NATIONAL ACADEMIES Sciences Engineering Medicine

BOARD ON LIFE SCIENCES

Mirror Image Biology: Pushing the Envelope in Designing Biological Systems – A Workshop

MONDAY, SEPTEMBER 29, 2025

Purpose

The Workshop Day 1 discussions will focus on the following Statement of Task questions:

- What is mirror biology and why is it being studied?
- What is the state of the science in mirror biology and recent milestones in mirror biology?
- What are the scientific and technological hurdles associated with mirror biology? What research is ongoing to overcome these challenges?
- What are the proposed applications for research involving mirror biology and what sectors are anticipated to benefit from such advances?

10:00–10:30 **Welcome, Introductions, and Framing**

Opening Remarks - Mirror Biology Dialogues Fund

Dr. James Smith, Mirror Biology Dialogues Fund

Opening Remarks - National Academies of Sciences, Engineering, and Medicine

Dr. Kavita Berger, Director, Board on Life Sciences

Project Purpose and Goals

Dr. Nicholas Adams and Dr. Harshini Mukundan, Planning Committee Co-chairs

Technology Overview

Dr. Michael Jewett, Planning Committee Member

10:30–11:30 **Panel 1: Defining Self-Replicating Mirror Biology**

Discussion on what self-replicating mirror life might be, what the building blocks or components are, and a high-level overview of potential opportunities and risks.

Dr. Lynn Rothschild, Senior Research Scientist, Bio and Bio-Inspired Technologies, Research and Technology Lead, NASA

Dr. Neal Devaraj, Professor of Chemistry and Biochemistry and the Murray Goodman Endowed Chair in Chemistry and Biochemistry at the University of California, San Diego

Dr. Alta Charo, Warren P. Knowles Professor Emerita of Law and Bioethics at the University of Wisconsin at Madison

Moderator: *Dr. Douglas C. Cameron, Planning Committee Member*

11:30–12:45 **Panel 2: Building Block Approach | First session**

Discuss the current state of research and biotechnology for the identified building blocks of mirror life and identify next steps.

Dr. Jevgenij Raskatov, Professor, Physical & Biological Sciences Division, University of California Santa Cruz

Dr. Jonathan Sczepanski, Professor, Department of Chemistry, Texas A&M University

Dr. Beat Vögeli, Associate Professor of Biochemistry and Molecular Genetics, University of Colorado Anschutz

Moderator: *Dr. Michael Jewett, Planning Committee Member*

12:45–1:30 **Lunch**

1:30–2:45 **Panel 3: Building Block Approach | Second Session**

Discuss the current state of research and biotechnology for the identified building blocks of mirror life and identify next steps.

Dr. Vincent Noireaux, Professor, School of Physics and Astronomy, University of Minnesota

Dr. Joel Schneider, Affiliated Professor, University of Delaware

Moderator: *Dr. Philip E. Dawson, Planning Committee Member*

2:45–4:00 **Panel 4: Industry Capabilities; Development and Investment Drivers**

Investment in the mirror biology component development is a critical pathway to enable research. A panel discussion on current industry capabilities, and what would motivate additional investment in the identified research areas.

Dr. Greg Went, CEO & Chairman, Dextera Biosciences

Dr. Michael Kay, Professor, Department of Biochemistry, University of Utah School of Medicine

Moderator: *Dr. Douglas C. Cameron, Planning Committee Member*

END OF DAY 1

TUESDAY, SEPTEMBER 30, 2025

Purpose

The Workshop Day 2 discussions will focus on the following Statement of Task questions:

- What are the accidental and deliberate biological risks associated with mirror biology? Which risk assessment methodologies are suitable to assess those risks?
- In what ways can the risks be minimized and benefits be maintained and/or maximized? Are these approaches similar for all relevant sectors (e.g., health, bioeconomy, agriculture, other)?
- What can be done both domestically and internationally to enable responsible innovation in mirror biology and its application to various sectors?

10:00–10:15 **Welcome and Introductions**

10:15–11:30 **Panel 5: Human Health Discussion**

Discuss current state of research and biotechnology as related specifically for human health for the identified building blocks of mirror life and identify the next steps.

Dr. Michael Imperiale, Arthur F. Thurnau Professor of Microbiology and Immunology, University of Michigan

Dr. Neha Kamat, Associate Professor of Biomedical Engineering and Chemical and Biological Engineering, Northwestern University

Dr. Purvesh Khatri, Professor of Medicine, Biomedical Informatics - Research Institute for Immunity, Transplantation and Infection, Stanford University

Dr. Jai Rudra, Associate Professor, Biomedical Engineering, Washington University in St. Louis

Moderator: *Dr. Karl M. Thompson, Planning Committee Member*

11:30–12:45 **Panel 6: Environmental Health**

Discuss current state of research and biotechnology as related specifically to environmental and ecological health for the identified building blocks of mirror life and identify the next steps.

Dr. Romy Chakraborty, Ecology Department Head, Earth & Environmental Sciences Area, Lawrence Berkeley National Laboratory

Dr. Karl M. Thompson, Associate Professor, Department of Microbiology, Howard University and Planning Committee Member

Moderator: *To be announced, Planning Committee Member*

12:45–1:30 **Lunch**

1:30–2:45 **Panel 7: Next Steps for Modeling and Experiments**

From the state of the technology, discuss possible next developments and the achievements needed to build mirror life, and potential modeling and experiments.

Dr. Neal Devaraj, Professor of Chemistry and Biochemistry and the Murray Goodman Endowed Chair in Chemistry and Biochemistry at the University of California, San Diego

Dr. Andrew Ellington, Professor, Molecular Biosciences, Interdisciplinary Life Sciences Graduate Programs, University of Texas at Austin

Moderators: *Dr. Nicholas Adams and Dr. Harshini Mukundan, Project Co-chairs*

2:45–4:00 **Panel 8: Committee Reflections and Key Themes**

Planning Committee's opportunity to reflect on the key themes and takeaways from the workshop.

MEETING ADJOURNS

SPEAKER BIOGRAPHIES

Romy Chakraborty is a Senior Scientist and Head of the Molecular Ecology and Biogeochemistry Department in the Earth & Environmental Sciences Area at the Lawrence Berkeley National Laboratory. As an environmental microbiologist, Romy's research has centered around unique microbes mediating critical recalcitrant carbon and nitrogen metabolisms in diverse ecosystems. She is involved in extensive outreach and mentorship in STEM. Romy is a member of the US Department of Energy's Biological and Environmental Research Advisory Committee. Romy earned a B.S. and an M.S. from the University of Mumbai, followed by a Ph.D. from the University of California, Berkeley.

Alta Charo is professor emerita of law and bioethics at the University of Wisconsin and now a consultant to companies, government, and NGOs on biotechnology ethics and regulatory policy. She has been elected to the American Academy of Arts and Sciences; to the American Association for the Advancement of Science; and to the National Academy of Medicine, where she co-chaired its committees on stem cell research and human genome editing. In government, Alta served as a legal or policy analyst for the (former) Congressional Office of Technology Assessment, the US Agency for International Development, and the FDA. She also served as a member of President Clinton's National Bioethics Advisory Commission and President Obama's HHS transition team. Alta earned a B.A. in biology at Harvard University in 1979 and a J.D. in law at Columbia University in 1982.

Neal Devaraj is a Professor of Chemistry and Biochemistry, the Murray Goodman Endowed Chair in Chemistry and Biochemistry, and Chair of the Department of Biochemistry and Molecular Biophysics at the University of California, San Diego (UCSD). A native of Southern California, he attended college at the Massachusetts Institute of Technology where he performed research in the lab of Prof. Moungi Bawendi. He earned his Ph.D. in Chemistry at Stanford University in the labs of Profs. James Collman and Christopher Chidsey. After a postdoctoral fellowship at the Harvard Medical School in the lab of Prof. Ralph Weissleder, he joined UCSD. His research interests are in artificial cells, lipid membranes, and bioconjugation

Andrew Ellington received his B.S. in Biochemistry from Michigan State University in 1981, and his Ph.D. in Biochemistry and Molecular Biology from Harvard in 1988. His post-doctoral work was with Dr. Jack Szostak at Massachusetts General Hospital, where he developed methods for the in vitro selection of functional nucleic acids and coined the term 'aptamer.' He originally received the Office of Naval Research Young Investigator, Cottrell, and Pew Scholar awards, and later was a Vannevar Bush Faculty Fellow of the DoD and a Howard Hughes Professor. Dr. Ellington's lab works centers on the development of nucleic acid circuitry for point-of-care diagnostics, on accelerating the evolution of proteins and cells through the introduction of novel chemistries, and on machine learning methods for engineering proteins and understanding evolutionary landscapes.

Michael J. Imperiale is Arthur F. Thurnau Professor Emeritus in the Department of Microbiology and Immunology at the University of Michigan. Michael received a Ph.D. in biological sciences from Columbia University and performed postdoctoral studies at The Rockefeller University before joining the faculty at Michigan. He served as associate vice president for research–research policy and compliance from 2017 to 2022. Michael's research interests focused on the study of human polyomaviruses, with an emphasis on how persistent and acute infections are regulated by viral and host factors. He served as an editor of the Journal of Virology, PLoS Pathogens, and mBio, and was the founding editor-in-chief of mSphere from 2015-2025. In 2009, he was the recipient of the University of Michigan Distinguished Faculty Achievement Award, and in 2016 he received the Rackham Distinguished Graduate Mentor Award. He was elected as a fellow of the American Academy of Microbiology in 2010 and as a fellow of the American Association for the Advancement of Science in 2011. Michael was an inaugural member of the National Science Advisory Board for Biosecurity from 2005 to 2014, served on the Planetary Protection Subcommittee at the National Aeronautics and Space Administration, and was a member of the board of directors of the Van Andel Institute Graduate School. He previously served as the chair of the National Academies of Sciences, Engineering, and Medicine's Committee on Strategies for Identifying and Addressing Potential Biodefense Vulnerabilities Posed by Synthetic Biology, co-chair of the NASEM Committee on Assessing and Navigating Biosecurity Concerns and Benefits of Artificial Intelligence Use in the Life Sciences, and as a member of the Committee on Science, Technology, and Law.

Michael Kay is a Professor in Biochemistry and H.A. and Edna Benning Presidential Chair in the School of Medicine at the University of Utah. He is also Director of the Utah MD-PhD Program and Medical Scientist Training Program. Before coming to Utah in 2001, he trained with Harold Scheraga at Cornell University (BA in Biology and Chemistry), Robert Baldwin at Stanford University (MSTP fellow in Biochemistry), and Peter Kim at MIT (Damon Runyon Postdoctoral Fellow). His lab employs mirror-image biology for the development of antiviral and antibacterial D-peptides, as well as for applications in synthetic biology.

Neha Kamat is an Associate Professor at Northwestern University in the Biomedical Engineering Department in Evanston, Illinois. She was trained as a bioengineer with special emphasis in biophysical analysis of biological and synthetic membranes, and in the production and characterization of membrane proteins using cell-free protein expression systems. She received a B.S. in Bioengineering from Rice University, a Ph.D. in Bioengineering from the University of Pennsylvania, and completed a postdoctoral fellowship at Harvard University Massachusetts General Hospital. At Northwestern University, Neha's lab's main research interests are to understand and harness biological membranes as a biomaterial for (1) fundamental biological studies related to membrane protein folding and function and (2) translational applications in diagnostics and disease. Neha is the recipient of a Young Investigator Award from the Air Force Research Office, an NSF CAREER Award, and the American Chemical Society's Synthetic Biology Young Innovator Award

Purvesh Khatri is a Professor in the Institute for Immunity, Transplantation and Infection and Division of Biomedical Informatics Research in the Departments of Medicine and Biomedical Data Science at Stanford University. His research focuses on developing AI and machine learning methods for leveraging biological, clinical, and technical heterogeneity across heterogeneous data to accelerate clinical translation. His lab has applied these methods for identification of immune response-based disease signatures that are diagnostic, prognostic, therapeutic and mechanistic across a broad spectrum of diseases including infections, autoimmune diseases, cancer, organ transplant, and vaccination. He is also a co-founder and Chief Scientist of Inflammatix, Inc., a commercial-stage company with FDA-cleared test focused on translating host response-based diagnostics to clinical care.

Vincent Noireaux is a Professor of Synthetic Biology and Biological Physics at the University of Minnesota. His lab utilizes cell-free transcription-translation (TXTL) to engineer biochemical systems outside of cells, including gene circuits, phages, and synthetic cells. Vincent earned a Ph.D. at the Curie Institute in Paris and completed a postdoctoral fellowship at The Rockefeller University in New York City.

Jevgenij Raskatov was born in Moscow, Russia. In 1994 his family moved to Germany, where he studied chemistry as an undergraduate at Heidelberg University. This was followed by a move to Oxford to perform his PhD studies in organic chemistry. In 2009 he moved to Caltech as a Humboldt postdoctoral fellow. He has held an independent position at University of California, Santa Cruz since 2014, where he is currently Professor of Chemistry and Biochemistry. The Raskatov lab studies aggregating peptidic systems involved in Alzheimer's and Diabetes. The lab is also interested in developing peptidic materials based on the rippled beta-sheet, which is an intriguing structural motif predicted by Pauling and Corey in 1953.

Lynn Rothschild is an evolutionary biologist, astrobiologist, and synthetic biologist at NASA's Ames Research Center as well as adjunct professor at both Brown University and Stanford University. Lynn received a B.S. in biology from Yale University, an M.A degree in zoology, and a Ph.D. in Molecular and Cell Biology from Brown University. Her research spans into how life—especially microbes—evolved in Earth's unique environments and how these lessons could apply to potential life beyond our planet. Lynn founded NASA's program in synthetic biology and explores how it could play a pivotal role in the future of space travel. Rothschild was the principal investigator of the first free-flyer synthetic biology payload, which flew on the Deutsches Zentrum für Luft- und Raumfahrt's Euglena and Combined Regenerative Organic-Food Production in Space (EuCROPIS) mission. Lynn's interest in synthetic cells is two-fold: how it can inform the origin, evolution and search for life elsewhere as well as how they could aid in space exploration and settlement. She has been named a NASA Innovative Advanced Concepts fellow five times and in 2015, Rothschild was awarded the Horace Mann Medal by the Brown University Graduate School as well as the American Humanist Association's Isaac Asimov Science Award. She is a fellow of the Linnean Society of London, the California Academy of Sciences, and the Explorer's Club. She also held the role of president of the Society of Protozoologists from 2002 to 2003.

Jai Rudra received his Ph.D. in Biomedical Engineering from Louisiana Tech University and completed his postdoctoral training in the lab of Dr. Joel Collier at the University of Chicago. He was recruited by the Sealy Center for Vaccine Development at the University of Texas Medical Branch as an Assistant Professor in the Fall of 2011, where he developed subunit vaccines based on supramolecular peptides for chronic infectious and non-infectious diseases, as well as drug addiction. Jai joined the Department of Biomedical Engineering at Washington University in St. Louis in the Fall of 2018. His research interests include harnessing of molecular and structural chirality in biomaterials and understanding the influence of chirality on immune cell behavior for applications in vaccine development and regenerative immunology. He is a recipient of the NSF CAREER award, and his lab is supported through active funding from the National Institute of Allergy and Infectious Diseases and National Institute on Aging. Jai is an editorial board member of Nature Partnership Journal npj Vaccines.

Joel Schneider received his Ph.D. in Chemistry at Texas A&M University before moving on to the University of Pennsylvania, School of Medicine as a postdoctoral fellow. After which, he joined the faculty at the University of Delaware (UD). As Professor of Chemistry and Biochemistry at UD, he was recruited in 2010 to the National Cancer Institute, Center for Cancer Research to serve as Chief and build their new Chemical Biology Laboratory. In his independent research, he develops biomaterials for use in the local delivery of therapeutics towards the treatment of cancer. He is particularly interested in peptide-based hydrogels formed by self-assembly. His work establishes how material composition and structure influences material function, which lays the foundation to ultimately translate materials to the clinic. Joel also serves as a Deputy Director of the Center for Cancer Research as well as the past president of the American Peptide Society. He remains adjunct Professor of Chemistry and Biochemistry at the University of Delaware.

Jonathan Szczepanski began his independent career at Texas A&M University in 2015 where he is currently a Professor of Chemistry and of Biochemistry and Biophysics. His research group combines expertise in nucleic acids chemistry, chemical and molecular biology, and directed evolution to address biologically relevant questions and human health needs. Key focus areas include (1) exploiting the bio-orthogonal nature of mirror image DNA and RNA for applications in biotechnology and medicine and (2) uncovering the molecular mechanisms underlying the regulation of DNA repair and DNA (de)methylation in biology and disease. Jonathan has made important contributions in diverse fields, including nucleic acid aptamers, molecular biosensors, DNA nanotechnology, and DNA repair biology. His research has garnered support from the National Institutes of Health (NIGMS, NIBIB, NIAID, and NICHD), the National Science Foundation, the Cancer Prevention and Research Institute of Texas (CPRIT), and Welch grants. He earned a Ph.D. in Chemistry from Johns Hopkins University in 2010 under the guidance of Prof. Marc Greenberg and pursued postdoctoral training at The Scripps Research Institute with Prof. Gerald Joyce.

Gregory Went is a scientist, inventor, investor, experienced entrepreneur and board member with multiple startups in the life sciences, including genomics, genetics, diagnostics and therapeutics. His companies have taken multiple products from invention through approval and commercialization, benefiting the lives of thousands of patients and their care partners. His journey began early in his Ph.D. program in Chemical Engineering at the University of California, Berkeley. During his post-doc at Cornell, he co-founded CuraGen Corporation, one of the first genomics companies, where he co-led the development of CuraGen's genomics platform and led the corporate partnering efforts. After spending about 5 years supporting VC firms and entrepreneurs, he co-founded Adamas Pharmaceuticals, serving as its CEO and Chairman, where the company discovered, developed and launched two commercial products: Namzaric® (with Allergan) and GOCOVRI®. He joined Dextera Biosciences in 2020, a company attempting to develop a new category of drugs called synthetic D-Proteins. His initial role was as an investor/Board member, but he then stepped into his current role as CEO and Chairman to drive the development of its platform and programs to the clinic.

Beat Vögeli specializes in the development and application of nuclear magnetic resonance (NMR) techniques to explore conformation and communication networks within and between proteins and nucleic acids. His current primary research interests include investigating functional disorder in microtubule-based intracellular transport and dynamics and functions of Z-form RNA and DNA. He earned his Ph.D. from the Swiss Federal Institute of

Technology (ETH) Zürich, pursued research at the National Institutes of Health in Bethesda, and now is an associate professor at the University of Colorado at Denver - Anschutz Medical School.