Free Executive Summary

Inspired by Biology: From Molecules to Materials to Machines

Committee on Biomolecular Materials and Processes,
National Research Council

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Executive Summary

The ability of biological systems to carry out extremely complex functions in a vast array of environments has long inspired scientists to create synthetic systems that function with similar precision and efficiency. A lack of understanding of how biological systems function has hampered the ability to make such materials and devices. Scientists are using an expanding toolbox of new ways to measure, manipulate, and compute properties of matter, living and nonliving. These efforts are beginning to uncover the principles that govern how biological systems work. Application of the principles uncovered by these investigations will allow scientists to create synthetic materials, processes, and devices that can carry out tasks with the precision of biological systems. As demonstrated by the opportunities and examples presented in this report, now is a very exciting time for research at the intersection of the biological and materials sciences.

Practical design of biologically inspired materials has the potential to improve the well-being of U.S. citizens and the nation's economic competitiveness by addressing some of the most urgent national challenges. Biomolecular materials and processes may improve medical therapeutics, allow the creation of reliable sensors to detect biological and chemical threats, and facilitate the path to energy independence. To realize these opportunities and fully harness the potential of biology to inform the development of materials and processes, further advances in fundamental physics, chemistry, and material science will be required. Three closely related strategies for the creation of new materials and systems may help realize the potential of biomolecular materials and processes:

Biomimicry. This strategy relies on first learning the mechanistic principle used by a living system to achieve a particular function. Then one attempts to copy the same scheme to achieve similar function in a synthetic material. One example is the design of materials where the building blocks themselves encode information during their synthesis. One can also try to create materials that mimic whole cells in responding to external stimuli. Such materials could be used in devices for detecting hazardous biological and chemical agents.

Bioinspiration. Merely knowing that a task can be achieved by a living system can inspire scientists to develop a synthetic system that performs the same function, even if the synthetic system uses a scheme quite different from that employed by the biological system. Nature provides examples of functional systems with exceptional materials properties and performance that would be useful to replicate for technological applications. Examples include the adhesive gecko's foot, self-cleaning lotus leaf, and fracture-resistant mollusk shell, which have fueled recent interest in "smart" biological materials. Yet attempts to create synthetic analogs have largely been unsuccessful, in part because the fundamental understanding of the biological systems is often limited.

Bioderivation. This strategy involves using an existing biomaterial in concert with artificial materials to create a hybrid. A prominent example is the incorporation of biologically derived proteins into polymeric assemblies for targeted drug delivery.

Progress in these areas will be facilitated by a number of actions and investment by research agencies, the scientific community, and other stakeholders. In particular, the following steps will help confront the scientific challenges associated with these strategies and to translate the resulting knowledge into societal and economic value:

- The synergistic application of approaches traditionally confined to distinct disciplines will be imperative. While such concerted efforts are already emerging in individual circumstances, substantial *interagency cooperation in support of such interdisciplinary research and development efforts will be needed*.

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Recommendation 1: DOE, NIH, NSF, and other relevant agencies should develop jointly sponsored multidisciplinary programs of innovative research at the crossroads of disciplines. New initiatives of this type will provide incentives for universities to break down and work across traditional departmental boundaries. OSTP should take the lead in coordinating this effort.

- Fundamental physical, chemical, and biological scientists need to work together with engineers to create new biomaterials and technologies. *Education of scientists and engineers that can work at the intersection of these fields is crucial.*

Recommendation 2: University physics, chemistry, biology, materials science, mathematics, and engineering departments and medical schools should cooperatively examine their curricula to identify ways to prepare scientists and engineers for research at the intersection of the physical sciences, engineering, and the life sciences. These educational programs should also be evaluated, incorporating a wide range of viewpoints, including input from leaders in industry and national laboratories.

- Communication between scientists and engineers from different disciplines is hampered by difficulties in understanding methods, concepts, and jargon. *Mechanisms for facilitating communication across and between disciplines are essential.*

Recommendation 3: DOE, NIH, NSF, and other relevant agencies should support the development of one- or two-week summer courses to train physical scientists and engineers in the tools and concepts of biology and medicine and conversely to train biologists in the tools and concepts of the physical sciences. Special attention should be given to developing ways of communicating fundamental physico-chemical concepts to biologists while using mathematical knowledge common to that community. Summer courses focused on these areas would help bridge the physical and life sciences communities to exploit research opportunities at the intersection of the fields.

- Fundamental research is necessary to realize the applications envisaged in this report and could lead to yet-unimagined technological applications, but translation of new discoveries into useful products is also crucial. Thus, *both fundamental and translational research should be emphasized*.

Recommendation 4: DOE, NIH, NSF, and other relevant agencies should collaborate to build bridges from the most fundamental research to commercial applications. While it is imperative to recognize and exploit the connections between fundamental advances and opportunities to translate the advances into practice, curiosity-driven fundamental research on outstanding unsolved questions should be encouraged as it could lead to currently unforeseen technological advances.

- It is difficult for a single laboratory to house the diverse instrumentation and expertise required for interdisciplinary research in biomolecular materials and processes. Standard equipment in biology laboratories, for example, is usually not found in engineering laboratories and vice versa. Further, many researchers do not have access to shared or private facilities containing such equipment and instrumentation. *National facilities that house clusters of small to mid-range instrumentation and associated expertise are important for fostering interdisciplinary research in biomolecular materials and processes.*

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Recommendation 5: DOE should continue to evaluate the effectiveness of recently created facilities to provide access to mid-range instrumentation and computational facilities for the advancement of interdisciplinary research in nanoscience and technology. Analogous, but distinct, centers could be created to facilitate research in biomolecular materials and processes.

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This study is based on work supported by Contract No. DE-FG02-05ER46197 between the National Academy of Sciences and the Department of Energy and Grant No. DMR-0426181 between the National Academy of Sciences and the National Science Foundation. 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 agency that provided support for the project.

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Preface

The National Research Council of the National Academies convened the Committee on Biomolecular Materials and Processes (BMAP) to assess current work and future promise at the intersection of biology and materials science. The Solid State Sciences Committee of the Board on Physics and Astronomy developed the charge for this study in consultation with the study's sponsors at the Department of Energy and National Science Foundation. The Committee on BMAP was charged to identify the most compelling questions and the emerging scientific opportunities at the interface between biology and condensed matter and materials research, suggest strategies to best meet the identified opportunities, and consider connections to national priorities including healthcare, security, workforce, economic, and other societal needs. The committee did not address tissue engineering in this report as it has been reviewed elsewhere[1] and was considered outside the scope of the committee's charge. The complete charge is reproduced in Appendix A.

The Committee on BMAP is composed of experts from many different areas of biomolecular materials research (see Appendix C for biographical sketches of committee members). The full committee met in person three times (see Appendix B) to address its charge. The committee formed subgroups to study areas in further detail and to develop the text of the final report. At its meetings, the committee heard from experts in the field and from the federal agencies that support BMAP research. Conference calls and email were used to coordinate the work of the committee between meetings. This final report reflects the committee's enthusiasm and excitement for the research opportunities in BMAP.

This report is the product of input from many people. On behalf of the committee, I extend my thanks and appreciation to all who participated in this endeavor. I also thank the speakers who made formal presentations at the committee meetings (Appendix B); those presentations and the ensuing discussions strongly informed the committee's deliberations. In addition, the committee would like to thank the following people for their insight: Ian Anderson, James R. Baker, Jr., Sergey Bezrukov, Mark S. Humayun, Nicholas A. Kotov, Ronald G. Larson, John Miao, Dean A. Myles, Kevin Plaxco, Rudi Podgornik, Clinton Potter, Roger Pynn, Don Rau, David A. Tirrell, Gregory Voth, Karen Wooley, Wenbing Yun, and Joshua Zimmerberg. In particular, Theresa Reineke is thanked for her insight and contribution to the challenges in the area of synthesis.

Finally, I also thank the NRC staff (Natalia Melcer, Adam Fagen, Don Shapero, Frances Sharples, Phillip Long, and Caryn Knutsen) for their guidance and assistance throughout the development of the report.

As chair, I am grateful to the committee members for their wisdom, cooperation, and commitment to ensuring the development of a comprehensive report.

Arup Chakraborty, *Chair*
Committee on BMAP

[1] National Research Council, *Capturing the Full Power of Biomaterials for Military Medicine*, Washington, D.C.: The National Academies Press, (2004).

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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 (NRC'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:

Robert H. Austin, Princeton University,
William F. Carroll, Jr., Occidental Chemical Corporation,
Robert J. Full, University of California at Berkeley,
Laura L. Kiessling, University of Wisconsin at Madison,
Robert S. Langer, Massachusetts Institute of Technology,
Monica Olvera de la Cruz, Northwestern University,
Jose N. Onuchic, University of California at San Diego,
Joel M. Schnur, Naval Research Laboratory, and
David A. Tirrell, California Institute of Technology.

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 Peter B. Moore, Yale University. Appointed by the NRC, 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.

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