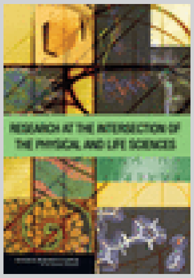

Research at the Intersection of the Physical and Life Sciences

ISBN
978-0-309-14751-4

124 pages
7 x 10
PAPERBACK (2010)

Committee on Forefronts of Science at the Interface of Physical and Life Sciences; National Research Council

Summary

". . . the action most worth watching is not at the center of things but where edges meet . . . shorelines, weather fronts, international borders . . ."

Anne Fadiman, *The Spirit Catches You and You Fall Down*

Almost since their inception, the natural sciences, those fields that use the scientific method to study nature, have been divided into two branches: the biological sciences and the physical sciences. In part, this division can be viewed as a convenient social contrivance. However, over time it has also served more functional purposes. Physical scientists, when seeking the fundamental laws, have found it necessary to focus on the simplest of systems—elementary particles, atoms, and molecules—items clearly not alive. It also has been convenient for biological scientists to investigate the immense diversity of living things and their elaborate inner workings without simultaneously accepting the burden of trying to follow these complexities down to their atomic level roots.

Today, while it still is convenient to classify most research in the natural sciences as either biological or physical, more and more scientists are quite deliberately and consciously addressing problems lying at the intersection of these traditional areas. This report focuses on their efforts. As directed by the charges in the statement of task (see Appendix A), the goals of the committee in preparing this report are several fold. The first goal is to provide a conceptual framework for assessing work in this area—that is, a sense of coherence for those not engaged in this research about the big objectives of the field and why it is worthy of attention from fellow scientists and programmatic focus by funding agencies. The second goal is to assess current work using that framework and to point out some of the more promising opportunities for future efforts, such as research that could significantly benefit society. The third and final goal of the report is to set out strategies for realizing those benefits—ways to enable and enhance collaboration so that the United States can take full advantage of the opportunities at this intersection.

CONCEPTUAL FRAMEWORK FOR ASSESSING THIS INTERSECTION

Any attempt to provide an all-inclusive framework for this work will inevitably leave out research that belongs within it. With that caveat, a good way to think of research at this intersection is that it turns ways of looking at things—both figuratively and literally—from their original purpose and uses them to tackle new problems, often in ways far removed from when they were first conceived.

Most—but not all—of the new problems being addressed at this intersection are biological ones, largely because of the incredible richness of this field. The realm of biology is immense, involving complicated structures as small as molecules and as large as the biosphere and timescales that range from submicroseconds to eons. Answers to these problems seek not only to describe how the individual structures, in their immense complexity and diversity, work but also how they interplay. A very rich source of potential questions indeed.

The ways of looking often come from the physical sciences. Those ways might be conceptual—approaches for looking at and solving problems—or analytical—methods for extracting understanding from data—or technical—tools for collecting information needed to address the problem at hand. But it is this intermingling of problems from one arena and ways of looking at them from another arena that makes this intersectional area between the biological and physical sciences so rich and offers many of the opportunities that reside there. The committee expects that ideas will emerge from such studies that will go well beyond the intersection and transform both the biological and physical sciences.

CURRENT WORK AT THE INTERSECTION

What, then, are some of the areas being explored at this intersection? Interestingly, many share common conceptual themes, several of which are discussed in this report. Interactions appear in both branches, albeit with much different content and contexts. Describing how individual particles interact—what forces and energy exchanges cause crystalline materials to form, and matter in all phases to display characteristic behavior and to undergo phase changes—are mainstays of the world of physics. However, these ways of thinking about and discussing how inanimate objects interact have been found useful to scientists attempting to answer questions about the interplay of biological matter at many different levels.

Another area finding fertile ground and producing fruitful cross-research opportunities centers on the dynamics of systems. Equilibrium, multistability, and stochastic behavior—concepts familiar to physicists and chemists—are now being used to tackle issues involved in living systems such as adaptation, feedback, and emergent behavior. Ideas of pattern formation that are at the heart of condensed matter physics now help us to understand biological self-assembly and the development of biological systems.

This report also discusses how some of the mysteries of the biological world have been unraveled using tools and techniques developed in the physical sciences. These tools include not only imaging devices, both photon- and matter-based, but also computational models and algorithms. While many of them are used interchangeably by the two fields, others must be modified. However, to reach the heart of biological systems, even more sophisticated investigatory technologies and tools will be needed, many of which have not even been imagined much less developed.

In preparing this report, the committee was mindful of the vastness of the number of topics that arguably comes within the ambit of this report's subject matter. Work taking place at the intersections of engineering and the life sciences and of materials development and the life sciences covers but two of such topics. Both are fascinating examples of where the meshing of different cultures and sets of ideas can produce much fruitful discussion and advancement.[1] However, the statement of task for this committee focuses on research, limiting this report to more basic activities than those typically involved in engineering and materials development. Further, the committee acknowledges that the research that is the subject matter of this report both arises from and depends upon the rich, ongoing efforts taking place within the core disciplines of the physical and life sciences. Such intersectional research serves to supplement rather than to supplant the scientific advances being made in the more traditional fields.

PROMISING OPPORTUNITIES FOR FUTURE EFFORTS

Some of the most fundamental challenges in this area and near-term prospects for successfully meeting them are discussed in the form of five Grand Challenges:

[1] Some have been covered in other NRC reports. See, for example, *Inspired by Biology: From Molecules to Materials to Machines*, Washington, D.C.: The National Academies Press (2008) and *A New Biology for the 21st Century*, Washington, D.C.: The National Academies Press (2009). Others might be the focus of future reports.

- *Grand Challenge 1.* Natural substances display remarkable architecture, demonstrating the immense breadth of what can be achieved in developing structures and systems. Can the skills and knowledge-sets of biological and physical scientists be combined to provide greater insight into identifying those structures, capabilities, and processes that form the basis for living systems, and then to use that insight to construct systems with some of the characteristics of life that are capable, for example, of synthesizing materials or carrying out functions as yet unseen in natural biology?
- *Grand Challenge 2.* The human brain may be nature's most complex system. Can we understand how it works and build on that understanding to predict brain function? Addressing this challenge will require drawing on the resources of the physical sciences, both existing and to be developed, from imaging techniques to modeling capabilities.
- *Grand Challenge 3.* Genes and the environment interact to produce living organisms. Can we deepen our understanding of those interactions to begin to comprehend how organisms change over time—how they age and heal, for example—and from that understanding realize the promise of personalized medicine and access to better health care?
- *Grand Challenge 4.* Earth interacts with its climate and the biosphere through strikingly different yet intertwined mechanisms that operate over vast ranges of time and space. Can life and physical scientists develop an effective approach for understanding how these mechanisms interplay and use that understanding to develop strategies that will preserve this heritage?
- *Grand Challenge 5.* Living systems display remarkable diversity, serving to protect communities from harm. This diversity is declining, however, as the result of human activities, yet efforts to understand its role in the health of a species or an ecosystem have only recently been undertaken. Can knowledge gained at the intersection of the life and physical sciences teach us how to prosper while sustaining the diversity that allows life to flourish?

Further research at this intersection not only will advance our understanding of the fundamental questions of science, but will also significantly impact public health, technology, and stewardship of the environment for the benefit of society. In the world of technology, our economy clearly is based on materials, but no synthetic material in use today is as complex as a dead piece of wood, let alone a living organism. Prospects for a material world as adaptive and robust as living things have been the stuff of science fiction for decades. To achieve these dreams requires a greater understanding of the organizing principles of life. For public health, the complexity of molecular recognition and the emergent regulation of physiology must be better understood if drug design is to progress from the art it is to engineering science. Without understanding the diversity encompassed in human biology, personalized medicine will remain more a hope than a reality.

We often think of environmental challenges as being biological ("Save the whales!") or physical ("Limit greenhouse gases!") but, again, this distinction between the disciplines is a distortion. The constant interplay between the biological sciences and the physical sciences is profound when Earth is viewed as an entire system.

STRATEGIES FOR ENABLING AND ENHANCING WORK AT THE INTERSECTION

Throughout the report, the committee recommends ways to accelerate progress in this field. Some of these recommendations are implicit. By describing the vast array of outstanding questions at this intersection, it hopes to intrigue some of its fellow scientists to venture into this area and perhaps find interesting questions to address. Of the report's explicit recommendations, several are directed to those administering the faculties and resources of our great research institutions. In both the academic and business world, the cultures of the biological and physical sciences have evolved separately. Indeed both of these broad areas maintain numerous subcultures within themselves. It might seem that the daily life of a physician and that of a professor of theoretical physics would have nothing in common, but they must appreciate each other's insights if the scientific challenges at this interface are to be met and the societal benefits realized. Just as important, educational institutions need to develop multidisciplinary research and education opportunities that transcend the traditional departmental structure. They need to establish curricula and training opportunities to prepare the next generation of scientists to grapple with the questions posed at this intersection.

The committee recognizes that the needed changes will not come about just because of this report. Federal and private funding agencies will have to establish policies and programs that provide the appropriate incentives. Professional societies will need to break down disciplinary barriers and promote scholarships at the intersection of disciplines. And academic leaders will need to take what steps they can to facilitate the changes. This report describes the many profound and societally important scientific issues yet to be explored in this area. In it, the committee hopes to make the case that inertia and the understandable resistance to change must be overcome and that necessary structural changes in academic departments and curricula need to be undertaken.

RECOMMENDATIONS

- **Universities should establish science curriculum committees that include both life scientists and physical scientists to coordinate curricula between science departments and to plan introductory courses that prepare both those who would major in the life sciences and those who would enter the physical sciences.**
- **Professional scientific societies should partner with peer societies across the life and physical sciences to organize workshops and provide resources that will facilitate multidisciplinary education for undergraduates.**
- **Federal and private funding agencies should offer seed grants to academic institutions to develop new introductory courses that incorporate both the physical and life sciences and to professional societies for organizing workshops and developing resources for multidisciplinary education. They should also support research to identify best practices in such education.**
- **Federal and private funding agencies should offer expanded training grants that explicitly include graduate students and postdoctoral researchers from fields across the life and physical sciences and that require the involvement of academic departments from both the physical and life sciences. Funding agencies should also offer administrative supplements to existing research grants that would enable a principal investigator in the life sciences to support a postdoctoral researcher with a background in the physical sciences, or vice versa.**

The report also makes recommendations to help provide better support and guidance for research in these areas. The committee hopes that this report makes the case that much of the best science at this intersection has difficulty finding a financial home and resources. All too often, the most interesting questions that researchers seek to address here do not readily fall within the purview of a particular agency program or review structure. Accordingly, the committee calls for changes in funding mechanisms that will produce effective collaboration and cooperation among federal agencies that support research in the physical and life sciences.[2] Established investigators trained in one discipline should have the opportunity to receive training in another, so they may apply their experience to multidisciplinary problems. Mechanisms need to be put in place to support investigator-initiated multidisciplinary research where review of the proposal assesses the candidate's previous work rather than just the research being proposed.

[2] See also the discussion in the NRC report *A New Biology for the 21st Century*, Washington, D.C.: The National Academies Press (2009).

RECOMMENDATION
The Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) should develop mechanisms to ensure effective collaboration and cooperation among federal agencies that support research at the nexus of the physical and life sciences. In particular, OSTP and OMB should work with federal science agencies to establish standing mechanisms that facilitate the funding of interagency programs and coordinate the application and review procedures for such joint programs. Moreover, the National Science and Technology Council should establish a standing interagency working group on multidisciplinary research within its Committee on Science, with focus on the intersection of the physical and life sciences.

RECOMMENDATION
Federal and private funding agencies should offer opportunities for both early-career and established investigators trained in one discipline to receive training in another and apply their experience and training to interdisciplinary problems. In particular, postdoctoral career awards should be established that facilitate the transition of a candidate prepared in a physical science field to apply that training to important questions in the life sciences and vice versa. Funding agencies should also provide expanded support for experienced investigators to receive training in a new field, perhaps in the form of sabbatical fellowships.

RECOMMENDATION
Federal and private funding agencies should enhance the ability of more than one researcher to serve as principal investigator (PI) on research projects. Each PI should receive full credit for participation on the grant, with the lead PI serving as the administrative contact.

RECOMMENDATION
Federal and private finding agencies should devote a portion of their resources to support potentially transformative research, including opportunities at the intersection of the physical and life sciences. These sponsors should have peer review procedures that incorporate the viewpoints of scientists from a variety of disciplines. Moreover, they should continually assess the effectiveness of these grant programs and the review procedures to ensure that they are meeting the desired aims.

RECOMMENDATION
Federal and private funding agencies should expand support for interdisciplinary and multidisciplinary research and education centers. In particular, extramural funding should be provided to establish and maintain center infrastructure and research expenses. Initial (e.g., 5-year) salary support for investigators performing research that spans disciplines should also be included, with continuing salary support for faculty associated with the center provided by the host institution(s) or department(s). To support these centers, universities will need to implement multidepartment hiring practices and tenure policies that support faculty working collaboratively within and across multiple disciplines, establish shared resources, and provide incentives for departments to promote multidepartmental research and cross-disciplinary teaching opportunities.

Many of these recommendations are not new, but instead resemble those rendered by previous committees about the need to break away from "stove piping"—narrowly focused and isolated funding programs—and to implement new ways for evaluating funding opportunities and prioritizing funding for the most promising research. These resemblances should be seen as a renewed acknowledgement by this committee that such changes remain important and continue to be necessary to take full advantage of the research opportunities at this interface.

As noted by President Obama in his remarks to the National Academy of Sciences in April 2009, change and convergence are key to fully meeting the challenges and opportunities at this intersection:

> In biomedicine . . . we can harness the historic convergence between life sciences and physical sciences that's underway today [by] undertaking public projects—in the spirit of the Human Genome Project—to create data and capabilities that fuel discoveries in tens of thousands of laboratories and identifying and overcoming scientific and bureaucratic barriers to rapidly translate scientific breakthroughs into diagnostics and therapeutics that serve patients.[3]

New cultures must be forged and scientists must grow as comfortable in them as they are in their existing subcultures. There must be funding for work in those new cultures that extends beyond existing-culture "stove pipes." Most important, they must prepare the rising generation to mine new-culture opportunities without losing touch with scientists in the traditional disciplines or the principles of such disciplines. The future will be driven by progress at this intersection.

[3] Remarks by the President at the National Academy of Sciences Annual Meeting on April 27, 2009; available at http://www.whitehouse.gov/the_press_office/Remarks-by-the-President-at-the-National-Academy-of-Sciences-Annual-Meeting/. Last accessed September 3, 2009.

Research at the Intersection of the Physical and Life Sciences

Committee on Research at the Intersection of the Physical and Life Sciences

Board on Physics and Astronomy

Board on Life Sciences

Board on Chemical Sciences and Technology

Division on Engineering and Physical Sciences

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This project was supported by the Department of Energy under Award No. DE-FG02-07ER46378, the National Science Foundation under Award No. CHE-0554275, the Department of Health and Human Services under Award No. N01-OD-4-2139, the Burroughs Wellcome Fund under Award No. 1007560, and the Research Corporation for Science Advancement under Award No. 7827. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the sponsors.

International Standard Book Number-13: 978-0-309-14751-4
International Standard Book Number-10: 0-309-14751-4
Library of Congress Control Number: 2010921434

Cover: Work at the intersection of the life sciences and the physical sciences has often been depicted in new ways of imaging or modeling biological specimens, some of which are illustrated on the cover: (1) three-dimensional distribution of membrane proteins within a cell revealed through iPALM imaging (courtesy of Harald F. Hess, Howard Hughes Medical Institute); (2) xylose isomerase crystal (courtesy of Department of Energy Office of Basic Energy Research (BER)-funded neutron Protein Crystallography Station at Los Alamos National Laboratory (LANL)); (3) simulation of confinement of DNA in viral capsid (courtesy of Molecular Dynamics and Statistical Mechanics Research Group, University of Wisconsin at Madison); (4) diffusion tension imaging of the human brain (courtesy of Thomas Schultz, University of Chicago); (5) chromosome pairs; (6) modeled structure for the enzyme D-xylose isomerase (courtesy of Department of Energy BER-funded neutron Protein Crystallography Station at LANL; (7) anglerfish ovary obtained using autofluorescence (courtesy of James E. Hayden, Wistar Institute, Philadelphia); and (8) rat cerebellum obtained using two-photon excitation fluorescence microscopy (courtesy of the National Center for Microscopy and Imaging Research at the University of California at San Diego and the National Institutes of Health.

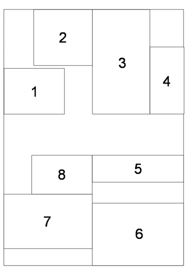

IMAGE SOURCES: (1) Harald F. Hess, Howard Hughes Medical Institute; (2) Department of Energy Office of Basic Energy Research (BER)-funded neutron Protein Crystallography Station at Los Alamos National Laboratory (LANL); (3) Molecular Dynamics and Statistical Mechanics Research Group, University of Wisconsin at Madison; (4) Thomas Schultz, University of Chicago; (6) Department of Energy BER-funded neutron Protein Crystallography Station at LANL; (7) James E. Hayden, Wistar Institute, Philadelphia; and (8) National Center for Microscopy and Imaging Research at the University of California at San Diego and the National Institutes of Health.

Copies of this report are available from: National Academies Press, 500 Fifth Street, N.W., Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet <http://www.nap.edu>; and the Board on Physics and Astronomy, National Research Council, 500 Fifth Street, N.W., Washington, DC 20001; Internet <http://www.national-academies.org/bpa>.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON RESEARCH AT THE INTERSECTION OF THE PHYSICAL AND LIFE SCIENCES

ERIN K. O'SHEA, *Co-Chair,* Harvard University
PETER G. WOLYNES, *Co-Chair,* University of California at San Diego
ROBERT H. AUSTIN, Princeton University
BONNIE L. BASSLER, Princeton University
CHARLES R. CANTOR, Sequenom, Inc.
WILLIAM F. CARROLL, Occidental Chemical Corporation
THOMAS R. CECH, Howard Hughes Medical Institute
CHRISTOPHER B. FIELD, Carnegie Institution Department of Global Ecology
GRAHAM R. FLEMING, University of California at Berkeley
ROBERT J. FULL, University of California at Berkeley
SHIRLEY ANN JACKSON, Rensselaer Polytechnic Institute
LAURA L. KIESSLING, University of Wisconsin at Madison
CHARLES M. LOVETT, JR., Williams College
DIANNE NEWMAN, Massachusetts Institute of Technology
MONICA OLVERA de la CRUZ, Northwestern University
JOSÉ N. ONUCHIC, University of California at San Diego
GREGORY A. PETSKO, Brandeis University
ASTRID PRINZ, Emory University
CHARLES V. SHANK, Lawrence Berkeley National Laboratory (retired)
BORIS I. SHRAIMAN, University of California at Santa Barbara
H. EUGENE STANLEY, Boston University
GEORGE M. WHITESIDES, Harvard University

Staff

DONALD C. SHAPERO, Director, Board on Physics and Astronomy
FRANCES E. SHARPLES, Director, Board on Life Sciences
DOROTHY ZOLANDZ, Director, Board on Chemical Sciences and Technology
ADAM P. FAGEN, Senior Program Officer, Board on Life Sciences
JAMES C. LANCASTER, Program Officer, Board on Physics and Astronomy
KATHRYN J. HUGHES, Program Officer, Board on Chemical Sciences and Technology
NATALIA MELCER, Program Officer, Board on Physics and Astronomy
LAVITA COATES-FOGLE, Senior Program Assistant

SOLID STATE SCIENCES COMMITTEE

BARBARA JONES, *Chair,* IBM Almaden Research Center
MONICA OLVERA de la CRUZ, *Vice-Chair,* Northwestern University
DANIEL AROVAS, University of California at San Diego
COLLIN L. BROHOLM, The Johns Hopkins University
PAUL CHAIKIN, New York University
GEORGE CRABTREE, Argonne National Laboratory
ANDREA J. LIU, University of Pennsylvania
JOSEPH ORENSTEIN, University of California at Berkeley
ARTHUR P. RAMIREZ, LGS, a subsidiary of Alcatel-Lucent, and Columbia University
RICHARD A. REGISTER, Princeton University
MARK STILES, National Institute of Standards and Technology
DALE J. VAN HARLINGEN, University of Illinois at Urbana-Champaign
FRED WUDL, University of California at Santa Barbara

Staff

DONALD C. SHAPERO, Director, Board on Physics and Astronomy
MICHAEL H. MOLONEY, Associate Director
JAMES C. LANCASTER, Program Officer
LAVITA COATES-FOGLE, Senior Program Assistant
BETH DOLAN, Financial Associate

BOARD ON PHYSICS AND ASTRONOMY

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Marlene Belfort, New York State Department of Health
Robert Dimeo, National Institute of Standards and Technology
James Heath, California Institute of Technology
Jennifer Lippincott-Schwartz, National Institutes of Health
Andrea Liu, University of Pennsylvania
Peter Moore, Yale University
Aravi Samuel, Harvard University
Philip Sharp, Massachusetts Institute of Technology
Erik Sorensen, Princeton University

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The

review of this report was overseen by W. Carl Lineberger, University of Colorado at Boulder. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

SUMMARY 1

1 INTRODUCTION 9

2 GRAND CHALLENGES 12
Grand Challenge 1. Synthesizing Lifelike Systems, 12
Grand Challenge 2. Understanding the Brain, 14
Grand Challenge 3. Predicting Individual Organisms' Characteristics from Their DNA Sequence, 15
Grand Challenge 4. Interactions of the Earth, Its Climate, and the Biosphere, 16
Grand Challenge 5. Understanding Biological Diversity, 18

3 SOCIETAL CHALLENGES 20
Identifying and Combating Biological Threats, 21
Early Detection and Intervention, 21
Prediction of Susceptibility to Disease and Its Prevention, 22
Climate and Its Interface with Biology, 23
Complex Feedback Loops in Climate Science, 23
Implications of Renewable Energy, 23
Medicine, 24
Imaging, 24
Treatment and Devices, 25

Agriculture as a Resource for Food and Energy, 25
Building Better Plants and Getting More Out of Them, 26
Hydrogenases and Synthetic Photosynthesis, 27
Beyond Combustion, 27
Materials Science, 28
Opportunities, 28
References, 29

4 COMMON THEMES AT THE INTERSECTION OF BIOLOGICAL AND PHYSICAL SCIENCES 30
Interaction and Information: From Molecules to Organisms and Beyond, 30
Dynamics, Multistability, and Stochasticity, 36
Self-organization and Self-assembly, 42
Conclusion, 48
References, 49

5 ENABLING TECHNOLOGIES AND TOOLS FOR RESEARCH 51
Introduction, 51
Physical Basis of Molecular Recognition, 52
Structures and Dynamics Within Cells, 53
Cellular Environment, 53
Interactions Within Cells, 55
Examining Structures Within Cells, 56
Theory and Simulations, 60
Collective Dynamics, 64
Complex Community Signals and Shared Resources at Large Length Scales, 65
References, 68

6 ENABLING RESEARCH AT THE INTERSECTION: PROMOTING TRAINING, SUPPORT, AND COMMUNICATION ACROSS DISCIPLINES 69
Connections Between Disciplines, 70
Culture of Separation Between the Life and Physical Sciences, 70
Culture and Organization of Academia, 72
Organization of Support for Research, 73
Supporting Transformative Research, 78
Educating Scientists at the Intersection of the Physical and Life Sciences, 82

Enabling Interdisciplinary Research Starting at the Undergraduate Level, 82
Integrating Life and Physical Sciences for Graduate Students and Postdoctoral Researchers, 85
References, 89

APPENDIXES

A Statement of Task 93
B Meeting Agendas 94
C Biographies of Committee Members 99