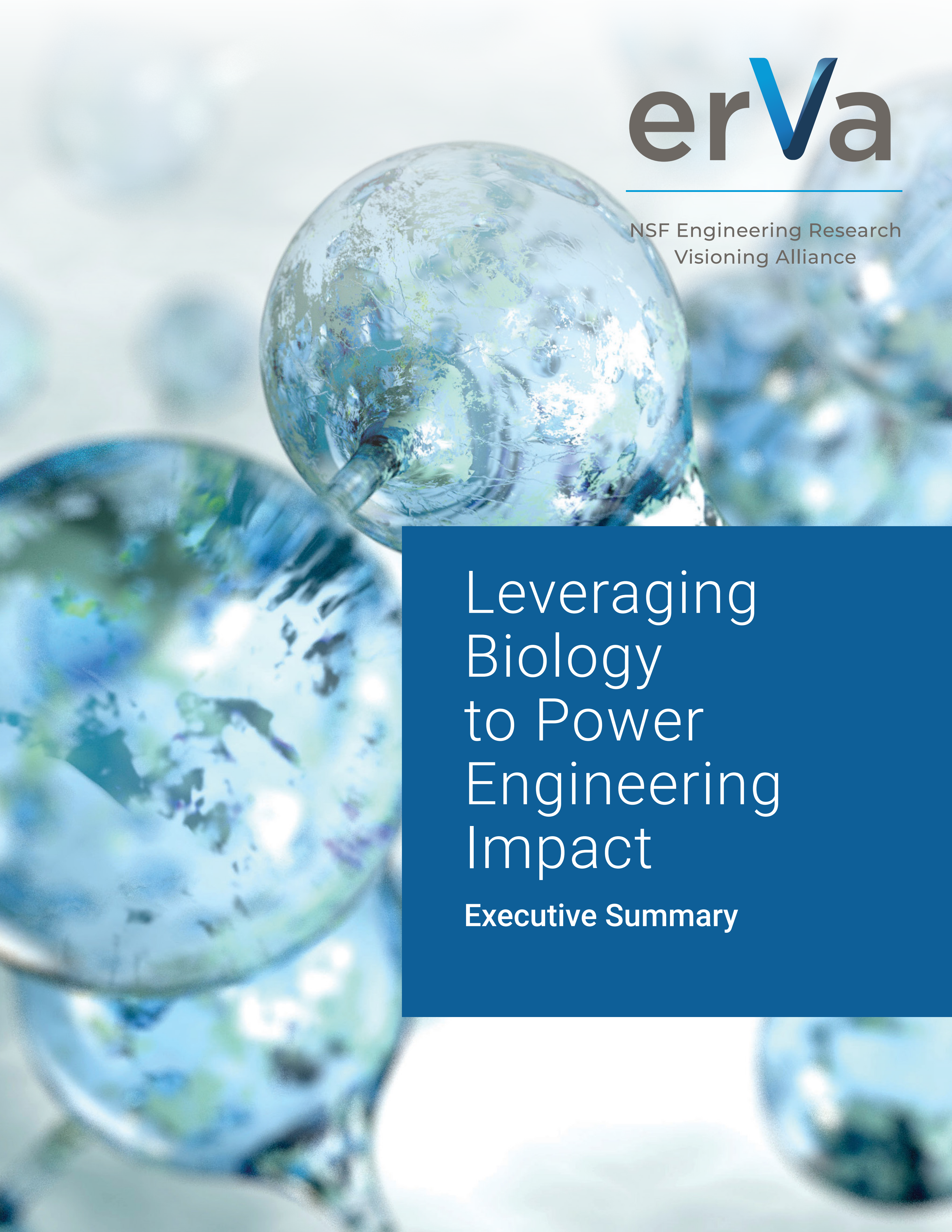

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NSF Engineering Research Visioning Alliance

Leveraging Biology to Power Engineering Impact

Executive Summary

Leveraging Biology to Power Engineering Impact

A Visioning Report of the Engineering Research Visioning Alliance

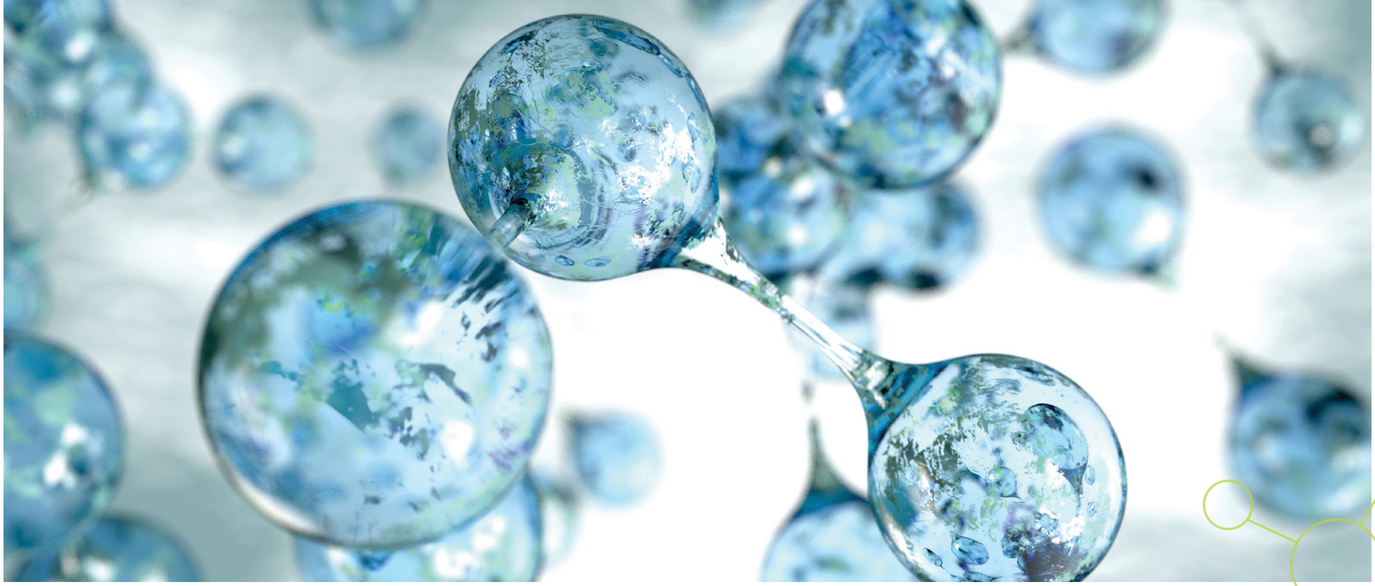
Report Finalized October 25, 2022

Co-Hosts:

This material is based upon work supported by the National Science Foundation (NSF) under award # 2048419. Any opinions, findings, interpretations, conclusions, or recommendations expressed in these materials are those of its authors and do not represent the views of the UIDP Board of Directors, UIDP's membership or the National Science Foundation.

The Engineering Research Visioning Alliance (ERVA) is a neutral convener that helps identify and develop bold and transformative new engineering research directions, directly supporting the nation's ability to compete in a rapidly changing global economy. Funded by the National Science Foundation (NSF) Directorate for Engineering, ERVA is a diverse, inclusive and engaged partnership that enables an array of voices to impact national engineering research priorities. The five-year initiative convenes, catalyzes and empowers the engineering community to identify nascent opportunities and priorities for engineering-led innovative, high-impact, cross-domain research that addresses national, global, and societal needs. Learn more at ervacommunity.org.

Suggested citation: Engineering Research Visioning Alliance, Leveraging Biology to Power Engineering Impact (October 25, 2022). Available at SSRN: ssrn.com/abstract=4258126.



Executive Summary

A phone that can regenerate itself. New York City with fresh mountain air. Plant-based, locally-grown manufacturing materials. All technical challenges seemingly impossible to execute, but incredible to imagine.

These are among the challenges presented to a diverse array of experts and practitioners with a clear objective: to envision bold engineering research priorities that can advance progress and address some of society's most pressing problems. Set in motion by the Engineering Research Visioning Alliance (ERVA), a Thematic Task Force with members from academia, industry, and the nonprofit sectors formulated "8 Impossible Things," each a statement accompanied by an image of an ideal future positively impacted through bold research--and subsequent innovation--at the intersection of biology and engineering. These eight challenges inspired more than 100 researchers to draw outside the lines and think outside the box to formulate research priorities not only imaginable, but achievable.

The NSF Engineering Directorate, led by Susan Margulies, set the course for discussions by framing three exploratory research domains at the intersection of biology and engineering:

01

Bio-Inspired/Bio-Informed
Inspiration from biology is used to engineer components and systems. Naturally occurring chemistry has driven advances in materials science. The design of engineered systems has been informed by nature-based mechanical solutions. Neuroscience is under scrutiny to provide inspiration for brain-based data storage and computational capabilities. In the future, we stand to learn much from biological mechanisms of resilience and adaptation to inform the design of engineering structures and systems.

02

Repurposing Biology
Biological constructs may be adopted and adapted for purposes beyond their existing biological function. A classic example of this is the use of DNA molecules for data storage, building on the remarkable integrity and potential for error-free replication of this macromolecule. Additionally, intense interest is focused on designer organisms, products of synthetic biology, that may afford functionalities from mining to agriculture, biofuels, to biofoundries. Engineered living systems may provide building blocks for next-generation sustainable engineering.

03

Improving on Biology
It's also possible to envisage engineering components and systems that go "beyond biology." One example is manipulating the interactions between species in different kingdoms. This "interkingdom engineering" has breathtaking potential to improve human health, for example by manipulating the human microbiome to ameliorate obesity or interrupting interspecies virus transfer to diminish disease spread.

The 8 Impossible Things

This report casts the findings of this visioning event within the framework of the three domains, using the 8 Impossible Things as a device to inspire bold, new engineering research directions.

- Smartphones don't need a trade-in; they reproduce
- A businesswoman flies to work using her new exoskeleton
- Your bathroom mirror performs hospital-grade diagnostics
- There's never another "your child has been exposed to..." sign at daycare
- Any-town USA manufactures all the chemicals and materials it needs from plants grown nearby
- Lifespans are no longer defined by ZIP code
- Central NYC residents breathe pristine mountain air
- A 100-year-old breaks the 100-meter sprint record

Three common threads are woven through the ideation inspired by these concepts:

- Sustainable solutions that involve repurposed or recycled materials;
- Inclusive design and research to serve all populations equitably; and
- Affordable approaches that ultimately provide low-cost solutions.

The research priorities outlined in this report lay the groundwork for achieving solutions for each of the 8 Impossible Things. The task force identified topics ripe for exploration that promise significant advances in how the world tackles some of its biggest problems.

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Engineering Research Opportunities Inspired by Nature

Although separate disciplines, the convergence of biology and engineering has enormous potential to solve some of our greatest problems. Bulletproof vests. Solar panels. Exoskeletons. These advances once seemed impossible to create, but they are now a part of our lives.

The 8 Impossible Things provide fertile ground to envision distinct topics for engineering research. Framed within the three exploratory research domains proposed by NSF, disparate priorities converge as opportunities for cross-cutting impact.

Research priorities that could rapidly advance engineering solutions in the bio-inspired/bio-informed domain include:

- **Biomaterials and biodegradables** to replace components that fill landfills today and may offer further benefits, such as the ability to resist disease pathogens;
- **Next-generation sensors, monitoring, and reporting systems** that detect pollution and infectious disease on surfaces, in municipal effluent systems, in homes, and in the environment, at scales ranging from cellular to an entire city or region; and
- **Discoveries that leverage commonalities among animals and plants with beneficial capabilities** such as long lifespans, limb regeneration, or the ability to live in extreme environments.

Using biological entities as building blocks, the repurposing biology domain offers engineering priorities ripe for exploration, to include:

- **New materials** that can sequester carbon and filter, remove, or transform pollutants into benign alternatives;
- **Leveraging the brain-machine interface** and systems intelligence to improve communication and computing devices; and
- **Stronger, long-lasting bio-based materials** for buildings and other infrastructure.

Research priorities that can be framed as improving on biology include:

- **Regenerative engineering and improvements on human biology**, from lightweight, human-powered prosthetics to improving communication through better understanding of the brain-machine interface and innovation in wearables or implants that enable new human-to-device interfaces;
- **Advances in additive manufacturing** enabling custom bio replacement parts;
- **Models to understand aging and its effects** with an eye toward cellular reprogramming and rejuvenation, including ways to short-circuit senescence and exploring DNA repair mechanisms

Prioritized by the participants, the fundamental research topics, as well as estimated timeframes to bring envisioned results to fruition, are provided on the following pages.

Identified Research Priorities

#1 impossible thing — SMARTPHONES DON'T NEED A TRADE-IN; THEY REPRODUCE

2 YEARS	5 YEARS	10 YEARS
The brain-machine interface and systems intelligence, with a vision for what's next in personal communication and computing devices (beyond the smartphone). Identifying market drivers and conducting life-cycle analysis to determine which components hold the most promise for R&D.	Advances in additive manufacturing to generate custom bio replacement parts.	Regenerative engineering, building off research into self-healing infrastructure.

#2 impossible thing — A BUSINESSWOMAN FLIES TO WORK USING HER NEW EXOSKELETON

2 YEARS	5 YEARS	10 YEARS
Data-sharing and monitoring systems (for safety and to identify maintenance and repair needs). Applying new functionalities for existing prosthetic devices.	Ultra-lightweight, high-density propulsion and power systems. Two-way, human-to-device interfaces using wearables or implants. For internal systems, ways to boost the human body's resources to power implant or prosthetic systems. Strong, lightweight materials, with bone as the optimal model.	Bio-inspired principles for navigating, landing, and avoiding physical structures.

#3 impossible thing — YOUR BATHROOM MIRROR PERFORMS HOSPITAL-GRADE DIAGNOSTICS

2 YEARS	5 YEARS	10 YEARS
Efficient data-sharing using a “physician in the loop” model that also ensures patient privacy. Methods to integrate data from multiple samples and platforms and to analyze these integrated databases for the greatest benefit for individuals and population health.	New testing platforms and sensors that are accurate using tiny biosample sizes. Methods and models to detect baseline changes in key biometric measures from a variety of sensing technology mechanisms and biosample types.	Purpose-designed artificial intelligence (AI) conversational interfaces that could be leveraged to detect changes in voice, expression, and appearance that correlate with health changes.

#4 impossible thing — THERE’S NEVER ANOTHER “YOUR CHILD HAS BEEN EXPOSED TO...” SIGN AT DAYCARE

2 YEARS	5 YEARS	10 YEARS
Passive sensing and health risk prediction technology for in-home use. Biologically-inspired sensors and diagnostics to monitor at larger (population) scale. R&D inspired by naturally anti-pathogenic surfaces (e.g., shark skin) and natural systems in biology that protect organisms living in fetid environments.	New smartphone interfaces for automated disease tracking. Models to quickly predict vaccine efficacy for emerging diseases. Evaluation of biofilms that could be repurposed to develop invisible “bioarmor” or a barrier to prevent entry of pathogens. Multi-faceted, multiplexed, dynamic models, devices, and sensors to identify environmental factors that affect pathology from air, surfaces, and effluent sources.	Machine learning and AI models to collect, track, and analyze data to predict future pathogens. Novel approaches for wearable devices for detection combined with targeted therapeutics to enhance immune activity for targeted patient groups. Methods to enable identification of people vulnerable to particular pathogens and systems to mitigate transmission.

#5 impossible thing
ANY-TOWN USA MANUFACTURES ALL THE CHEMICALS AND MATERIALS IT NEEDS FROM PLANTS GROWN NEARBY

2 YEARS	5 YEARS	10 YEARS
Life-cycle analysis and techno-economic analysis to determine what processes are the best targets for future engineering research and development and what specific communities need, as well as predictive models for technology transfer and process scale-up. Biological systems for biomanufacturing potential (biomining the full periodic table). Low-cost infrastructure development for local data-sharing that is cybersecure.	Novel, low environmental impact methods (e.g., net zero carbon intensity and low-water consumption) to process and purify finished materials. Methods to prioritize production of chemicals and materials based on technical and economic feasibility for their use and projected societal benefits.	New, truly low-cost methods to cultivate and process local lignocellulosic feedstocks as a sustainable source to replace fossil feedstocks. Improved real-time monitoring, including better imaging for collecting data in large-scale systems to facilitate high-fidelity scale-up and more efficient large-scale equipment design and operation.

#6 impossible thing
LIFESPANS ARE NO LONGER DEFINED BY ZIP CODE

2 YEARS	5 YEARS	10 YEARS
Improving the methods and models to collect, mine, analyze, and visualize integrated datasets and data infrastructure to make information more usable, accessible, and accurate using AI and machine learning. Enhancing capabilities in data access, management, and security, working in collaboration with stakeholders and communities to ensure the design meets their needs.	Developing new types of targeted sensors and monitoring systems that can collect multiple endpoints and generate maps to track data over time.	Collaborative efforts to prioritize collection of data with the strongest connection to positive clinical outcomes that can be leveraged for targeted follow-up studies and analyses.

#7 impossible thing: CENTRAL NYC RESIDENTS BREATHE PRISTINE MOUNTAIN AIR

2 YEARS	5 YEARS	10 YEARS
Improving devices for air quality monitoring and source identification to determine the causes of pollution at a more granular level (e.g., pollution from indoor heating systems; automobile exhaust; industry, agriculture, etc. New materials inspired by biology that sequester carbon, filter pollutants, or make pollutants benign. Bio-based materials for civil infrastructure that maintain strength and longevity.	Rapid adaptation and scaling of existing technologies and solutions for pollution capture or mitigation. Methods for upgrading existing infrastructure to accommodate sustainable, efficient power grids. Understanding the role of carbon capture in improving air quality. Filters and other technology that can sense, capture, and remove pollutants directly from the air.	New bioremediation materials that can remove pollutants on contact.

#8 impossible thing: A 100-YEAR-OLD BREAKS THE 100-METER SPRINT RECORD

2 YEARS	5 YEARS	10 YEARS
New ways to test how human performance relates to aging, nutrition. and physical training, with an eye toward longer-term research to develop devices such as biomimetic chips to empower muscles or optogenetic chips to promote regeneration or repair.	Advances in lower-cost prosthetics and mobility solutions to enhance wearable devices and materials to improve athletic performance.	Models to better understand cellular aging and promote cellular health through reprogramming and rejuvenation, as well as testing ways to short-circuit senescence, targeting DNA repair mechanisms in particular. Effective models to discover and assess commonalities among animals and plants that are long-lived, have special capabilities (such as limb regeneration), or that inhabit extreme environments.

Research in these areas can move the 8 Impossible Things that inspired this visioning report into the “possible” column. Advances in biomanufacturing, in turn, will move research discoveries from the laboratory into the hands of industry and society. This report identifies a number of engineering research priorities to enable this important technology transfer mechanism.

Taking Action

The full ERVA report provides a unique look at transformational priorities where engineering and biology can have impact while contributing to an inclusive research community. The aim is to inspire researchers and sponsors (public, private, and nonprofit) to support aligned research leading to innovation and pursue these priorities. ERVA challenges readers to disseminate this report and prioritize areas with potential for the greatest return on investment.

These priority research directions can build momentum to innovate and create meaningful solutions. Sensors can be improved to capture accurate data and diagnostics. Robotics can be leveraged to improve and extend human performance. Materials can be developed to enable local manufacturing and resolve supply chain issues. Pursuing these research endeavors highlights the synergy between engineering and biology to advance technologies that ultimately create cost-saving, equitable, and sustainable solutions for society.

“Engineers must lead the biotechnology revolution by unleashing biology’s potential and fueling transformative impacts on society, the economy, and our planet.”

SUSAN MARGULIES
NSF Assistant Director for Engineering

NSF Engineering Research
Visioning Alliance

Our mission is to identify and develop bold and transformative new engineering research directions and to catalyze the engineering community's pursuit of innovative, high-impact research that benefits society.

ERVA IS FUNDED BY THE NATIONAL SCIENCE FOUNDATION THROUGH AWARD NUMBER 2048419

This material is based upon work supported by the National Science Foundation under Grant # 2048419. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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