DOE Office of Biological & Environmental Research: a Strategic Plan for Research at the Interface of the Biological and Physical Sciences

I. Current Situation

Many remarkable advances in biology achieved during the past century have been underpinned by breakthroughs in the physical sciences. The success of the Human Genome Project and its predecessor projects have made it clear that (l) biological mechanisms are much more complex than previously thought and (2) the physical and mathematical sciences have critical roles to play in understanding biology. The interface between biology and the physical sciences reflects the interplay between technology innovations by the physical sciences and new tools for biological inquiry. The ability to analyze and characterize at increasing resolutions and scales provides biologists with not only new tools, but enables fundamental discovery in system behavior, driving further new hypotheses and paradigms. The most success is achieved where the development and the benefits are shared on both sides of the interface.

Advances resulting from multi-disciplinary approaches provide an unprecedented sense that a deeper understanding of the natural world can be achieved at all levels – spatially, temporally, and organizationally. Disciplines such as systems biology and earth systems science, and applications such as the use of neural network models to simulate ecological systems are examples of how deeper understanding of complex systems can be approached through collaborations among physical, computational, behavioral, social, and biological scientists and engineers. Close interaction and cross-fertilization between the biological and physical sciences may lead to new, multidisciplinary areas of science to advance our understanding of important biological and environmental systems. Such scientific understanding can inform solutions to major complex national and global issues such as energy resources, climate change, environmental sustainability and national security.

Understanding the relationship between the genome and functional processes is the most significant challenge and potentially enabling advancement that faces modern biology. Elucidating this connection presents opportunities for realizing sustainable energy solutions and responsible management of natural resources. Understanding the function of the genome is at the core of the Department of Energy’s (DOE) Genomic Science program and is central to realizing DOE’s mission goals in bioenergy research, carbon management and environmental stewardship. Just as genomic science is central to these mission goals, technology advancements are central to genomic science and to unlocking the connections between the genome and functional processes occurring at cellular to organisms to global environmental scales. New developments in characterization technologies for understanding complex biological systems will be essential for driving advances in genomic science and in our understanding of the genomic, and thus the biological, bases of natural processes. Equally critical to the development of multi-disciplinary approaches and tools is the commitment to nurture cross-training opportunities for biologists and physical scientists.

II. Inputs

DOE and BER (together with its research partners across the federal government) support fundamental research and technology development at the interface of biology and the physical sciences that can be leveraged to make transformational advances in biology. These investments include:

- DOE Light Sources and Neutron Sources

  DOE laboratories, in particular the light sources (National Synchrotron Light Source at Brookhaven, the Advanced Light Source at Berkeley, the Advanced Photon Source at Argonne, the Stanford Synchrotron Radiation Light Source and neutron sources (High Flux Isotope Reactor [HFIR] and Los Alamos Neutron Science Center [LANSCE] offer opportunities for state-of-the art research in materials science, biology, chemistry, physics, and the environmental sciences, including x-ray microscopy of biological samples.

- BER's Specialized Facilities

  BER maintains specialized facilities for biological and environmental research. Two of those facilities, the Joint Genome Institute and the Environmental Molecular Sciences Laboratory, also contribute to the development and use of cutting edge technology and methods. The Joint Genome Institute (JGI) occupies a unique niche as a national user facility dedicated to harnessing the power of information embedded in an organism's DNA, especially microbes and plants of interest to DOE, through DNA sequencing. The JGI is continuously drawing upon technological developments to improve its DNA sequencing and analysis capabilities. The Environmental Molecular Sciences Laboratory provides integrated experimental and computational resources, including proteomics technology development, for discovery and technological innovation in the environmental molecular sciences.

- BER's Field-Scale Research Sites

  BER also funds research at multiple sites that will continue to contribute to the development of technology and that will also benefit from advances in technologies to date typically used for the physical sciences. These sites include:

  The Free-Air CO_2 Enrichment (FACE) Facility, which experimentally enriches the atmosphere with controlled amounts of CO_2 (and in some cases, other gases), without using chambers or "walls". The goal is to study effects of elevated atmospheric CO_2

concentration on plants and ecosystems under relatively undisturbed conditions (i.e., to avoid the changes in microclimate caused by most chamber systems). FACE has sites in Oak Ridge, TN, Mercury, NV, Durham, NC, and Rhinelander, WI.

Integrated Field-Scale Subsurface Research Challenge (IFRC) Sites, which engage in fundamental research to understand the physical, chemical, and biological nature of our environment, for the purpose of solving problems in environmental remediation and stewardship.

The AmeriFlux Network, which was established in 1996 to coordinate continuous observations of ecosystem level exchanges of CO_2, water, energy and momentum spanning diurnal, synoptic, seasonal, and interannual time scales. The Network is currently composed of sites from North America, Central America and South America.

- DOE's Computing Programs

  Advanced databases and computational approaches are needed for integrating and analyzing biological information and for developing and using complex systems models at multiple scales. Effective modeling of biological systems will help identify new or modified measurement technologies using an iterative cycle of modeling, technology development and experimentation. DOE's computational resources and capabilities include:

  The Scientific Discovery through Advanced Computing (SciDAC) program that brings together the nation's top researchers to tackle challenging scientific problems. Multidisciplinary SciDAC projects are aimed at developing future energy sources, studying global climate change, accelerating research in designing new materials, improving environmental cleanup methods, and developing multi-scale models of microbial metabolic pathways relevant to biofuel production.

  The Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program was launched in 2003 to seek out computationally intensive, large-scale research projects with the potential to significantly advance key areas in science and engineering.

  Leadership Computing Facilities at Argonne National Laboratory and the Oak Ridge National Laboratory provide the world's most powerful computing facilities for open scientific research.

- Initiatives of Other Federal and Private Research Organizations

NIH, DoD, NSF, and other private organizations (e.g. the Howard Hughes Medical Institute or the Carnegie Institution for Science) within and outside the U.S. are also working to advance the application of tools and instruments for the physical and medical sciences which may ultimately be useful to DOE in furthering its mission areas.

Recognizing its unique opportunity to advance this field, BER has held two recent workshops to explore possibilities at the interface of the biological and physical sciences..

One workshop, held on November 4-5, 2008, focused on "New Frontiers of Science in Radiochemistry and Instrumentation for Radionuclide Imaging." Experts from nuclear medicine, biology, and the environmental sciences discussed new paradigms that represented the first step in exploring the potential of radiotracer imaging to solve biological problems in energy and environmentally-responsive contexts.

The second workshop, held on May 13-14, 2009, focused on "New Frontiers in Characterizing Biological Systems." A diverse array of scientists and engineers with expertise in the biological and environmental sciences and in the analytical and physical sciences discussed the major challenges facing the biological and environmental science communities, including the need to better understand: 1) the cell and its response to chemical and physical perturbations; 2) interactions between cells; and 3) functioning of biological systems across multiple scales of time and distance. They also discussed the specific technical capabilities needed to fill these gaps, including: 1) expanding and integrating global characterization capabilities; 2) identifying and measuring important molecular species, events, and cells; 3) simultaneously measuring many chemical and biological species across broad spatial and temporal ranges; and 4) integrating and interpreting diverse information and technology platforms.

BER also co-sponsored two National Research Council studies to identify strategic opportunities at the interface. "A New Biology for the 21st Century" examines the current state of biological research in the United States and recommends how best to capitalize on recent technological and scientific advances that have allowed biologists to integrate biological research findings, collect and interpret vastly increased amounts of data, and predict the behavior of complex biological systems.

The second NRC study and report entitled "Research at the Intersection of the Physical and Life Sciences" (2010), is intended to: 1. Develop a conceptual framework for the scientific forefronts at the interface between the physical and life sciences and conduct an assessment of the work; 2. Identify and prioritize the most promising research opportunities at this interface, articulate the potential benefits to society, and recommend strategies for realizing them; 3. Explore ways to enable and enhance effective interdisciplinary collaboration, such as education, training, instrumentation, and cyberinfrastructure, which bring together the life and physical sciences to address the most compelling opportunities.

III. Near-Term Goals (1-3 Years):

- Development of new tools, technology, and models to study biological systems and processes

  Understanding the relationship between the genome and the functional processes of a biological system requires the development of advanced tools, technologies, and models that allow the integration and characterization of biological processes over a wide range of spatial and temporal ranges. To accomplish this goal, research on innovative technologies that will allow imaging, detection, and sensing in real-time, as well as high-through-put characterization and analysis, will be needed. The overarching goal will be to measure relevant biological events/changes in spatial and temporal dimensions necessary to understand the biological processes of that system with minimal perturbation to the system. Development of Quality Assurance plans for data quality, accessibility and interoperability is a strong component of this goal.

- Integrate research and training for biologists and physical scientists

  The complex and diverse nature of biological systems requires the integration of the biological sciences with analytical and computational technologies. As a near term goal, integrated training programs are needed for graduates and post graduates from the biology, environmental sciences, physics, mathematics, chemistry, computation, engineering, and materials sciences fields to help train the next generation of inter disciplinary scientists.

IV. Mid Term Goals (4-6 years)

- Test, validate, prototype, and scale next generation tools, technologies, and models for use in studying simple and complex systems.

  As a mid-term goal, the tools and technologies developed in the near-term will be prototyped and evaluated in various biological systems to determine their usefulness and functionality. Initially, these new tools will be evaluated in simple biological systems that are relevant to BER’s mission while gradually moving into more complex biological systems. Major projects should demonstrate continued commitment to Quality Assurance for data generation, accessibility and interoperability.

- Enhance research and cross training programs for biological and physical scientists

During the mid-term phase, training programs that were initiated to integrate scientists across scientific disciplines will be expanded. This will include cross-training and research opportunities for young scientists in different scientific disciplines that will benefit their research efforts. Involvement will be encouraged by creating incentives for individuals and institutions to collaborate, including accessible user facilities that house high-end instrumentation and provide technical support and data interpretation and the development of high-capability instrumentation that is affordable to small groups of scientists.

V. Long Term Goals (7-10 years)

- Enabling tools/technologies for biology are fully integrated into BER biological research portfolio

Tools and technologies developed over the previous periods will be fully integrated into BERs diverse research programs. These tools will allow the characterization of complex living systems and their surrounding environments at spatial and temporal resolutions critical for the complete understanding of the biological system under study. This will include linking cellular, multicellular, and environmental interactions in experimental settings as well as in their natural environment. With the development of these advanced tools and strong commitment to Quality Assurance, the capability to manipulate biological components and accurately measure the response in real-time, identify biologically relevant events in heterogeneous environments, and accurately model these complex systems in a predictable fashion, will be achievable.

VI. Outcomes – Impacts on Science and Society

New, long-needed and sought after insights will be enabled by advancements in tools, technologies, and models:

- on the function, regulation, and four dimensional organization of complex biological systems from single cells to multicellular organisms and ecosystems.
- on the signaling, cross-talk, and response and interaction of multi-cellular biological systems to and with their environment.

This new, integrated understanding at multiple temporal and spatial scales, will result in new applications that take advantage of how the fundamental laws governing physical systems drive the dynamics and complexity of living systems. The science required for our missions in bioenergy, subsurface biogeochemistry, and climate change will no longer be confined to disciplinary boundaries, but will be informed by the collaborative and creative convergence of technology and innovation.