging from jamming in glass-forming liquids, foams and granular materials, to biophysical self-assembly in actin structures and other systems. The idea of jamming is that slow relaxations in many different systems, ranging from glass-forming liquids to foams and granular materials, can be viewed in a common framework. For example, one can define jamming to occur when a system develops a yield stress or extremely long stress relaxation time in a disordered state. According to this definition, many systems jam. Colloidal suspensions of particles are fluid but jam when the pressure or density is raised. Foams and emulsions (concentrated suspensions of deformable bubbles or droplets) flow when a large shear stress is applied, but jam when the shear stress is lowered below the yield stress. Even molecular liquids jam as temperature is lowered or density is increased; this is the glass transition. They have been testing the speculation that jamming has a common origin in these different systems, independent of the control parameter varied. On the biophysical side, her research has been motivated recently by the phenomenon of cell crawling. The morphology of the resulting structure is of special interest because it determines the mechanical properties of the network. Her group is developing dynamical descriptions that capture morphology. In addition, they are exploring models for how actin polymerization gives rise to force generation at the leading edge.

Mary E. Maxon

Member

Dr. Maxon is the Associate Laboratory Director for Biosciences at Lawrence Berkeley National Lab. Dr. Maxon oversees Berkeley Laboratory's Biological Systems and Engineering, Environmental Genomics and Systems Biology, and Molecular Biophysics and Integrated Bioimaging Divisions and the DOE Joint Genome Institute. She earned her B.S. in biology and chemistry from the State University of New York, Albany, and her Ph.D. in molecular cell biology from the University of California, Berkeley. Dr. Maxon has worked in the private sector, both in the biotechnology and pharmaceutical industries, as well as the public sector, highlighted by her tenure as the Assistant Director for Biological Research at the White House Office of Science and Technology Policy (OSTP) in the Executive Office of the President.

Jose N. Onuchic

Member

Dr. José Onuchic is the Harry C & Olga K Wiess Professor of Physics and Astronomy, Chemistry and Biosciences at Rice University and the co-director of the NSF-sponsored Center for Theoretical Biological Physics. His research looks at theoretical methods for molecular biophysics and gene networks. He has introduced the concept of protein folding funnels. Energy landscape theory and the funnel concept provide the framework needed to pose and to address the questions of protein folding and function mechanisms. He developed the tunneling pathways concept for electron transfer in proteins. He is also interested in stochastic effects in genetic networks with applications to bacteria decision-making and cancer. Further expanding his ideas coming from energy landscapes for protein folding, his group is now exploring chromatin folding and function and therefore modeling the 3D structure of the genome. He has received much recognition for his achievements. He was elected to the National Academy of Sciences in 2006. He received the ICTP Prize in honor of Heisenberg in Trieste, Italy (1989) and the Beckman Young Investigator Award (1992). He is a fellow of the American Physical Society (1995), the American Academy of Arts and Sciences (2009), the Brazilian Academy of Sciences (2009), the Biophysical Society (2012), and the American Association for the Advancement of Science (2017). He was awarded the Einstein Professorship by the Chinese Academy of Sciences (2011). In 2014 he received the Diaspora Prize from the Ministry of Foreign Affairs and the Ministry of Industrial Development and Foreign Trade from Brazil. In 2015 he was awarded The International Union of Biochemistry and Molecular Biology (IUBMB) Medal and in 2017 he was elected fellow of the American Association for the Advancement of Science (AAAS). In 2018 he received National Order of Scientific Merit by the Brazilian National Council in Science and Technology chaired by the Brazilian President. He has just been awarded the 2019 American Physical Society's Max Delbruck Prize in Biological Physics.

Mark Schnitzer

Member

Dr. Schnitzer is an investigator of the Howard Hughes Medical Institute and a professor at Stanford University with a joint appointment in the Departments of Biology and of Applied Physics. He is co-director of the Cracking the Neural Code (CNC) Program at Stanford University and a faculty member of the Neuroscience, Biophysics, and Molecular Imaging Programs in the Stanford School of Medicine. Dr. Schnitzer received his Ph.D. from Princeton University in Physics prior to his appointment at Stanford University. His research concerns the innovation of novel optical imaging technologies and their use in the pursuit of understanding neural circuits. The Schnitzer Lab has invented two forms of fiber-optic imaging, one- and two-photon fluorescence microendoscopy, which enable minimally invasive imaging of cells in deep brain tissues. The lab is further developing microendoscopy technology, studying how experience or environment alters neuronal properties, and exploring two different clinical applications. The group has also developed two complementary approaches to imaging neuronal and astrocytic dynamics in awake behaving animals. Much research focuses on cerebellum-dependent forms of motor learning. By combining imaging, electrophysiological, behavioral, and computational approaches, the lab seeks to understand cerebellar dynamics underlying learning, memory, and forgetting. Further work in the lab concerns neural circuitry in other mammalian brain areas such as hippocampus and neocortex, as well as the neural circuitry of *Drosophila*.

Clare M. Waterman

Member

Dr. Waterman is a Distinguished Investigator, Chief of the Laboratory of Cell and Tissue Morphodynamics, and Director of the Cell Biology and Physiology Center at the National Heart, Lung, and Blood Institute, in the National Institutes of Health. Dr. Waterman received her bachelor's degree in biochemistry in 1989 from Mount Holyoke College and her M.S. in exercise science from the University of Massachusetts Amherst prior to obtaining her Ph.D. in cell biology from the University of Pennsylvania in 1995. After completing post-doctoral training at the University of North Carolina in Chapel Hill in 1999, she joined the Department of Cell Biology at the Scripps Research Institute in La Jolla, California. After obtaining tenure at Scripps as an Associate Professor, Dr. Waterman joined the NHLBI in 2007. She has also trained hundreds of Ph.D. candidates and post-doctoral scholars through her teaching in the Physiology Course at the Marine Biological Laboratory in Woods Hole, where she served as faculty from 2000-2009, and as its first female director from 2009 – 2014. The Physiology Course is an intensive seven-week laboratory summer course that has run for over 125 years. It is designed to bring together senior Ph.D. candidates and early post-doctoral researchers to work on cutting-edge questions in cell physiology. Her research program is focused on understanding how proteins self-organize into cell-scale macromolecular ensembles that mediate the dynamic morphological and physical processes driving cell migration. The ability of cells to directionally move is critical to embryogenesis, development of the vascular and nervous systems, immune response and wound healing, and its regulation is compromised in vascular disease, immune disease, and cancer. Dr. Waterman invented the method of Fluorescent Speckle Microscopy (FSM) and used this and other state-of-the art light microscopy methods to elucidate how macromolecular protein complexes self-organize at the cell-scale to mediate directed physical outputs that drive specific cell shape change and movement. She has pioneered an integrated approach that demonstrated how cellular structures composed of the microtubule, filamentous actin, and integrin adhesion proteins, are dynamically built and maintained, how they physically interact with one another, and how cell signaling coordinates their structure and dynamics to specifically mediate cell migration. Her work has shown that specific transient protein-protein interactions in a “molecular clutch” generate organized and directed forces in the cytoskeleton and transmit them through integrin-based focal adhesions to the extracellular environment to drive cell motility and morphogenesis of the vasculature.