Workshop Session on Transformative S&T for the Department of Defense: Synthetic Biology for Biomanufacturing and Predictable Engineering

KECK 100, 500 5th St NW, Washington, DC
JULY 1, 2025

Purpose

The National Academies' Standing Committee on Transformative Science and Technology for the Department of Defense, sponsored by OUSD(R&E), is organizing a series of workshop sessions each of which explores potentially transformative science and technology topics of relevance to the Department of Defense.

Advances in biotechnology and biomanufacturing are essential for the United States to maintain global leadership as well as for supporting economic and national security interests. Biology provides the basis for innovations from medicine, health, and agriculture, to defense, energy, and manufacturing.

This workshop session will include discussion of recent recommendations provided by the National Security Commission on Emerging Biotechnology’s report on *Charting the Future of Biotechnology*.

In addition, the session may explore within the context of synthetic biology opportunities for enhanced DoD-industry-academic collaboration including how to strengthen partnerships across sectors.

About the Workshop

This public, on-the-record workshop session is part of an ongoing series highlighting emerging trends in science and technology that could transform how the Department of Defense approaches research and engineering, and is aimed at a non-expert audience. An online proceedings-in-brief will feature video highlights and summarize insights from the discussions.

AGENDA

TUESDAY, JULY 1, 2025

OPEN SESSION

8:30 AM	BREAKFAST
8:50 AM	**Workshop Introduction** • Richard Murray and Darlene Solomon, *workshop session organizers*
9:00 AM	**Biomanufacturing Frame Setting Talks** (20 minute presentation followed by 10 minutes for Q&A) • Reshma Shetty, Co-Founder, Ginkgo Bioworks • Christina Smolke, CEO and Co-Founder, Antheia • James Clomburg, Director of Advanced Biosystems Technology, LanzaTech
10:30 AM	BREAK
10:45 AM	**Collaboration Opportunities Between Academia, Industry, and the Department of Defense** (10 minute remarks followed by panel discussion) *This panel will emphasize the collaboration that is required across sectors to tackle complex, interdisciplinary goals in biomanufacturing and predictably engineerable biology and explore prior efforts at collaboration in these areas.* • Kate Sixt, Principal Director for Biotechnology, Office of the Under Secretary of Defense for Research and Engineering; • Melanie Tomczak, Head of Programs and Chief Technology Officer, BioMADE • Erik Pierstorff, Small Business Innovation Research and Small Business Technology Transfer Program Director, National Science Foundation • Sarah Glaven, Visiting Fellow, Andlinger Center for Energy and the Environment Princeton
12:00 PM	LUNCH

1:00 PM	**Predictable Engineering Frame Setting Talks** (20 minute presentation followed by 10 minutes for Q&A) • Adam Arkin, Professor of Bioengineering, University of California, Berkeley; Senior Faculty Scientist, Lawrence Berkeley National Laboratory • Angela Belcher, Professor of Biological Engineering and Materials Science, Massachusetts Institute of Technology • Chang Liu, Professor and Chancellor's Fellow of Biomedical Engineering, Chemistry, and Molecular Biology & Biochemistry, University of California, Irvine • Amarda Shehu, Inaugural VP and Chief AI Officer, Professor of Computer Science, George Mason University
3:00 PM	BREAK
3:15 PM	**Global Outlook on Biotechnology** (10 minute remarks followed by panel discussion) *This panel will discuss global leadership in biotechnology and the impact on international norms and standards, controls of critical supply chains, and the societal and national security benefits of bio-based advancements.* • Anne Cheever, Technology and Security Policy Fellow, RAND • Rhys Dubin, Policy Advisor, Office of the Special Envoy for Critical and Emerging Technology, U.S. Department of State • Steven Moss, Senior Policy Advisor, National Security Commission on Emerging Biotechnology
4:15 PM	**Wrap-up Discussion**
5:00 PM	ADJOURN

SPEAKER BIOGRAPHIES

Adam Arkin is the Dean A. Richard Newton Memorial Professor in the Department of Bioengineering at the University of California, Berkeley and Senior Faculty Scientist at the Lawrence Berkeley National Laboratory. He and his laboratory develop experimental and computational technologies for discovery, prediction, control and design of microbial and viral functions and behaviors in environmental contexts. He is the chief scientist of the Department of Energy Scientific Focus Area, ENIGMA(Ecosystems and Networks Integrated with Genes and Molecular Assemblies, http://enigma.lbl.gov), designed to understand, at a molecular level, the impact of microbial communities on their ecosystems with specific focus on terrestrial communities in contaminated watersheds. He also directs the Department of Energy Systems Biology Knowledgebase (KBase) program: (http://kbase.us) an open platform for comparative functional genomics, systems and synthetic biology for microbes, plants and their communities, and for sharing results and methods with other scientists. He is director of the newly announced Center for Utilization of Biological Engineering in Space which seeks microbial and plant-based biological solutions for in situ resource utilization that reduce the launch mass and improves reliability and quality of food, pharmaceuticals, fuels and materials for astronauts on a mission to Mars. Finally, he is the Co-Director of the Berkeley Synthetic Biology Institute, which brings together U.C. Berkeley and Lawrence Berkeley National Laboratory Scientists with Industry Partners to forward technology and applications for sustainable biomanufacturing.

Angela Belcher is the James Mason Crafts Professor of Biological Engineering, Materials Science and the Koch Institute for Integrative Cancer Research at MIT. She is a biological and materials engineer with expertise in the fields of biomaterials, biomolecular materials, organic-inorganic interfaces and solid-state chemistry and devices. Her primary research focus is evolving new materials for energy, electronics, the environment, and medicine. She received her B.S. in Creative Studies from The University of California, Santa Barbara. She earned a Ph.D. in inorganic chemistry at UCSB in 1997. Following her postdoctoral research in electrical engineering at UCSB, she joined the faculty at The University of Texas at Austin in the Department of Chemistry. She joined the faculty at MIT in 2002. In July 2019, she took over as the head of the Biological Engineering Department at MIT until 2023.

Anne Cheever is a Technology and Security Policy Fellow at the RAND Corporation, where she focuses on the intersection of emerging technologies and national security. Previously, she served as director for Technology and National Security at the National Security Council and is known for her leadership role at the Defense Advanced Research Projects Agency (DARPA), where she managed the Biomanufacturing: Survival, Utility, and Reliability beyond Earth (B-SURE) program. Prior to joining DARPA, Cheever was a lead biotechnologist at MITRE Corporation, where she provided scientific and strategic support to multiple federal institutions in the areas of biodefense, biosecurity, disruptive technologies, and emerging infectious disease. She also led a team focused on COVID-19 vaccine acceleration, communications, security, and data analytics in support of

Operation Warp Speed (OWS) and the Department of Defense (DoD). Previously, Cheever was a senior lead scientist at Booz Allen Hamilton, where she contributed to the development of capabilities in synthetic biology and biosecurity for intrinsic and extrinsic control of genome editors and gene drives. Cheever received her PhD in cell and developmental biology, BS in ecology, ethology, and evolution; and certificate in business administration from the University of Illinois at Urbana-Champaign.

James Clomburg is the Director of Advanced Biosystems & Technologies at LanzaTech, leading a diverse team focused on engineering and characterizing gas-fermentation platforms through state-of-the-art strain engineering, automation, and analytical capabilities. This includes a vertical program within LanzaTech's platform to establish alternative microbial gas fermentation system(s) to convert low-cost gaseous carbon feedstocks to fuels, chemicals, and materials. Throughout his nearly 20 years of experience in metabolic engineering and synthetic biology spanning academia and industry, James has led numerous projects combining broad-based knowledge of metabolic pathways, biochemical reactions, and microbial metabolism to design and optimize biological platforms for a variety of product applications. James earned his B.S. in Chemical Engineering from The University of Texas and his Ph.D. in Chemical and Biomolecular Engineering from Rice University.

Rhys Dubin is a policy advisor and biotechnology policy coordinator in the Office of the Special Envoy for Critical and Emerging Technology at the U.S. Department of State. Previously, Mr. Dubin was a fellow at the Council on Strategic Risks, where his research focused on the intersection of emerging technology and arms control, and served in editorial roles at Foreign Affairs magazine and Foreign Policy. He has a master's degree in international relations from the University of Oxford and a bachelor's degree from Yale University.

Sarah Glaven is a distinguished authority in biotechnology and biomanufacturing currently serving as a Visiting Fellow with the Andlinger Center for Energy and the Environment at Princeton University. She is also Founder and Principal of Marathon Bio where she is advising startups focused on industrial biotechnology and national security. She is a former senior biologist at the United States Naval Research Laboratory where she pioneered a field called electromicrobiology, the study of the interaction between microbes and electronic devices. In this role she created partnerships with the private sector through cooperative research and development agreements and patent licensing, and by establishing the Tri-Service Biotechnology for a Resilient Supply Chain program, a $300 million effort to move biotechnology for defense from the lab to prototype and demonstration. From 2023-2025, Dr. Glaven served as Principal Assistant Director for Biotechnology and Biomanufacturing in the White House Office of Science and Technology Policy. She led the National Biotechnology and Biomanufacturing Initiative by establishing and chairing the National Bioeconomy Board. In this role she oversaw coordination and implementation of over $15 billion in federal funding across the executive branch, including the Department of Defense, Department of Energy, Department of Health and Human Service, United State Department of Agriculture, and the National Science Foundation. She also worked with the Science Advisor to the President and the National Security Council to advise the President on all areas of the bioeconomy, including research and development, data, infrastructure, procurement, workforce, regulation, biosafety and biosecurity, international engagement, and national security.

Chang Liu is Professor and Chancellor's Fellow of Biomedical Engineering, Chemistry, and Molecular Biology & Biochemistry, the Director of the Center for Synthetic Biology, and the Director of the Engineering + Health Institute at UC Irvine. After graduating summa cum laude and Phi Beta Kappa from Harvard in 2005 with a bachelor's degree in chemistry, Liu carried out his PhD at the Scripps Research Institute. His PhD work, done in the laboratory of Peter Schultz, focused on expanding bacterial genetic codes for the co-translational incorporation of post-translational modifications and using expanded genetic codes in the evolution of novel protein function. From 2009-2012, Liu was a Miller Fellow at UC Berkeley where he worked with Adam Arkin on the predictable design of complex regulatory systems using the special properties of RNA switches. In 2013, Liu started his lab at UC Irvine. Liu's research is in the fields of synthetic biology, protein engineering, and molecular evolution. His group engineers specialized genetic systems that continuously and rapidly mutate user-selected genes in vivo. These systems allow researchers to evolve proteins at unprecedented speed, scale, and depth in order to engineer new protein functions, probe the rules of evolution, and understand the fundamental sequence-function relationships governing proteins and other macromolecules. These systems also allow researchers to record transient information as heritable mutations in order to track animal and cancer development at high cellular resolution.

Steven Moss is a Senior Policy Advisor for the National Security Commission on Emerging Biotechnology (NSCEB) where he focusses on policy around the convergence of emerging areas of science and technology with biotechnology. Prior to joining NSCEB, Steven was a Senior Program Officer at the National Academies of Sciences, Engineering, and Medicine (NASEM). At NASEM he worked on their Board on Life Sciences, focused on a portfolio of projects related to advancing the bioeconomy and the future of biotechnology. Steven comes from a laboratory background, having spent 10 years in chemistry and biology laboratory settings. Much of his lab work focused on understanding the molecular mechanisms of disease with projects on infectious bacteria, cancer, and chronic pain. Steven also serves as the Chair of the American Chemical Society's Committee on Environment and Sustainability and a judge for the international Genetically Engineering Machine (iGEM) competition. Steven holds a Ph.D. in Chemistry and Chemical Biology from the University of California, San Francisco, and a B.S. in Biochemistry from American University.

Erik Pierstorff joined the U.S. National Science Foundation as a SBIR/STTR program director in 2019. Prior to joining NSF, he was chief of operations and led research and development at O-Ray Pharma, where he focused on integrating biology and biomedical engineering focused on drug development and sustained drug delivery for the treatment of hearing loss and other ear disorders. During his time working at early stage companies, he helped secure both angel investment and non-dilutive funding in the form of licensing and co-development deals. Additionally, Erik served as principal investigator on several Phase I, II and IIB SBIR grants from the National Institutes of Health and NSF. His research interests have focused on the intersection of the biotic and abiotic, spanning molecular and cell biology, materials science, gene therapy, nanomaterials and drug delivery. Erik has a doctorate in molecular and cell biology from the University of California, Berkeley, and a bachelor's in biology from Emory University.

Amarda Shehu is a Professor of Computer Science in the College of Engineering and Computing at George Mason University, where she is also an Associate Dean for AI Innovation, Associate Vice Provost for Research for the Institute for Digital Innovation, and Mason representative in the National Institute of Standards and Technology AI Safety Institute Consortium. Shehu is also the 2024 Inaugural VP and Chief AI Officer, a position through which she is advancing an AI growth roadmap for the university, supporting the mission of a public R1 university on research, education, workforce development, community engagement, and partnerships. Shehu served as an NSF Program Director in the Directorate for Computer and Information Science and Engineering (CISE) from 2019 to 2022, where she led the National Science Foundation (NSF)-wide working group on the Harnessing the Data Revolution: Data Science Corps program and led CISE efforts in the COVID-19 RAPID Program and the Molecular Foundations in Biotechnology Program. Previously an NIH Predoctoral Fellow in the Nanobiology Program at Rice University, Shehu’s research advances foundational and use-inspired AI research to enable and advance scientific discovery. Her laboratory has made significant advances at the intersection of AI, generative AI, and molecular biology. She is a 2022 Fellow of the American Institute for Medical and Biological Engineering and has received several awards, including the 2022 Outstanding Faculty Award from the State Council of Higher Education for Virginia, the 2012 NSF CAREER Award, and two Director Recognition award for her work at NSF. Shehu received a Ph.D. and M.S. in computer science from Rice University.

Reshma Shetty co-founded Ginkgo Bioworks in 2008. As President, Chief Operations Officer, and member of our board of directors, she has seen the company grow to over 500 people. Reshma has been active in the field of synthetic biology for 15+ years, and in 2006, she was an advisor to the iGEM competition where she was best known for engineering bacteria to smell like bananas and mint. Forbes magazine named Reshma one of 2008’s Eight People Inventing the Future, and Fast Company named her one of 100 Most Creative People in Business in 2011. Dr. Shetty has a B.S. degree in Computer Science from the University of Utah and a Ph.D. in Biological Engineering from MIT.

Kate Sixt served as the Principal Director for Biotechnology in the Office of the Under Secretary of Defense for Research and Engineering. In this capacity, Dr. Sixt lead the

Department of Defense's research and engineering efforts to advance military capabilities through biotechnology innovation and maintain a competitive advantage in biotechnology. Prior to joining the Department, Dr. Sixt was an Assistant Director and then the Acting Director of the Strategy, Forces, and Resources Division at the Institute for Defense Analyses in Alexandria, Virginia, from 2019 to 2022. This Division houses a diverse body of technology and policy research in national security, including strategy and risk, international arms markets, forces and capabilities, readiness, and defenses against weapons of mass destruction. As a researcher, Dr. Sixt led the Chemical, Biological, Radiological, and Nuclear Analysis group, and she spearheaded technical analyses in national security topics related to weapons of mass destruction as well as emerging and dual-use technologies. This body of research included the technology opportunities for national security modernization focused on biotechnology, including technology protection and norms of biotechnology applications in military and civil domains.
Dr. Sixt joined the Institute for Defense Analyses in 2013 after completing her postdoctoral fellowship at the National Cancer Institute in Bethesda, Maryland. She holds a Ph.D. in biochemistry, cellular and molecular biology, and neuroscience from the Johns Hopkins School of Medicine in Baltimore, Maryland, and a bachelor's in biochemistry from St. Bonaventure University in St. Bonaventure, New York. In addition, she is completing her master's in the law of armed conflict at the Geneva Academy in Geneva, Switzerland, where her research focuses on the role of technology norms on the means and methods of warfare.

Christina Smolke is CEO and co-founder of Antheia Inc., and adjunct professor of bioengineering at Stanford University. She earned her B.S. in chemical engineering at the University of Southern California in 1997, and her Ph.D. in chemical engineering at UC Berkeley in 2001. Dr. Smolke, a pioneer in the fields of synthetic biology and metabolic engineering, joined Caltech's faculty in 2003 as an assistant professor of chemical engineering, and joined Stanford's faculty in 2009, where she was professor of bioengineering. Her early work pioneered the design and application of a broad class of RNA molecules—RNA switches—that detect chemical signals and regulate targeted protein activities, providing programmable platforms for building biological sensors and control systems. At Stanford, Dr. Smolke's team led the breakthrough research to engineer baker's yeast to produce some of the most complex and valuable plant-based essential medicines known to humankind. At Antheia, her vision and leadership has enabled a synthetic biology platform that dramatically expands the diversity and complexity of molecules that can be reconstructed, enabling new possibilities for drug discovery as well as efficient, sustainable, transparent, on-demand drug manufacturing at scale.

Melanie Tomczak is BioMADE's Head of Programs and Chief Technology Officer. Her scientific expertise is in co-opting what nature does well through biotechnology, biochemistry, and biosensor development. To her role as CTO, Melanie brings expertise in building diverse technical teams to tackle complicated projects and achieve program goals. Prior to joining BioMADE in 2022, she was Director of Biological and Nanoscale

Technologies at UES, Inc. During her tenure at UES, Melanie grew the “bio group” from 5 to 95 employees through winning competitive Air Force Research Laboratory on-site contracts repeatedly as well as being awarded 15+ Small Business Innovation Research grants from agencies including NIH, USDA, EPA, DTRA, DARPA and Army. She was a founding governing council member of the Nano Bio Manufacturing Consortium (NBMC) and served as Co-Chair of the Technical Working Group, and was active with several Manufacturing Innovation Institutes. Dr. Tomczak was a postdoctoral fellow in Biochemistry at Queen’s University, Canada. She holds a Ph.D. in Plant Biology from the University of California – Davis, where she was an NSF-sponsored Plant Cell Biology Trainee, and a B.S. from the University of Illinois at Urbana-Champaign, where she was both a Hugh Morrison Scholar and a Jonathan Baldwin Turner Scholar.

BACKGROUND MATERIALS

Charting the Future of Biotechnology

- **Launch Grand Research Challenges to Unlock Leap-Ahead Capabilities (NSCEB Report, Section 4.3)**
  Source: National Security Commission on Emerging Biotechnology (NSCEB), 2025
  Purpose: The topics of this workshop were inspired by the grand research challenges recommended by the Commission in this report.
  Link: https://www.biotech.senate.gov/final-report/chapters/chapter-4/section-3/
  Abstract: *Section 4.3 of Chapter 4 in the Senate's "Charting the Future of Biotechnology" report advocates the launch of two ambitious "Grand Research Challenges" to solidify U.S. leadership in biotechnology. First, it recommends Congress establish six Biotechnology Centers within the existing National Laboratory network, equipped with interdisciplinary teams, high-end instrumentation, and computing infrastructure, to anchor expansive, high-risk, high-reward research (Recommendation 4.3A). Second, it urges the initiation of a multi-billion-dollar research challenge aimed at making biology "predictably engineerable," funding transformative efforts in design, modeling, measurement, and interdisciplinary innovation with $5 billion over five years (Recommendation 4.3B). Third, it calls for a parallel challenge to revolutionize biomanufacturing scale-up—ensuring processes are rapid, cost-effective, and reliable—to complement physical capacity expansion (Recommendation 4.3C). Together, these initiatives aim to catalyze breakthrough capabilities in engineered biology and biomanufacturing, enhancing competitiveness, security, and innovation in U.S. biotechnology.*

Biomanufacturing

- **Biomanufacturing 101**
  Source: NSCEB, 2024
  Purpose: Introductory guide to the concepts, policy context, and national relevance of biomanufacturing.
  Link: https://www.biotech.senate.gov/wp-content/uploads/2024/04/NSCEB_WP_Biomanufacturing.pdf
  Abstract: *This white paper by the National Security Commission on Emerging Biotechnology introduces biomanufacturing as a transformative extension of the biotechnology industry, emphasizing its critical role in enhancing U.S. national security, economic leadership, and supply chain resilience. Biomanufacturing leverages fermentation-based processes to convert biological inputs—such as microorganisms, feedstocks, and water—into a diverse array of clinical and commercial products including pharmaceuticals, biomaterials, and biofuels. By aligning domestic feedstock availability with scalable biomanufacturing infrastructure, the U.S. can strengthen supply chain independence and stimulate*

job creation across industries. The paper outlines a four-stage biomanufacturing process: selecting and engineering inputs, initiating bioprocesses within bioreactors, isolating valuable outputs, and refining them into end products. It highlights the field's potential to support environmentally sustainable manufacturing and promote innovation in high-performance materials, including synthetic spider silk and algae-derived bioplastics. The report advocates for strategic investment and education to realize biomanufacturing's full promise in the U.S. bioeconomy.

- **Biomanufacturing in the U.S.: A MIT Policy Brief**
  Source: MIT, 2024
  Purpose: Outlines key priorities and policy options for strengthening the U.S. biomanufacturing ecosystem.
  Link: https://dspace.mit.edu/bitstream/handle/1721.1/158134/Biomanufacturing%20in%20US%20MIT%20Brief.pdf
  Abstract: *This MIT policy brief explores the strategic importance of biomanufacturing for U.S. economic security, resilience, and leadership in the global bioeconomy, which is projected to generate over $4 trillion in revenue within the next decade. While the U.S. excels in biotechnology innovation, it lags significantly in domestic biomanufacturing capacity, relying heavily on overseas infrastructure—particularly in China—for production. The brief identifies critical gaps, including insufficient facilities, bespoke and non-scalable manufacturing processes, and limited adoption of disruptive technologies. It proposes transformative solutions such as developing modular, low-cost, and energy-efficient biomanufacturing platforms; fostering standardization and platform-based production; and de-risking emerging technologies through research, development, and demonstration (RD&D) investments. The report advocates for robust federal support through financial incentives, innovation hubs, regulatory streamlining, and workforce development to establish a sustainable, secure, and innovation-aligned biomanufacturing ecosystem. A comprehensive national strategy is deemed essential for the U.S. to reclaim leadership in the bioindustrial revolution and ensure long-term competitiveness, sustainability, and supply chain resilience.*

- **EuropaBio Biomanufacturing Global Series**
  Source: EuropaBio, 2024
  Purpose: Provides international perspectives and benchmarks on biomanufacturing strategies and capabilities.
  Link: https://www.europabio.org/wp-content/uploads/2024/02/Biomanufacturing-Global-Series.pdf
  Abstract: *This document presents a comparative overview of biomanufacturing strategies and policy developments across four global leaders: the United States, India, Japan, and China. It synthesizes national priorities, investment trends, and strategic targets that position biomanufacturing as a critical driver of economic growth, sustainability, and technological leadership. The United States leads in*

commercialization and investment, guided by executive mandates focused on climate, health, and national security. India's National Biotechnology Development Strategy aims to scale its biotech ecosystem by 2025 through innovation, affordability, and global competitiveness. Japan's Bioeconomy Strategy 2019 envisions becoming the world's most advanced bioeconomy by 2030 through targeted market expansion, community building, and data-driven innovation. China integrates biomanufacturing into its national industrial plans—Made in China 2025 and the 14th Five-Year Plan—emphasizing strategic emerging industries, regional development, and dual-use (civilian and defense) applications. Together, these national approaches underscore a global consensus on the strategic value of biomanufacturing in shaping future-ready economies.

- **Fungible and Non-Fungible Technologies in Biomanufacturing Scale-Up**
  Source: Nature Communications Biotechnology, 2024
  Purpose: Examines flexible vs. fixed infrastructure models in scaling biomanufacturing processes.
  Link: https://www.nature.com/articles/s44286-024-00093-7
  Abstract: *Sang Yup Lee evaluates the distinct roles of interchangeable ("fungible") and specialized ("non-fungible") technologies in expanding biomanufacturing to industrial scale. Lee argues that maximizing production capacity requires not only broad, adaptable innovations—such as high-efficiency metabolic engineering and feedstock versatility—but also targeted technologies for high-value or chemically complex products that resist standard scaling approaches. Emphasizing the importance of optimizing feedstock supply chains and establishing robust infrastructure, the article highlights strategic investment in both generic, scalable platforms and niche biomanufacturing pathways. Together, this dual-technology paradigm is presented as essential for realizing large-scale, sustainable bioproduction.*

- **Bioprocessing 4.0 in Biomanufacturing: Paving the Way for Sustainable Bioeconomy**
  Source: Bioengineering Reviews, 2023
  Purpose: Reviews smart, digital, and sustainable technologies reshaping industrial bioproduction.
  Link: https://link.springer.com/article/10.1007/s43393-023-00206-y
  Abstract: *The past decade has been envisaged as a period of unprecedented growth and development in the bioprocessing industry due to the increasing prominence of manufacturing bioproducts encompassing day-to-day life. Bioprocesses are the heart of biotechnology and represent the most dynamic constituent for conceptualizing the bioeconomy as it has the potential to tackle the most burgeoning problems such as climatic adversity, global population growth, reduced ecosystem resilience. The promising amalgamation of digitalization, biologicalization, and biomanufacturing paved the way for an emerging concept of*

"bio-intelligent value addition" or more prominently Bioprocessing 4.0 that enables the transformation in the landscape of biomanufacturing. Despite its positive credentials, the technology is facing technical, organizational, economical, and likely some unforeseen challenges that must be resolved for its successful implementation for hailing the sustainability development goals (SDGs) of bioeconomy. Though the road of bioeconomy is quite arduous, the continuous demand for bioproducts and their timely delivery at a faster rate necessitates the culture of sharing knowledge, digitalization, automation, and development of flexible modular and podular facility footprints to accelerate biomanufacturing. Therefore, it is worth summarizing the major portfolios of Bioprocessing 4.0 such as conception of biofoundry, bioprocess intensification strategies, process and data analytics, software and automation, and its synergistic correlation with bioeconomy. Thus, the present article advocates about the technological glance of Bioprocessing 4.0 along with technical challenges and future research priorities for sparking the glory of this industrial landscape for enshrining the bioeconomy.

- **Successes and Challenges in Biomanufacturing: Proceedings of a Workshop-in-Brief**
  Source: NASEM, 2023
  Purpose: Summarizes expert discussions on biomanufacturing opportunities, gaps, and next steps.
  Link: https://nap.nationalacademies.org/catalog/26846/
  Abstract: *The use of living organisms and biological components in manufacturing processes is increasing across manufacturing sectors. However, biomanufacturing faces several bottlenecks and challenges to continued growth. To share practices and potential solutions, the National Academies of Sciences, Engineering, and Medicine hosted a workshop titled Successes and Challenges in Biomanufacturing on October 24-25, 2022. The workshop brought together biomanufacturing stakeholders across industry, academia, and government with expertise across diverse fields, including U.S.-based and international speakers. Discussions spanned the breadth of biomanufacturing contexts and applications, including bioindustrial and biopharmaceutical manufacturing. This Proceedings of a Workshop-in Brief provides a high-level summary of the topics addressed at the workshop.*

- **Biohybrid Materials and Technologies for Today and Tomorrow: Proceedings of a Workshop**
  Source: NASEM, 2023
  Purpose: Explores intersections between biology and materials science to enable advanced biomanufacturing.
  Link: https://nap.nationalacademies.org/catalog/26910
  Abstract: *Biohybrid materials and devices - which integrate both biological and engineered components - offer exciting opportunities to create new functionalities*

and support sustainability. Scientists and engineers are exploring biohybrid materials and devices for applications in a broad range of areas including robotics, health, manufacturing, architecture, and agriculture. To highlight emerging science and technology in this area and examine innovation drivers and barriers, the National Academies of Sciences, Engineering, and Medicine hosted a workshop, Biohybrid Materials and Technologies for Today and Tomorrow, January 12-13, 2023. Presenters and attendees from government, academia, and industry gathered in person and online to share examples of biohybrid technologies, identify potential research needs and opportunities, and discuss issues involved in translating this work into commercial markets and applications. This Proceedings of a Workshop-in Brief provides a high-level overview of the event.

Predictably Engineerable Biology

- **Synthetic/Engineering Biology: Issues for Congress**
  Source: Congressional Research Service (CRS), 2022
  Purpose: Provides a concise overview of key policy, security, and funding considerations related to synthetic and engineering biology at the federal level.
  Link: https://www.congress.gov/crs-product/R47265
  Abstract: *Synthetic biology—also known as engineering biology—is an emerging subfield of biotechnology that applies engineering principles and design tools to reprogram cellular systems at the genetic level for targeted functional outcomes. Despite its growing relevance, the lack of consistent definitions across overlapping disciplines such as genetic engineering and genome engineering complicates efforts to track trends in research funding, investment, and regulatory oversight. Synthetic biology has potential applications across diverse sectors, including biomanufacturing, medicine, agriculture, energy, and environmental remediation, with implications for rural economic revitalization and equitable innovation. U.S. federal research funding for synthetic biology rose from approximately $29 million in FY2008 to nearly $161 million in FY2022, though these figures may underestimate true investment levels. As access to synthetic biology tools expands, new communities of practice—including those outside traditional scientific institutions—are influencing education, innovation, and democratization of the field. However, growing accessibility and deployment raise biosafety, biosecurity, and ecological concerns, particularly for applications designed for environmental release. These challenges intersect with broader strategic issues, including U.S. competitiveness and security in relation to nations like China. Policymakers may need to evaluate the adequacy of current regulatory frameworks—such as the Coordinated Framework for the Regulation of Biotechnology—and consider whether additional oversight, public engagement, and strategic assessments are warranted. Legislative initiatives like Title IV of P.L. 117-167 and Executive Order 14081 signal increasing federal attention to synthetic biology, though their full impact will depend on forthcoming implementation and appropriations.*

- **Present and Future of Synthetic Cell Development**
  Source: Adamala et al., Nature Reviews Molecular Cell Biology, 2023
  Purpose: Offers a forward-looking review of synthetic cell technologies and the scientific milestones needed to replicate life-like functions in artificial systems.
  Link: https://www.nature.com/articles/s41580-023-00686-9
  Abstract: *In this Viewpoint article, a panel of leading experts is convened to explore the conceptual and practical progress toward engineering fully synthetic cells. They define synthetic cells as minimally designed systems that emulate living functions—such as metabolism, replication, and environmental responsiveness—and survey cutting-edge achievements including genome repackaging, compartmentalization strategies, and programmable genetic circuits. The authors identify persistent technical hurdles, including the integration of subsystems, control of biochemical reaction networks, scalability, and long-term stability. Looking ahead, they highlight opportunities enabled by advances in microfluidics, novel biomaterials, and computational design to construct modular, programmable synthetic cells. Such systems, they argue, could revolutionize applications across biotechnology, medicine, biosensing, and fundamental research into cellular origins*

- **Building Synthetic Cells-From the Technology Infrastructure to Cellular Entities**
  Source: Hilgers et al., ACS Synthetic Biology, 2024
  Purpose: Explores the development of foundational technologies and infrastructures required to enable synthetic cells, highlighting emerging tools and interdisciplinary approaches.
  Link: https://pubs.acs.org/doi/10.1021/acssynbio.3c00724
  Abstract: *The de novo construction of a living organism is a compelling vision. Despite the astonishing technologies developed to modify living cells, building a functioning cell "from scratch" has yet to be accomplished. The pursuit of this goal alone has–and will–yield scientific insights affecting fields as diverse as cell biology, biotechnology, medicine, and astrobiology. Multiple approaches have aimed to create biochemical systems manifesting common characteristics of life, such as compartmentalization, metabolism, and replication and the derived features, evolution, responsiveness to stimuli, and directed movement. Significant achievements in synthesizing each of these criteria have been made, individually and in limited combinations. Here, we review these efforts, distinguish different approaches, and highlight bottlenecks in the current research. We look ahead at what work remains to be accomplished and propose a "roadmap" with key milestones to achieve the vision of building cells from molecular parts.*

- **Technologies for Design-Build-Test-Learn Automation and Computational Modelling Across the Synthetic Biology Workflow: A Review**
  Source: Beal et al., Bioengineering Review, 2024

Purpose: Reviews state-of-the-art DBTL platforms, automation strategies, and modeling tools that are reshaping the pace and predictability of bioengineering innovation.
Link: https://link.springer.com/article/10.1007/s13721-024-00455-4
Abstract: *Motivated by the need to parameterize and functionalize dynamic, multiscale simulations, as well as bridge the gap between advancing in silico and laboratory Synthetic Biology practices, this work evaluated and contextualized Synthetic Biology data standards and conversion, modelling and simulation methods, genetic design and optimization, software platforms, machine learning, assembly planning, automated modelling, combinatorial methods, biological circuit design and laboratory automation. This review also discusses technologies related to domain specific languages, libraries and APIs, databases, whole cell models, use of ontologies, datamining, metabolic engineering, parameter estimation/acquisition, robotics, microfluidics and touches on a range of applications. The discussed principles should provide a strong, encompassing foundation for primarily dry laboratory Synthetic Biology automation, reproducibility, interoperability, simulatability, data acquisition, parameterization, functionalization of models, classification, computational efficiency, time efficiency and effective genetic engineering. Applications impact the design-build-test-learn loop, in silico computer assisted design and simulations, hypothesis generation, yield optimization, drug design, synthetic organs, sensors and living therapeutics.*

- **Engineering Tomorrow: DARPA's Push into the Frontier of Synthetic Biology**
  Source: SynBioBeta, 2025
  Purpose: Highlights DARPA's current investments in synthetic biology as a strategic technology frontier, including its implications for national security and innovation.
  Link: https://www.synbiobeta.com/read/engineering-tomorrow-darpas-push-into-the-frontier-of-synthetic-biology
  Abstract: *This article highlights the U.S. Defense Advanced Research Projects Agency's (DARPA) intensified investment in synthetic biology, positioning it as a strategic frontier at the intersection of digital precision and organic complexity. Under the oversight of Mike Koeris and DARPA's Biological Technologies Office (BTO), the agency is mobilizing moonshot programs—such as Switch and Living Foundries—that blend AI-driven design, modular genetic platforms, and scalable bioprocessing to solve the longstanding challenge of translating laboratory innovations into industrial-scale biomanufacturing. These programs aim to create agile, reprogrammable microbial systems capable of consuming diverse feedstocks and producing multiple products on-demand, enhancing both supply chain resilience and defense readiness. DARPA's decentralized, high-risk, high-reward model—empowered through short-term Program Managers—facilitates rapid iteration, cross-sector collaboration, and dual-use applications spanning national security, healthcare, and environmental mitigation. The brief concludes that DARPA's synthetic biology initiatives—coupling engineering principles with*

biological systems—are poised to redefine manufacturing, strengthen U.S. technological leadership, and deliver next-generation capabilities with both military and civilian utility.

- **Artificial Intelligence and Automated Laboratories for Biotechnology: Leveraging Opportunities and Mitigating Risks: Proceedings of a Workshop-in Brief**
  Source: NASEM, 2024
  Purpose: Explores the convergence of AI and lab automation in biotechnology and its implications for innovation and oversight.
  Link: https://nap.nationalacademies.org/27469
  Abstract: *Artificial intelligence (AI) and automation are increasingly being used to aid biological discovery and biotechnology development. Robotic and remotely controlled equipment is being used to accelerate research, while AI is opening new opportunities to explore the natural world and inform efforts to build biological entities with useful capabilities. Such technologies are poised to drive beneficial advances in health, biomaterials, environmental remediation, biomanufacturing, agriculture, and other areas. However, these developments also raise new questions and potential risks. Researchers, policymakers, and the public have sought to examine how applying AI and automation in biotechnology might lead to new challenges for biosecurity, health and safety, the environment, the integrity of scientific data, and economic development and national competitiveness.*
  To examine these issues, the National Academies of Sciences, Engineering, and Medicine hosted a workshop titled Artificial Intelligence and Automated Laboratories for Biotechnology: Leveraging Opportunities and Mitigating Risks, on April 3-4, 2024. Participants from government, academia, nonprofit organizations, and private industry communities gathered virtually and in person to explore the use of AI and automation in biological research and development; discuss considerations relevant to national security; and share perspectives on potential future pathways for technology and policy development. This Proceedings of a Workshop-in Brief provides the rapporteurs' high-level overview of the event.

- **The Age of AI in the Life Sciences: Appendix Mapping the Landscape of AI-Enabled Biological Design**
  Source: NASEM, 2025
  Purpose: Provides an in-depth mapping of AI applications in biological design, including tools, gaps, and interdisciplinary opportunities.
  Link: https://nap.nationalacademies.org/28868
  Abstract: *Artificial intelligence (AI) applications in the life sciences have the potential to enable advances in biological discovery and design at a faster pace and efficiency than is possible with classical experimental approaches alone. At the same time, AI-enabled biological tools developed for beneficial applications could potentially be misused for harmful purposes. Although the creation of biological*

weapons is not a new concept or risk, the potential for AI-enabled biological tools to affect this risk has raised concerns during the past decade.
This report, as requested by the Department of Defense, assesses how AI-enabled biological tools could uniquely impact biosecurity risk, and how advancements in such tools could also be used to mitigate these risks. The Age of AI in the Life Sciences reviews the capabilities of AI-enabled biological tools and can be used in conjunction with the 2018 National Academies report, Biodefense in the Age of Synthetic Biology, which sets out a framework for identifying the different risk factors associated with synthetic biology capabilities.

TRANSFORMATIVE S&T STANDING COMMITTEE

The Standing Committee on Transformative Science and Technology for the Department of Defense (DoD) will organize a seminar series, designed for a non-expert audience, on emerging trends in science and technology (S&T) that could transform the Department's approach to research and engineering (R&E). The seminar series will aim to (1) foster scientific awareness within the DoD leadership of emerging trends in S&T; (2) generate robust discussion on the applications of these most recent scientific discoveries; and (3) explore opportunities to transform and disrupt traditional R&E strategies and adopt innovative solutions that enable the United States to maintain a scientific and military advantage.

Members