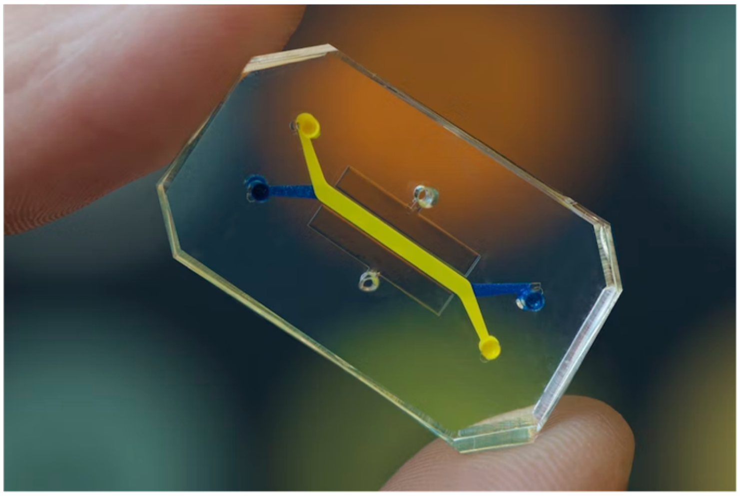
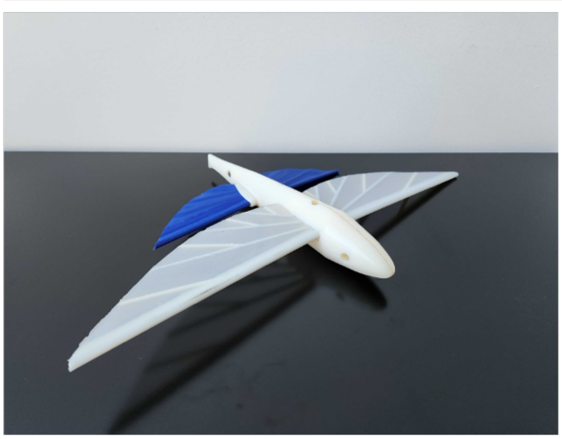
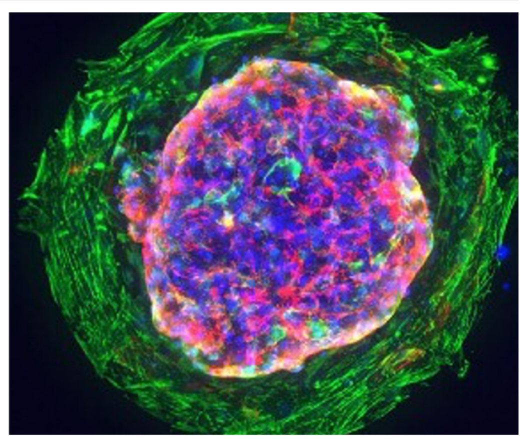


NSF-Funded Convergence Accelerator Workshop

Bio-inspired Design





Workshop Activities Fall 2022, Report January 2023

Executive Summary

Existing and near-future technologies that rely on standard design and manufacturing techniques are not sufficient to address a suite of urgent problems facing our society, including challenges in our natural environment (climate change, pollution), our built environment (failing infrastructure, integrated manufacturing), and those involving human resources or health (aging populations, food scarcity, vaccine development). Bio-Inspired Design – the process of developing concepts, approaches and technologies that build and control the way nature does – offers potentially transformative solutions to these problems. Bio-inspired technologies share function (e.g bio-inspired robot locomotion) or structure (e.g. DNA-based self-assembly or synthetic biology protein production) with nature. Because bio-inspired design focuses on a *process* for driving forward technological innovation, rather than a fixed set of platforms, it is a great theme for a convergence accelerator track. Bio-inspired design is inherently convergent, drawing on approaches from the life sciences, the physical sciences, engineering, and medicine.

The workshop has identified several components that would contribute to the **intellectual merit** of a Convergence Accelerator track in bio-inspired design. Such a track would result in new connections between disparate fields including synthetic biology, material design, self-assembly, organismal biology, and robotics. We expect that those new connections will generate collaborative projects using multiple approaches from these different fields to better achieve specific bio-inspired functionalities, and also to overcome hurdles from individual approaches that are preventing translational relevance. In addition, translational work in bio-inspired design often drives a deeper understanding of the basic sciences, captured by the Feynman quote: "What I cannot create, I do not understand."

Bio-inspired design is primed for acceleration into translation, leading to **broader impacts** to society, including to consumers and in national security. In this report, our community has identified a series of bio-inspired platforms (such as DNA nanotech and self-assembly) that serve as building blocks for a set of convergent tasks and functionalities (such as prototyping at speed and scale), which in turn enable specific use-cases, products, and applications in several overarching industrial categories: (1) medicine and health; (2) materials and manufacturing; (3) environment and infrastructure; and (4) agriculture, food, and personal care. We enumerate applications in each category that are de-risked – they have an obvious market use and are quite likely to be brought to market in a 2-3 year timeframe under the guidance of a Convergence Accelerator program, as well as applications that are high-reward and still need to be de-risked – the market value needs to be clarified and if so the project could be made ready for VC or follow-on/ non-profit/ DARPA/ IARPA funding in 2-3 years. Examples include: industrial-scale, climate-friendly manufacturing of proteins and artificial foods enabled by synthetic biology; synthetic systems for energy harnessing and storage inspired by living systems; autonomous robot swarms for construction and civil engineering; hybrid biomaterials that interact seamlessly with the human body for wound healing and tissue engineering; and nature-inspired metamaterials that mimic natural structures for enhanced strength, resilience, and enhanced optical properties.

Track Integration activities would include exporting best practices from "bio-design foundries" such as the Wyss Institute and Chan-Zuckerberg Biohub, which have excellent academic-industrial translation pipelines, but with interactions that are largely restricted to small numbers of researchers in limited geographic regions. We identify specific best practices from these foundries that could be disseminated and activated at institutions across the U.S., increasing both the diversity of the pipeline and ensuring good ideas are not lost to translation simply because they are under-resourced. Additional track integration activities would include education and workforce development activities, such as creating a bio-inspired educational network to connect currently isolated clusters of researchers and develop shared training modules, internship platforms, industry partnership paradigms, as well as building support programs and leveraging existing partnerships with minority-serving institutions to increase the diversity of the pipeline. Bio-inspired design can enable unique educational activities focused on intuitive bio-inspired examples to help build STEM identity in underserved populations. A third set of track integration activities would involve bioethics, science communication, and public policy. Several bio-inspired design platforms are potentially sensitive to negative public perception (e.g., growing replacement organs, self-replicating materials) and also will push the limits of existing regulations and public policies (e.g. completely synthetic cells). As a consequence, we envision unique opportunities for interactions with humanists and social scientists to construct bioethical standards, develop science communication strategies for researchers around these issues, and coordinate with government organizations and regulatory agencies to coordinate best practices and regulations.

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Report authors and contributors: Dr. Lisa Manning, Syracuse University, Dr. Aimy Wissa, Princeton University, Dr. Don Ingber, Wyss Institute, Dr. Luisa Ruge-Jones, University of Dayton, Dr. Jeremy Steinbacher, Syracuse University, Dr. Wallace Marshall, University of California San Francisco, Dr. Peter Niewiarowski, University of Akron, Dr. Kate Adamala, University of Minnesota.

Cover image: Top left: A human organ-on-a-chip microfluidic culture device created with soft lithography and lined by living human cells that recapitulates the 3D structure and function of major functional units of living organs, such as the lung alveolus (Huh, Matthews et al. 2010). **Top right:** 'Shrilk' Biodegradable Plastic that mimics the multilaminate structure of insect cuticle. The name comes from the use of layers of chitosan from shrimp shells and fibroin from silk. (Fernandez and Ingber 2014). Center: Photo from in-person workshop at the Wyss Institute, October 3 and 4th, 2022 (photo courtesy Jeremy Steinbacher). **Bottom Left:** Robotic model organism mimicking a four-winged flying fish in gliding flight (Saro-Cortes, Cui et al. 2022). **Bottom Center:** A four-winged flying fish in gliding flight (photo courtesy Roshan Kamath on Pexels, https://www.pexels.com/photo/flying-fish-1661337/). **Bottom Right:** Pluripotent stem cell cardiac organoid, with potential future applications in toxicity screening (unpublished image courtesy Plansky Hoang, Zhen Ma lab, Syracuse University).

A. Introduction

A1. What is bio-inspired design? What grand challenges does bio-inspired design address? How is it different from traditional areas in science or engineering?

The United States, and the world more broadly, face a series of major urgent problems that cannot be adequately addressed using standard or existing man-made technologies. Examples include challenges in our natural environment (climate change, pollution), those in our built environment (failing infrastructure, integrated manufacturing, burgeoning computational needs), and those involving human resources (aging populations, food scarcity, societal fragmentation) or human health (replacement organs, vaccine development, treatments for the elderly). **Bio-Inspired Design – the process of developing concepts, approaches and technologies that build and control the way nature does – offers potentially transformative solutions to these problems.** Bioinspiration relies on sharing function or structure with nature. Bioinspired products can involve fully synthetic systems that are informed by the physics and principles implemented by natural organisms (e.g., a bio-inspired robot). Other bio-inspired products or systems share the same structure as nature. These often involve utilizing or interfacing with biological components within the product.

Because bio-inspired design focuses on a ***process*** for driving forward technological innovation, rather than a fixed set of platforms, it is a great theme for a Convergence Accelerator track. It provides a concrete conceptual framework that links together disparate projects, it explicitly encourages innovation by spurring researchers to capture complex features of living systems, and it is flexible enough to allow new ideas to flourish as our technological capacity increases.

Bio-Inspired Design builds upon traditional fields such as bioengineering and robotics, which have focused on making materials or devices that interface with human bodies, or advanced manufacturing, which has focused on developing methods and machines for producing devices and materials in new ways, sustainably, at scale. It also has been transformed by advances in synthetic biology that enable reprogramming of living cells. Bio-inspired design is able to achieve many of the goals of bioengineering and advanced manufacturing by identifying biological systems that have evolved to achieve similar goals and reverse engineering similar behavior.

More importantly, bio-inspired design has already generated an unexpectedly large number of products and societal impacts (as described in Section A.3 and D), given that it is a relatively new field that has been recognized only over the past decade. It clearly has the power to disrupt markets and generate intellectual property because it promotes outside-the-box thinking that identifies radically different solutions to existing problems. Despite the number and superior performance of several bioinspired products compared to their counterparts, there has been a lack of translational machinery needed to drive large scale innovation, especially outside "bio-design foundries" in a few major geographic hubs (Boston, San Francisco) in the United States.

Strategic connections between the academic field of bio-inspired design, industry, and the translational machinery, have not been well-organized. Conversations at our workshop suggest that this may be because many academics who make discoveries in this space often begin their research by considering basic science questions: e.g., "how does a fish swim?", or "how does this genetic circuit function?" When they realize their discoveries could be used for technology platforms, they lack the connections and tech transfer background to establish collaborations with industry. Through this lens, the (typically one-off) translational successes of bio-inspired design become even more striking, and this idea also helps to explain the incredible, outsize success of the few existing "bio-design foundries". It suggests that with systematic, strategic investment and education of academic researchers, as well as implementation of new approaches to technology translation at the academic-industrial interface, this field is poised for significant societal impact. In other words, our community anticipates that the Convergence Accelerator paradigm could have outsize impact in this field.

A.2 Bio-inspired design is convergent. Bio-inspired design is inherently convergent, as it requires analyzing mechanisms and constituent building blocks from the life sciences, using insights from the physical science to develop a mechanistic description of those processes, and deploying techniques from engineering and medicine to develop technologies based on those principles.

As highlighted in Fig. 1, active researchers in bio-inspired design include i) life scientists: molecular, cell, developmental, organismal and plant biologists, ecologists and evolutionary biologists, and biochemists and biophysicists; ii) physical scientists: materials scientists, physicists, chemists, and soil scientists; and iii) engineers and health researchers: mechanical and electrical engineers, bioengineers, biomechanicians, mechanobiologists, roboticists, manufacturing technologists, and medical doctors.

Importantly, however, researchers in these disparate areas rarely interact with one another, and to our knowledge there have not been any national-scale workshops or conferences in this space. This is a missed opportunity, as it is clear from past work that convergent interactions between these groups can drive innovation: for example, robot swarms that use synthetic-biology-driven organoids as the robots (such as xenobots (Kriegman, Blackiston et al. 2021)) could potentially execute a broader range of autonomous behaviors compared to traditional robotic agents. Similarly, 3D bio-printed living structures could facilitate more efficient industrial-scale cell culture for food production as well as medical applications.

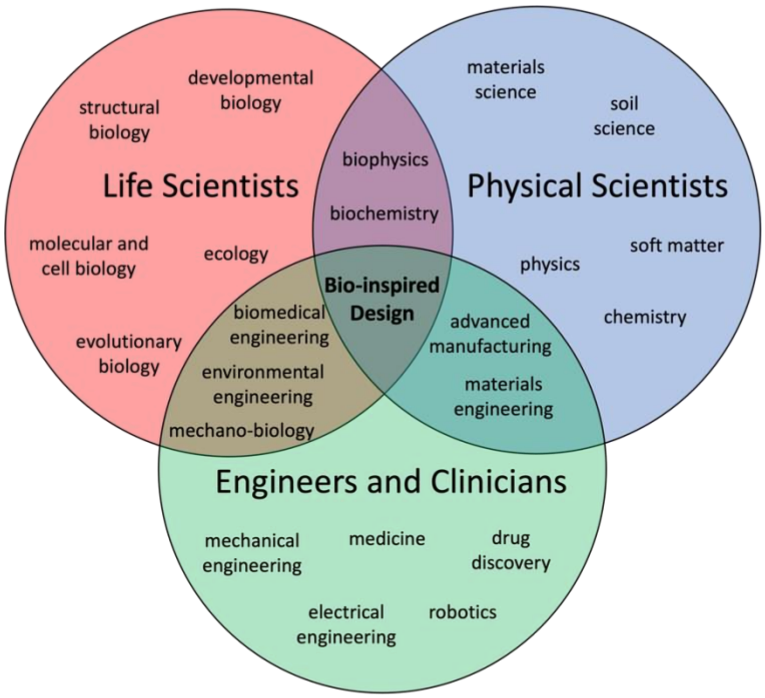

Figure 1. Venn diagram highlighting convergence of multiple areas of inquiry in Bio-inspired design. As highlighted in the workshop and in the report, bio-inspired design requires authentic partnerships between life scientists, physical scientists, engineers, and medical clinicians.

As highlighted in Section B below, our in-person workshop allowed these disparate groups to come together and identify common themes and potential convergent applications. The success of the workshop and the positive feedback from participants, as well as enthusiastic participation in follow-up virtual meetings and surveys, suggest that these researchers are primed and excited to work together on convergent teams to advance the field of Bio-Inspired Design. Section D provides specific examples of industrial and other societal applications that require multiple researchers with diverse scientific backgrounds to work together.

A.3. Bio-inspired design is ready for acceleration into translation and commercialization. The projects in Section D highlight not only the convergent nature of applications of bio-inspired design, but also show that the field is primed for translation on a short timescale. As a brief overview, there are several examples of bio-inspired design solutions that are already being investigated and on the cusp of being useful to society, including: industrial-scale, climate-friendly manufacturing of proteins, cells (Mirasol 2022), and artificial foods enabled by synthetic biology; synthetic systems for energy harnessing and storage inspired by living systems (Ren, Liu et al. 2021); autonomous robot swarms for construction and civil engineering (Melenbrink, Werfel et al. 2020); hybrid biomaterials that interact seamlessly with the human body for wound healing and tissue engineering (Monroe, Easley et al. 2018); nature-inspired metamaterials that mimic natural structures for enhanced strength, resilience, and enhanced optical properties (Chen, Huang et al. 2021); and programmable molecular robots for nanofabrication of high density multifunctional materials (Zhang, Marcos et al. 2018). Several of these examples, and many more, are highlighted in a recent report discussing commercialization potential of bio-inspired technology by Terrapin Bright Green LLC (Smith, Bernett et al. 2015), and shown in Fig. 2 below.

Although these examples highlight the obvious translational promise of bio-inspired design, our workshop and subsequent virtual meetings suggest that the field is being held back by specific hurdles that an NSF Convergence Accelerator track, and track integration activities, could overcome.

One key integration activity will be actively disseminating best practices for translation in bio-inspired design. There are a few existing “bio-design foundries” such as The Wyss Institute and the Chan-Zuckerberg Biohub that have done an excellent job of driving bio-inspired ideas to translation. Over the past 14 years, the Wyss has generated over 4000 patent applications with 1200 issued, 115 licenses, 55 startups, 1600 jobs created by those startups and over $2 billion raised in startup funding. The Chan-Zuckerberg Biohub is much newer (started ramping up in 2017), but already has 130 patents and 186 open science projects. This confirms that dedicated translation activities are very effective at driving bio-inspired products to market.

A major challenge is that those benefits have so far been limited geographically to researchers and even largely companies in a narrow region around the foundries, and also limited in workforce development to the relatively small number of people directly affiliated with the foundries. As discussed in more detail in Section E, an NSF Convergence Accelerator track could provide the impetus and mechanisms to identify best practices that can be disseminated and activated at institutions across the U.S., increasing both the diversity of the pipeline and ensuring good ideas are not lost to translation simply because they are under-resourced. Additional hurdles that would be addressed in track integration activities include: i) working with multiple stakeholders to drive public policy discussions – such as developing a bioethics and FDA regulatory framework for synthetic cells – ii) developing workforce training programs at the intersections of entrepreneurship, industry, and bio-inspired design to build translational capacity outside of foundries, and iii) creation of education programs that use bio-inspired design modules to highlight unexpected applications of STEM fields and broaden the STEM pipeline.

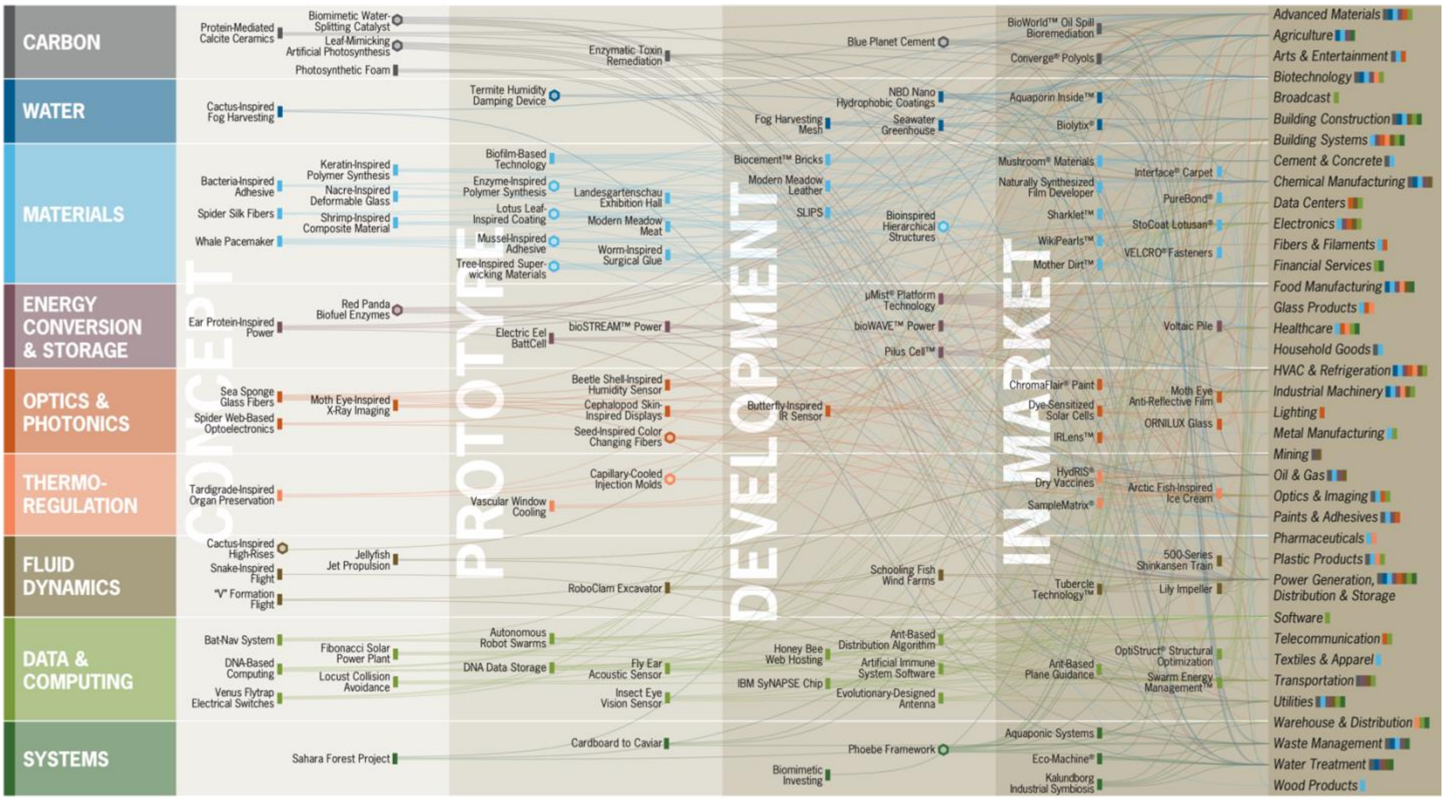

Figure 2. Market readiness of BioInspired Innovations, from (Smith, Bernett et al. 2015), Terrapin Bright Green LLC. The is an immense pipeline of bio-inspired innovations at various stages of development with impacts on a huge number of industries. This demonstrates the promise of bioinspired design, but our workshop highlighted that academic researchers outside a few large hubs (Boston, San Francisco) lack the tools and resources to make connections to industry and drive their ideas to market. This represents significant untapped potential.

Taken together, this suggests that Bio-Inspired design is on the cusp of being ready to deliver high-impact translational solutions at the national scale, and that focused attention in this space could drive forward societally-important use-cases.

A.4 Intellectual Merit

This proposed Convergence Accelerator track has significant potential to advance knowledge, as it will catalyze convergent research thrusts amongst scientists, engineers and industry partners, who have individually produced high-impact work, and even demonstrated convergent research on small teams. However, given the current lack of academic infrastructure in the U.S. (conferences, funding mechanisms, departments) centered on bio-inspired design, academic researchers have rarely been brought together to identify common themes across bio-inspired approaches. Therefore, a Convergence Accelerator track is likely to result in new connections between disparate fields including synthetic biology, material design, self-assembly, organismal biology, and robotics. We expect that those new connections will generate collaborative projects using multiple approaches from these different fields to better achieve specific bio-inspired functionalities, and also to overcome hurdles from individual approaches that are preventing translational relevance.

In addition, one of the major recurring themes that came out of our workshop is that translational work in the area of bio-inspired design often drives a deeper understanding of the basic sciences. For example, the process of designing a specified synthetic biology control circuit that utilizes a specific biomolecule often leads to a deeper, mechanistic understanding of the regulation of that biomolecule in the wildtype cell. Similarly, creating a robotic fish tail and studying how hydrodynamic efficiency changes as a function of the tail shape can help explain how specific morphological changes to the tails alter swimming locomotion in actual fish, as well as identifying possible evolutionary design pressures on the organism.

A.5 Broader Impacts

Our workshop and follow-up meetings have identified a large number of high-leverage projects in multiple industries that are primed for translation. As highlighted in Section D of this report, several of these projects have already been de-risked (i.e. have an obvious market use, identified competitive advantage, and can be brought to market quickly, in a 2-3 year timeframe) while others require de-risking (i.e. market value needs to be clarified, could be made ready for VC or follow-on/non-profit/DARPA/IARPA funding in 2-3 years, and so may need a longer timescale to be brought to market.) In both cases, a Convergence Accelerator track in bio-inspired design will lead to direct societal impacts because it will educate and fund teams of scientists and entrepreneurs to be able to overcome the hurdles necessary to bring ideas to market or de-risk high-reward ideas to prepare them for follow-on funding. In addition to consumer outputs, bio-inspired design holds great promise for producing new materials and novel manufacturing methods in the national security space as recognized a decade ago by the Department of Defense (Office of Technical Intelligence 2015). Its continued relevance today is highlighted by a National Academies-sponsored workshop in January 2023 focused on “Biohybrid Materials and Technologies for Today and Tomorrow”. Indeed, advanced materials and biotechnology are “critical technology areas” with director-level leadership within the Undersecretary of Defense for Research and Engineering and a dedicated Biological Technologies Office at DARPA. Convergence Accelerator activities that broaden the base of practitioners in the field and lower barriers to commercialization will strengthen this key component of the national security apparatus.

In addition to these direct outputs, track integration activities will lay the foundation for intermediate and long-term societal impact. One set of track integration activities, discussed in section E, will identify and facilitate public policy discussions required to support and regulate these emerging technologies.

Another set of track integration activities, or possibly individual pilot projects within the Convergence track, could test curricular, co-curricular, and educational research interventions that use bio-inspired design to drive systemic change in science and engineering workforce development. A key barrier to translation in bio-inspired design solutions is the persistent siloing of disciplines and sectors that participate over many stages in the non-linear process starting from inspiration or problem definition through ideation, customer and market research, investment solicitation, prototyping, and product development. This is not a barrier unique to bio-inspired design, but it is one that bio-inspired design is uniquely situated to address. Indeed, NSF, AAAS, and HHMI co-sponsored national studies and reports over the last decade (e.g. the AAAS Vision and Change report (Austin 2018) call for reform in how we train life scientists to emphasize:

- the problem-solving context of biology through exposure to cross-cutting themes with engineering, physics, math, and chemistry
- the societal impact dimension of biological science and study especially as it relates to the potential for addressing grand challenges such as sustainability, public health, renewable energy, clean water, and affordable food
- building capacity of students and faculty to dynamically team with colleagues from other disciplines in search of solutions to the complex and hyperdisciplinary wicked problems of the 21st century.

A Convergence Accelerator in bio-inspired design that supports identification and dissemination of existing bio-inspired design curricula that break down the boundaries among the life sciences, engineering, business, design, the arts and humanities can address the call of Vision and Change in a way that few other platforms can match. Moreover, due to broadly distributed, but largely isolated curricular programs in bio-inspired design programs at many universities, instituting a network approach among these programs would enable rapid and significant impact on literally thousands of students over the next 3-5 years.

B. Workshop Goals and Structure

B.1 Vision, Goals and Process Overview. The overall goal of this workshop was to bring together researchers across the Bio-Inspired Design space to share perspectives, define important problems that a Bio-Inspired Design approach could solve, and identify obstacles that are holding the back the advancement of the field.

The more specific objectives of this workshop were two-fold: 1) to facilitate discussions of how different approaches achieve bio-inspired functionalities and identify similarities and synergies, and 2) to identify the highest value key challenges that are most approachable using Bio-inspired design, and then to identify hurdles that are currently preventing bio-inspired design ideas from being practicable. Specifically, we hoped to address the following questions: What are the major reasons these materials/concepts/machines are not being used already? What problems do we have to solve before these would be able to be used in industry/manufacturing/healthcare, or succeed in targeted DARPA/IARPA-style awards? Are there any examples of 'low hanging fruit' where faster proof-of-principle could be demonstrated in terms of both addressing key issues and attracting investor interest in supporting commercialization of the bio-inspired technologies already being developed?

The grant proposal for the workshop was written by Lisa Manning (PI, Syracuse University), and co-PIs Aimy Wissa (Princeton University), Don Ingber (Wyss Institute), and Wallace Marshall (UCSF). The workshop was organized by this team, with input from an external advisory committee (Bob Full, UC Berkeley; Mike Levin, Tufts; Pam Silver, Harvard; William Shih, Wyss; Kate Adamala, Minnesota), facilitator Dr. Luisa Ruge-Jones (University of Dayton), and staff members Dr. Jeremy Steinbacher, Ms. Karen Low, Mr. Jacob Watts and Ms. Ana Carolina Villar.

The organizers and advisory committee decided to hold the workshop in person, as there are no regular meetings or conferences for the bio-inspired design community in the U.S. The team felt that an in-person meeting would facilitate community building and conversations that may not happen easily in a virtual environment between participants who have never met previously. For the workshop, we also focused on trying to achieve a diverse set of viewpoints across many sectors in bio-inspired design, while maintaining a small enough number of participants that discussions could occur between the majority of participants.

Figure 3. In-person Bio-inspired Design workshop at the Wyss Institute. The facilitator Dr. Luisa Ruge-Jones led the group through small-group activities that alternated between integration and differentiation under the "nominal group technique" process to identify convergent themes and applications in bio-inspired design, which were further expanded in virtual activities and surveys. A summary of convergent tasks and applications highlighted by this process appear in Fig. 5 in Section D. Photos courtesy of Jeremy Steinbacher and the Wyss Institute.

The Wyss Institute for Biologically Inspired Engineering at Harvard University, where the workshop was held, is widely recognized as a leader in translational impact. It has already demonstrated the feasibility of leveraging bio-inspired design to develop new technologies and translate them into commercial products, spinning out over 50 startups and licensed over 100 technologies over the past 14 years, emphasizing that bio-inspired design can be translational. However, this impact has been limited to one small group of investigators in one city, and we wanted to identify best practices to ignite similar bio-design inspired efforts across the nation and to determine a broad set of possible use-cases that might become achievable in the context of a nation-wide Convergence Accelerator track.

After collating information from the workshop, we used the in-person workshop outputs to develop virtual discussion formats (zoom meetings, surveys, shared online documents) to gather additional information and feedback from a broader set of academic, government, and industry participants.

B.2. In-person workshop structure and process. On October 3-4, 2022, the organizers gathered a cohort of 40 participants, organizers, and personnel to engage in productive conversations about the intersection and potential of commercializing bio-inspired design research. The organizers and external advisory committee.

Participants represented 32 unique institutions across the United States and approximately 16 different disciplinary topic areas of study. These disciplinary areas included synthetic biology, organismal biology, robotics, plants and soil science, biomanufacturing, nanobiotechnology, and biohybrid materials.

Over the course of the workshop, the cohort engaged in a series of activities designed to:

1. Share emerging research and knowledge as it related to commercialization of bio-inspired design
2. Generate ideas surrounding the challenges and opportunities for translating and commercializing bio-inspired design research
3. Develop concrete paths forward that engage a variety of approaches and applications in the realm of bio-inspired design toward commercialization
4. Build a sense of community and shared understanding across disciplines in bio-inspired design

Participants gathered for a welcome reception on October 3, in which they engaged in informal discussions. The organizers presented an overview of the workshop. The majority of activities occurred on October 4, 2022. Current research in team science argues that a successful brainstorming session will oscillate between two different activity phases: integration and differentiation (Wilson, Barley et al. 2020). Differentiation activities include periods of time to focus on different needs of stakeholder groups, while integration activities include periods of time to focus on similarities and convergence of ideas. This workshop was designed with the principles in mind. Table 1 highlights the overall structure of the workshop as it related to differentiation and integration of activities.

Table 1. Workshop Activity Structure

Activity	**Activity Phase**
Welcome and Opening Remarks	Integration
Affinity Group Discussion	Differentiation
Panel	Integration
Nominal Group Technique Activity	Differentiation > Integration
Working Lunch	Integration
Panel	Integration
Iterating Enablers Activity	Differentiation
Idea Presentations	Integration
Closing	Integration

In the first session, participants learned about the NSF Convergence Accelerator program and its goals. Then, participants had a conversation within their disciplinary clusters. Thus, in this activity, participants were divided into four main disciplinary groupings: a) Organismal Biology (6 participants), Materials (11 participants), Nanobiology and Cells (10 participants), and Synthetic Biology/Robotics (7 participants). Within these “affinity groups”, participants discussed a) the research questions and areas of inquiry that are important to their subdisciplines and b) what they bring to the table of bio-inspired design from their discipline's perspective. Each group then shared to the full cohort their disciplinary needs and strengths to help the whole cohort gain an understanding of the different disciplinary perspectives and priorities present in the room.

Following this affinity group discussion, the cohort heard from three panelists about their current efforts and successes in commercializing bio-inspired design work. The panelists included:

- Don Ingber, *Founding Director, Wyss Institute at Harvard University*
- Wallace Marshall, *Principal Investigator, Laboratory of Cell Geometry at University of California, San Francisco*
- Amy Herr, *Professor of Bioengineering, University of California Berkeley and Chief Technology Officer, Chan Zuckerberg Initiative*

In the second session period of the workshop, participants were divided into three groups of approximately 10-11 people each. They engaged in the nominal group technique process (Delbecq, Van de Ven et al. 1975, Potter, Gordon et al. 2004) to generate ideas around the prompt "what are the challenges and opportunities in translating and commercializing bio-inspired design research? In this activity, participants generated 110 ideas across the 3 groups. Participants then anonymously voted on the ideas that were a) most impactful for society and b) most immediately feasible or pressing to address. This voting procedure resulted in participants identifying ideas that were both impactful and feasible, creating a list of 34 enablers to seed more concrete ideas for immediate commercialization potential. The organizers worked to compile a list of these enablers for use in a later activity. During lunch, the participants were divided into new groups to share the ideas they were excited about and to continue discussions of potential ideas.

Figure 4. Organizations and Institutions for workshop activities. The workshop and follow-up virtual activities solicited input from researchers and technologists from academic institutions across the U.S. and internationally, as well as bio-design "foundries", non-profits, start-ups, industry boards, and government organizations.

A second panel followed the Nominal Group Technique session. Two sets of speakers presented their current research in bio-inspired design. The speakers included:

- Aimy Wissa, *Assistant Professor of Mechanical and Aerospace Engineering, Princeton University* and Marianne Alleyne, *Assistant Professor of Integrative Biology, University of Illinois at Urbana-Champaign*
- William Shih, *Professor of Biological Chemistry and Molecular Pharmacology, Harvard Medical School*, and Kate Amadala, *Assistant Professor of Genetics, Cell Biology, and Development, University of Minnesota*

In a final session, participants selected 6 of the 34 enablers and identified direct applications of these enablers in the realm of bio-inspired design that are ready for commercialization, including 20 short term (~3 years) commercialization ideas, 21 intermediate term (~5-10 years) commercialization ideas, and 15 long term (~15-20 years) commercialization ideas.

Following the workshop, participants continued to iterate on the short term ideas generated during the workshop. We present a few of these ideas below as indicators of the efficacy of bio-inspired design in commercialization.

B.3. Workshop and Follow-up Activities Participants. Invitees for the workshop were selected from a broad list assembled by NSF program officers in relevant units, the organizers, our external advisory committee, and suggestions from invitees who could not attend. At the workshop, the community identified sets of "platforms", high-level "tasks" that could be accomplished by such platforms, impactful "applications" of those tasks, and expected timeframes. As the workshop did not gather a fully representative subset of researchers working on a given platform, we wanted to reach additional experts needed to fill in specifics and use-cases. Therefore, we organized a series of follow-up surveys and virtual meetings in small groups of researchers working in roughly similar platforms. These follow-up activities sought to define the tasks and applications of those platforms, identify barriers to their success, and develop programs to help mitigate those barriers. For a full list of program participants, including name, institution, and type of participation (in-person, virtual/survey), see Appendix 1. Demographic information is presented here in Table 2.

Table 2. Participant Demographics

Institution Type	Number (%)
Academia	59 (84%)
Industry	5 (7%)
Government/Non-Profit	6 (9%)
Total	**70**

An important question is whether a potential Convergence Accelerator track in Bio-inspired design could draw sufficient participation from industry and government/non-profits, as this is absolutely critical for success in translation. While we received significant input and important feedback from our industry and government/non-profit partners in our workshop and follow-up activities, the fraction of such participants was lower than the organizing committee invited and anticipated. In follow-up conversations with potential industry/non-profit participants who were invited to the workshop but unable to participate, it became clear that the in-person nature of workshop was a significant barrier to their participation, which was an unintended consequence of that choice, and may be a useful consideration for future Convergence Accelerator workshops. In particular, invitees who declined cited the ubiquity of virtual workshops/meetings in industry, which made it more difficult to justify in-person travel/time-commitment, and also in some situations there were concerns that IP in start-ups might be contaminated by open discussions at a workshop focused on new ideas for translation-ready technologies.

However, there are concrete reasons to think that many more industry/government/non-profit participants would be interested and ready to partner within the more structured framework of a Convergence Accelerator. The very large number of startups and companies already involved in bringing bio-inspired technologies to market, as well as the number of government program (DARPA/IARPA) with programs in bio-inspired space – highlighted in section D of this report – indicate that the appetite for such partnerships is large and sustained. Moreover, bio-design foundries like the Wyss Institute report hundreds of commercial inquiries from diverse geographic locations about IP opportunities highlighted on their website [https://wyss.harvard.edu/technologies/], also suggesting the pool of potential industry participants is large. The community recognizes that these relationships must be leveraged and strengthened in a Convergence Accelerator track.

C. What are the tools and platforms in BioInspired design that enable unique tasks/functionality that are different from those delivered by other technologies?

Over the course of the workshop and subsequent discussions, participants identified a set of core, broad "platforms" – or cohesive sets of technology and scientific methodologies – that are emerging enablers of bio-inspired design work:

- Self-assembly, 3D nanofabrication, and improved 3D printing
- Synthetic biology (cell-free, engineered cells and synthetic cells) and organoid technologies
- Robotics and organismal biology, including collective behavior and swarms
- Novel materials design and manufacture
- Computational modeling and theory

Participants also emphasized that bio-inspired design has a unique power to generate new platforms as new biological mechanisms are discovered and harnessed.

The utility in identifying these platforms is two-fold. First, it allowed our community to identify subsets of researchers and industrial partners who are already talking or working together within a platform, and consider how approaches within a given platform enable convergent tasks or functionalities that can be important in applications across industries. It also enables us to discuss cross-platform tasks that are possible or most efficient when these disparate platforms are joined together.

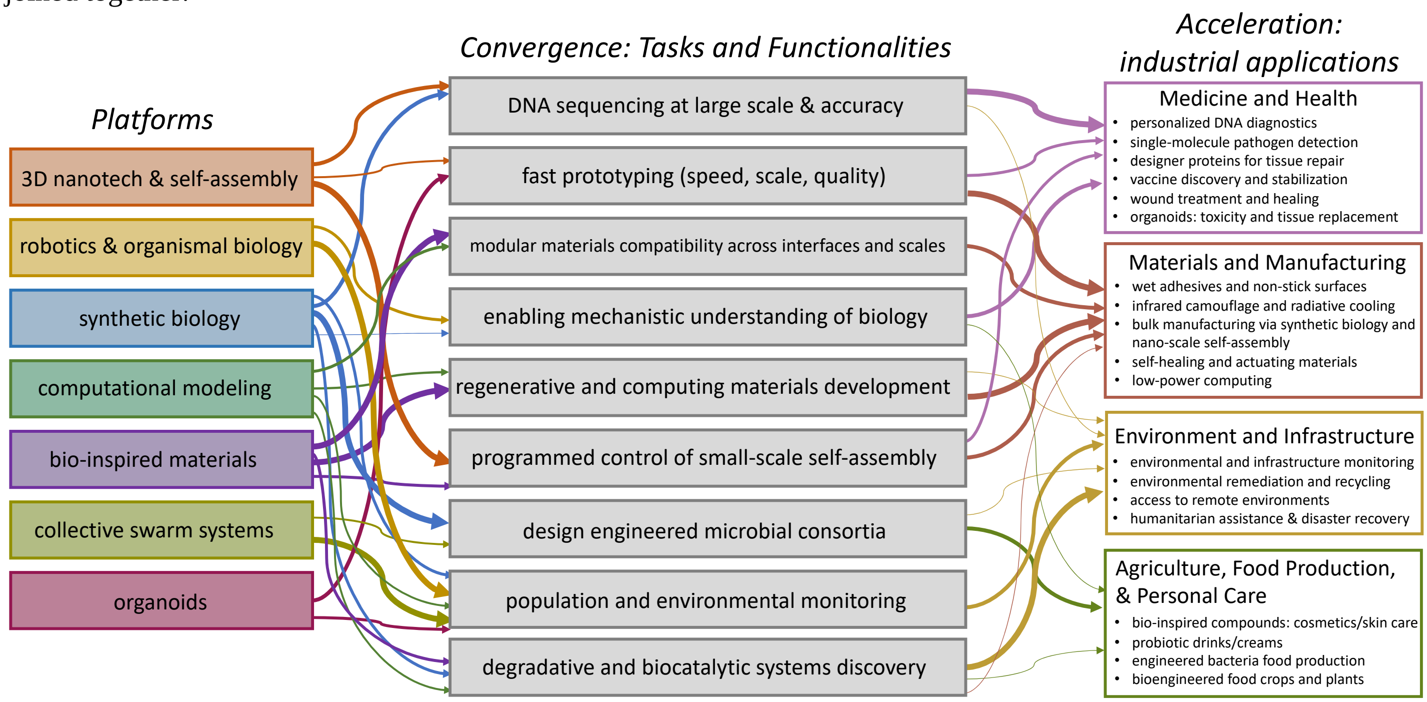

Figure 5. Workshop output highlighting bio-inspired platforms that enable convergent tasks/functionalities. These functionalities are primed for acceleration towards translation and applications in major industrial categories. Below, we detail how these tasks and functionalities have the potential to enable (or have already enabled) specific, market-ready use-cases of bio-inspired design.

At our workshop, participants highlighted a subset of convergent tasks or functionalities that they viewed as most important for bio-inspired design:

- Fast prototyping: increasing speed, scale, quality, and decreasing cost
- Interfacing across materials and facilitating modular materials compatibility
- Spanning scales from nano to micron, including in biological systems
- Enabling new understanding of biology: identifying new targets for therapeutics, and understanding mechanisms and development across species
- Developing materials and systems with specified/optimized functionality: regenerative, sensing, and self-healing, able to retain memories, compute, and evolve
- Discovery and engineering of degradative and biocatalytic systems
- Characterization of robustness and a framework for programmed control of nano- and micron-scale self-assembly
- Designing engineered microbial consortia and consortia of mixed live and synthetic cells
- DNA sequencing at large scale and accuracy
- Prediction of protein function based on sequence: improved accuracy and speed
- Comprehensive population monitoring for climate and environmental impact

In several cases, these tasks can be enabled by multiple platforms: for example, fast prototyping can be accomplished via self-assembly and synthetic biology approaches, with specific benefits and drawbacks depending on the specific application. In other cases, tasks are best accomplished by multiple platforms working together: for example, developing computing materials can be accomplished by a combination of methods from traditional materials science, self-assembly, and computational modeling.

By identifying these convergent functionalities, the emerging field of bio-inspired design can develop a concrete framework for identifying tradeoffs in using different platforms for a specified task, which sharpens analysis of market use and evaluating risk. In addition, it emphasizes similarities between different platforms, and in some cases suggests convergent approaches or new applications. Some of the new approaches may take advantage of the properties of living systems, particular their ability to evolve. Using Darwinian selection, synthetic living systems such as synthetic cells can potentially find solutions to complex problems that might not otherwise be found by design.

D. What will convergence and acceleration deliver to society? On what timeframe, with what level of risk?

This section focuses on specific industrial applications and societal use-cases that the bio-inspired design community views as achievable in a short timeframe (2-3 years).

We have highlighted four overarching industrial categories (1) medicine and health; (2) materials and manufacturing; (3) environment and infrastructure; and (4) agriculture, food, and personal care. In each category we enumerate several types of applications. Some we highlight are de-risked – they have an obvious market use and are quite likely to be brought to market in a 2-3 year timeframe under the guidance of a Convergence Accelerator program. We also enumerate applications that are high-reward and still need to be de-risked – the market value needs to be clarified and if so the project could be made ready for VC or follow-on/ non-profit/ DARPA/ IARPA funding in 2-3 years. It is clear that funders like DARPA and IARPA are already interested in this space; for example, in the past IARPA has funded industry participant Ginkgo Bioworks as part of their FELIX initiative (Intelligence Advanced Research Projects Activity 2023) and DARPA funded specific bio-inspired synthetic biology applications in their BRICS program (Defense Advanced Research Projects Activity 2023), so driving basic research towards these follow-on funding opportunities is reasonable and will drive societal impact.

Finally, we highlight recent success stories – examples where bio-inspired design has already brought a product to market or has leveraged follow-on funding – demonstrating the feasibility of this approach. Where appropriate, we also emphasize the convergent functionalities from Section C that enable these applications, to highlight that progress in one aspect of bio-inspired design can immediately impact multiple industries.

D.1 Medicine and Health. Perhaps it is not surprising that bio-inspired design enables better interfaces with cellular components (DNA, proteins), cells, tissues and organisms, which can in turn be harnessed for health and medicine.

At the smallest scales, several bio-inspired platforms could drive cheaper and more accurate DNA sequencing. One example is the creation of self-assembled, DNA-origami-based structures. The recent start-up Nanogami (Nanogami 2022) focuses on this technology and highlights its translational feasibility. The reduction in cost and size could eventually lead to hand-held DNA sequencers. Of course, the RNA-vaccines that altered the course of the COVID pandemic are another example of a technology designed by mimicking the behavior of viruses. An idea that is emerging from recent progress in the field of synthetic biology is developing RNA vaccines that turn themselves on or off depending upon signals from the patient's body, to help regulate their activity and prevent unwanted side effects. Such smart RNA vaccines would need to be de-risked, but would be high-reward because they may encourage more vaccine acceptance, and could potentially be de-risked enough to acquire follow-on funding in 3 years.

More generally, nanoscale self-assembly promises to transform sensing of small numbers of molecules inside cells (for diagnostics) or in built environments (for pathogen/toxin sensing in biochem/defense applications). Some approaches focus on ***enhancing specificity*** using nucleic acid sequence (hybridization), structure (aptamers), or patterning (origami). One example is DNA origami-assembled plasmonic nanodevices, which are promising for identifying individual molecules, with some research-use examples already commercially available (tilibit GmbH, gattaquant GmbH) (Dass, Gur et al. 2021). Other nano-fabrication approaches instead ***amplify the signal*** using self-assembly or optical effects. These types of advances could lead to auto-screening for disease, and because there is clear market use, the community expects translation in 2-3 years. The opportunities for translation in using this technology to detect pathogens or toxins are even more obvious. The company Palamedrix, spun out from Cal Tech, (SomaLogic 2022) has developed a multiplexed single-molecule detection biochip that uses precisely these technologies in “counting molecules to save lives”.

At a similar scale, synthetic biology approaches can be used to design custom proteins with a variety of attributes from different proteins found in nature. For example, one can design a protein that has the modules to form a material, such as silks, with a specific amount of stretch, like resilin, and cellular binding domains to support cellular penetration and growth. This could enable medical implant materials that are specifically tuned for tissue repair. Current biomaterials do not have the same localized precision that is possible using proteins. These are “easy” to make in lab, but the market needs to be de-risked and validated, so this is something that we expect could be developed for follow-on funding in a 3-year timeframe. Global application of protein-based biologicals, such as vaccines and antibodies, are currently limited in many cases by the need to maintain them at a cold temperature. One synthetic biology approach to solving this cold chain problem is to use intrinsically disordered proteins, such as those from tardigrades, to stabilize the vaccine or antibody.

Alternate approaches involve searching for biomolecules that have evolved within organisms to provide specific therapeutic functionalities, and adding those molecules to synthetic systems. Examples include the polysaccharide chitosan, which promotes blood clotting in animals, and can be synthesized at low cost and has been developed into a foam material for bleeding control that has been spun out into a company – Medcura (Medcura 2022) – and is available at drug stores. Other promising avenues for translation include plant-derived phenolic acids with antimicrobial and anti-inflammatory properties that can be incorporated into biomaterial scaffolds (Liu, Du et al. 2020).

On slightly larger scales, new techniques in self-assembly are just now allowing robust constructs on the scale of microns, instead of nanometers; at the workshop we heard some new results on multi-scale construction using DNA origami. This immediately opens up the opportunity to create micron-scale interfaces with biological cells for immune-engineering and vaccine applications, such as developing an artificial antigen-presenting cell, enabling the manufacture of artificial T-cells for therapeutics much more quickly and at lower cost than existing technologies. Given that the DNA and immune system components are well-established and commercialized, we expect this technology could also be delivered in a 3-year timeframe.

Synthetic cells represent another area of medical application at the size scale of microns. Potential applications include synthetic platelets that could sense injured vasculature and trigger coagulation to stop bleeding (previously explored by Allen Liu), synthetic blood cells to replace those that a patient may have lost, artificial antigen-presenting cells, and engineered synthetic cells that could circulate in the body and deliver toxins to tumors.

At even larger scales, the emerging field of designed synthetic organoids (*in vitro* constructs of one or more types of differentiated cells organized into complex tissues or organ-like structures) enables a host of other applications. “Organ-on-a-chip” technologies that allow for toxin screening or drug discovery are now well-established and have led to multiple start-ups. One example is “Emulate” (Emulate 2022) from Harvard/Wyss/Don Ingber. There is still additional room in this space for creating systems that are more physiological and higher throughput; several of our participants have recently received patents for developing new types of fluidic devices for culturing and interrogating organoids. In several cases, computational modeling of cells interacting with scaffolds has helped to optimize such structures and capture more physiological and morphological features, improving the accuracy of screening. Emerging areas that are primed for translation include evaluating the function of engineered muscle microtissues (heart, skeletal, uterine) and growing patient-specific organoids, both for drug screening or discovery. Several more recent examples of IP and spin off companies in this space include Trestle Biotherapeutics (Trestle Biotherapeutics 2022) for kidney tissue and Curi Bio (Curi Bio 2022) for muscle tissue, where the companies are able to use organoid platforms to accelerate the earliest stages of clinical testing of new medicines. Longer-term, organoid and tissue engineering approaches can also be used to both manufacture (e.g., using 3D printing) and to improve the growth of replacement tissues that address large defects from trauma or diseases like cancer.

Another emerging multi-cellular system is the use of engineered microbial consortia, where synthetic biology techniques are utilized to engineer strains of bacteria that can interact physically and biochemically with one another. By designing interactions and even spatial structures, it is possible to engineer specific functionalities into the cell collective. Although some high-impact applications (e.g., enhancement of metabolic functions) are still years from market, an application in fighting or preventing disease in the gut are on the cusp of translation. The company Synlogic (Synlogic 2022) is already creating engineered “smart” probiotics to treat metabolic diseases in the gut.

D.2. Materials and Manufacturing. In addition to being their own industrial sectors, materials development and manufacturing are key enablers of innovation in other sectors, including defense, infrastructure and the built environment, energy, and agriculture. Below we highlight bio-inspired design applications in several broad areas, including novel materials with structured surface properties, new methods for the bulk manufacturing of materials, and "active" materials that accomplish tasks such as computing, healing, or actuation. Where appropriate, we emphasize how these applications intersect with a much broader set of industries.

One area where bio-inspired design has already led to a large number of commercial products, with extensive opportunities for future impact, is developing nano- or micro-structured material surfaces that are inspired by biological systems. One set of examples are new types of adhesive or non-adhesive/non-wetting materials that are tunable, safe, and non-toxic, modeled on ubiquitous examples in organisms including mussels, geckos, and fish. Some utilize structure alone: a 3D printed adhesive device based on remora fish adhesion works on principles independent of length-scale, dry or wet, and on surfaces of nearly any roughness or compliance (Gamel, Garner et al. 2019). This could be developed for market in less than three years. Others use a mixture of chemistry and nano-structured components to change the wetting properties of surfaces, such as the superhydrophobic neverwet spray (NeverWet 2022) that functions as an anti-microbial, anti-stain, and anti-corrosion coating, as it allows water-based materials to slide over surfaces, using structures similar to those in organisms like lotus leaves and cicadas (Darmanin and Guittard 2015). Similarly, a collaboration between an organismal biologist and a polymer chemist led to the development of "Geckskin", an adhesive material modeled after Gecko adhesion (Geckskin 2022, UMass Amherst 2022), and a newly commercialized "sharklet" antimicrobial material is based on replicating features of sharkskin nano-structures. Future design ideas for antimicrobial materials include dynamic nanostructures based on scalable platforms like shape memory polymers that can change the surface topography and dislodge biofilms after passively sensing the presence of bacteria. Across many of these cases, a combination of organismal biology observation, computational modeling, and theory to optimize the design parameters, and materials science and manufacturing techniques (3D printing, polymer synthesis, nano-particle manufacturing) were necessary for product development. Clearly these types of materials have applications in other sectors, such as health and medicine, food packaging, consumer goods, construction, and infrastructure maintenance.

Another class of materials with interesting surface properties are bio-inspired infrared adaptive materials (Yang, Zhang et al. 2021). Many animals have evolved skin that modulates incident electromagnetic radiation to alter the reflected infrared spectrum, which is felt by humans as heat and also known as "thermal radiation", since most objects at room temperature emit infrared radiation. For example, cephalopods can camouflage themselves in the IR spectrum, based on changing nano-architectures via muscle cells that contract pigment cells. Several researchers have developed electronically driven thermal camouflage based on directly mimicking this architecture (Xu, Stiubianu et al. 2018), while others have developed graphene nanomaterials that use plasmonic resonance to manipulate electromagnetic radiation with similar effects (Salihoglu, Uzlu et al. 2018). We expect these and other thermal camouflage technologies could be made ready for funding from defense agencies and other follow-on funders in three years. A second application of infrared adaptive materials is radiative cooling, with applications in energy-efficient construction. Saharan silver ants possess micron-scale hairs that act as guides for electromagnetic radiation, reflecting visible light and emitting radiation in a regime of the infrared that is not easily absorbed by the atmosphere, which allows very strong cooling. With the significant advancements in nano-scale self-assembly platforms highlighted in Section C, it is possible to design structured surfaces with these radiative cooling capabilities, including already commercialized "cool roof" materials. Additional applications include personal thermal management devices and apparel.

In addition to surface modulation, another area where bio-inspired design can have high impact is the bulk manufacturing of materials – including new manufacturing methods for molecules that simply cannot be made at scale via other methods, or developing faster or more sustainable manufacturing processes. For example, a current barrier to DNA-based self-assembly technologies is the lack of ability to generate specific DNA sequences at sufficient scale. Recent bio-inspired advances in cell-free synthetic biology – where researchers exploit modularity to assemble genetic pathways that operate outside of cells – are enabling very large-scale manufacture of designer molecules such as DNA without onerous isolation and purification steps, and a Convergence Accelerator track could help companies that currently provide nucleic acids to biology researchers pivot towards using these scalable methods to target material science applications. Cell-free synthetic biology could also be used to generate other useful molecules at scale, such as engineered Polyhydroxyalkanoates (PHAs) that are widely used in the fields of tissue engineering and reconstruction due to their superior biocompatibility and biodegradation properties (Miu, Eremia et al. 2022).

Additional progress is being made in engineered or synthetic cells on sustainable methods to produce industrially relevant chemicals via pathways that do not require or produce toxic intermediates (e.g. products of petrochemicals, see cosmetics example in Section D.4 below), and also allow manufacture at the point-of-use to avoid transport and allow production on demand. One such example is the manufacture of specific polysaccharides that can be turned into sustainable packing materials (Zhao, Li et al. 2021). Another set of examples, discussed in section D.4 below, are cell-based approaches for manufacturing components of food and cosmetics. An example with the potential for very high societal impact is recent work focused on developing so-called “dairy-farm” bacteria systems to generate biofuels and reusable fuels. At the workshop, we heard from a speaker who had developed a promising synthetic biology candidate microbe for manufacturing biofuel, and secured venture capital funding in this space, but a dramatic drop in overall fuel prices due to expansion of fracking and natural gas squeezed the market and vacated the initial market analysis. A Convergence Accelerator track could help researchers working on these technologies identify market opportunities where bio-inspired features – such as sustainability or ability to manufacture the fuels at point-of-use – allow these products to outcompete other platforms.

Part of the challenge of using cells to produce value products is the regulatory issues surrounding containment. By using synthetic cells that mimic biochemical activities of real cells, but are not alive and cannot replicate, many of these hurdles could be avoided.

One obvious feature of living systems that is not strongly featured in the previous paragraphs is the ability of the materials that comprise living systems to take in energy at small scales (e.g. via ATP) and use that energy to create adaptive, active, regenerative materials – in other words, materials that natively perform functions. While these materials are mostly at earlier stages along the translation pipeline, their potential is so highly transformative that we think that under the auspices of a Convergence Accelerator track they could be driven to the point of securing follow-on funding in 2-3 years, especially from programs like DARPA/IARPA.

One category of materials now under development are self-healing self-assembled materials: microscale and nanoscale responsive nanostructured materials with active defect and damage repair mechanisms, based on DNA and peptide nanoengineering at the intersection of the synthetic biology and self-assembly platforms (Chen, Zhong et al. , Le Feuvre and Scrutton , Tang, An et al.). A second category of active bio-inspired materials are actuators for soft robotics or medical applications. Some of these are composed of engineered organoids or tissue constructs (Park, Gazzola et al.), while others are developing synthetic actuators with high power density inspired by animal muscle (Kim, Choi et al.).

A third category is developing materials that can perform computing tasks with low power consumption. This is especially important for reducing energy consumption and climate impact, as artificial neural networks are being used for a rapidly expanding number of AI applications, but when run on traditional computing architectures they require enormous power compared to, for example, animal brains. Optical neural computing is promising since it can be performed passively with minimal energy consumption. It also promises a fast speed, operating at the speed of light. More importantly, its intrinsic parallelism leads to greatly enhanced computing throughput. The significant obstacle for realization of these ideas is limited methodology to form optically active 2D and 3D materials with desired properties that can support computation, and one very promising approach is the DNA-programmable nanoscale self-assembly platform.

For example, the standard lithographic approach for manufacturing photonic integrated circuits cannot control material composition at small scales, resulting in performance degradation. Instead, linear transformation layers or nonlinear activation layers in the photonic integrated circuit could be replaced with a precisely assembled nanoparticles structure designed to function as a scattering medium. A longer-term, but completely transformative approach would be to design 3D nano-media to perform a variety of prescribed computations on a physical level, for example, to perform a matrix multiplication or to realize recurrent neural networks. Although the DNA-based assembly methods have demonstrated an ability to form structures relevant for these new optical computational modalities, it is not known yet how to co-design optical and structural properties, how to establish practical DNA assembly methods for targeted fabrication of optical circuits, and how to integrate different processes and mitigate imperfections. Understanding this design space to de-risk this application could be an important output of a Convergence Accelerator track.

D.3. Environment and infrastructure. In this section, we highlight how bioinspired technologies can have a direct impact on the environment and infrastructure within the next two to three years. These impacts are feasible due to advances in bioinspired areas such as sensing, actuation, materials, locomotion, collective behavior, motion planning, and self-healing, as well as an improved understanding of physiology, morphology, and biomechanics. Integrating these fields have direct applications for the environment and infrastructure.

Several companies produce and showcase bioinspired robots for environmental and infrastructure monitoring. Companies such as Boston Dynamics, Festo, and Ghost robotics, to mention a few, have successfully demonstrated bioinspired robots that rely on various natural locomotion strategies. These companies have collaborated with universities and academic institutions to leverage fundamental advances in sensing, actuation, and control strategies. However, most of the robots currently on the market would be considered locomotion specialists, which limits the environments and scenarios in which these robots can be deployed. Thus, one aspect that a bioinspired design Convergence Accelerator can assist in developing in the next two to three years is locomotion generalists that can access any environment. An example of such a system is the multi-legged robot developed by Ground Control Robotics for weed control (Ground Control Robotics 2022).

Additionally, recent advances in swarm robotics, collective behavior, motion planning, and AI can be leveraged, through a Convergence Accelerator, to deploy a swarm of low-cost autonomous robots for environmental monitoring and infrastructure inspection. A recent collaboration between Rolls Royce and the Wyss Institute showcase that swarm robotics is ready for translation to applications such as engine inspections as an example of critical infrastructure monitoring (Rolls-Royce 2022).

Developing and deploying such examples of non-humanoid, small, cheap, networked autonomous systems can enable real-time adaptive environmental monitoring. Such systems can collectively adjust their behavior to both disperse and converge in location in response to diurnal, seasonal, and longer period shifts in gradients that demarcate environmental information such as tide flux, temperature mosaics, and species movements.

Another environment that would especially benefit from bioinspired systems is the ocean. Recent advances in underwater robotics and systems enable us to survey the oceans, map the ocean floor and track marine life in exciting new ways that are now possible because of recent advances in soft robotics, additive manufacturing, and bioinspired adhesion. The remora adhesive discussed above in Section D.2 is long-term and reversible, making them suitable for animal tracking and underwater environmental monitoring (Lee, Song et al. 2019).

In addition to environmental and infrastructure monitoring, bioinspired systems can directly impact remote environment exploration and search rescue. A success story for a bioinspired search and rescue system is the snack-inspired robot that worked collaboratively with emergency personnel to search the rubble of an earthquake in Mexico for survivors (Hutson 2017). Bioinspired systems can also aid in remote environmental exploration, such as in space or deep into the ocean. For example, NASA has relied on several bioinspired strategies to develop drillers and robots for planetary exploration (Borgatti and Love 2019).

Finally, the platforms and convergent functionalities identified in Section C can have a tremendous impact on mitigating climate change by remediation and reducing waste. Cleaning the air or the ocean faster than we foul it is currently too expensive. However, AI has proven that it can create self-replicating biobots: mm-sized machines built solely from biological components that can build copies of themselves, do useful work along the way, and naturally "die" and degrade back into biomass. Such carbon neutral, biocompatible and biodegradable exponential technologies—technologies that do increasing amounts of useful work as they spread—may completely rebalance the economics of remediating environments at scale, safely, and economically. This would enable targeted biodegradation/bioremediation for landfills/oceans.

Another area in waste remediation and recycling involves water reclamation. Tools from synthetic biology can be used to create microbes that upcycle simple inputs into high value products for waste stream conversion. Synthetic biology can also be used to build and enhance metabolic pathways in non-standard microorganisms to upcycle waste streams. Such tools need further development. However, a bioinspired Convergence Accelerator with a theme in environmental remediation and recycling can help build infrastructure to scale these tools for deployment at later stages.

Institutes and non-profits are also recognizing the potential impact of bio-inspired technologies on the environment. Less than two months before our workshop, the biomimicry institute announced a new cohort of bioinspired startups participating in the Ray of Hope Prize program. Common to all these startups is how they are translating various bioinspired technologies for a societal impact related to the environment—including inventing higher-performing and more sustainable renewable energy systems, reducing food waste, and solving the plastic waste problem (Biomimicry Institute 2022).

D.4. Agriculture, food production, and personal care. Bio-inspired design has already begun to transform aspects of our everyday lives, ranging from making the food we eat more sustainable and resistant to effects of climate change to creating new paradigms for personal care products such as cosmetics and probiotics. As highlighted below, a Convergence Accelerator track would allow the field to build on these initial commercial successes to drive paradigm-changing technologies in these sectors.

Cosmetics and skin care represent a fertile space for bio-inspired design. One path forward is identifying molecules or nanostructures in biological organisms that help protect them from environmental hazards, and then developing and validating cosmetics and personal care products that contain that molecule. For example, a chemical biologist studying cephalopods identified a biochrome in those organisms that acts as a UV-filter, and created a spin off company, Seaspire Skincare, to develop sunscreens and other products based on that technology (Creason 2022). Another approach is to take advantage of the microbial consortia that already live on the skin and develop an engineered microbial treatment that could potentially address skin conditions like acne or provide moisturizers. A generic "skin probiotic" could likely be brought to market quite quickly. Longer term, one could envision developing custom-engineered microbial consortia for individual patients that are tailored to address imbalances in their skin, and can react in different ways over time or space. One could even imagine synthetic biology approaches that allow microbes to manufacture the bio-inspired protective molecules discussed above in response to environmental features like UV light.

Engineered microbial consortia could also be used in more traditional probiotic applications for gut health. In addition to developing improved over-the-counter probiotic drinks and supplements, researchers are developing tailored engineered probiotics to address specific conditions. One example is a hangover prevention drink made from engineered microbes from the company ZBiotics (ZBioitics 2022). Another set of examples in personal care are technologies that use synthetic biology techniques to generate "clean" versions of the chemical and raw materials used in beauty and cosmetics. Most of those products traditionally have components based on petrochemicals, which some consumers would prefer to avoid and are willing to pay significantly more to do so. One such example is technology from the new company Amyris, which uses a synthetic-biology-based lipid platform to produce cosmetics.

In the agricultural and food sectors, bio-inspired design platforms are replacing animal-based food production and its associated significant energy and environmental impacts with microbial production. They are also engineering new types of plants that can be farmed more sustainably.

In food production, multiple companies have used the "dairy farm bacteria" paradigm discussed in Section D.2 above to generate food proteins at scale. Examples include "Impossible Foods" for proteins responsible for taste and color in meat that are used in plant-based meat replacements, "Perfect Day" that produces milk proteins for vegan milk replacements, and "Geltor" that produces engineered plant-based gelatin. These are all examples where animal-based foods that are energy-intensive to produce can be replaced with plant-based alternatives that are likely to have less impact on the environment, and also fill a market niche for those who choose not to consume animal products. An exciting recent twist on these ideas are microbe-based processes that act as a carbon sink to remove greenhouse gasses. One such example is the start-up Circe (Wyss Institute 2022), which uses an engineered microbe-based fermentation process that takes in CO_2 and produces food-grade fats.

In agriculture, there are many opportunities for synbio engineered plants. One example is low-maintenance plants (which can be crops or also ornamentals like grass) that rely less on chemically enhanced soils and pesticides. These could prevent fertilizer run-off pollution, which is a major environmental impact. In general, some of the new tools developed within the synthetic biology platform could improve a wide variety of plant biotech goals: creating plants that require less water, crops with more nutrients, and biofuel candidates that are easier to process sustainably.

E. What are the opportunities for track integration activities? These include activities related to education, training, diversity and inclusion, workforce development, and public policy to address barriers to bio-inspired technology translation and acceptance by society.

E.1 Exporting best practices for translation from existing "bio-design foundries". As discussed in the introduction, it is clear that there are a few "foundries" in the space of bio-inspired design, such as the Wyss Institute and Chan-Zuckerberg Biohub, that have figured out how to make academic-industrial translation work well. These organizations are responsible for a large number of patents, start-ups companies, and licensing agreements that have driven new products and societal impact. While we would like to export these best practices to other institutions across the U.S., a challenge is that the existing foundries are extremely resource intensive, utilizing hundreds of millions of dollars in investment from private donors. Simultaneously, there are a few isolated "breakout" academic groups and individual PIs who have managed to be remarkably successful in translation of bio-inspired ideas despite more limited resources. Therefore, one of the proposed track integration activities for our accelerator will be focused on supplementing established Convergence Accelerator techniques to enhance translation with best practices from foundries and "breakout" faculty in bio-inspired design, and then assessing which interventions are most effective.

Some possible interventions include:

- *A student-based market analysis based on the successful UCSF Catalyst intern program:* Developing institution-specific small teams of students, drawing from science and business backgrounds, assigned to faculty to help put together a target product profile document in which the competitive landscape and commercialization potential can be researched and documented to help institutional technology transfer offices understand the development and file IP on it.
- Identifying appropriate, interested industry partners is perhaps the largest hurdle this area faces in bringing novel solutions to market, and some field are far ahead of others in integrating industry partners into academic interactions. For example, professional meetings in the field of Chemistry are fully integrated between industry and academia and can serve as a template for this Convergence Accelerator- students attending an ACS meeting expect to meet with industry scientists there, industry scientists routinely attend ACS. Academic chemists also regularly give seminars and consult at large industrial campuses (e.g., Pfizer in Groton, Connecticut). This is largely not the case for meetings outside the field of Chemistry. Similar industrial visit relationships are also not the norm. Track integration activities could include training sessions for participants and trainees around choosing meetings that have a significant industry presence, and how to productively engage and network with industry scientists at meetings. Possible examples are Materials Research Society and the ACS/FDA Innovations in Active Food Packaging meeting.
- University technology transfer offices are generally effective at intellectual property disclosure and patent filings, but lack the detailed knowledge and extensive resources necessary to quickly and efficiently license these patents. (This is a major advantage at the foundries). The Convergence Accelerator could provide resources to pay staff (possibly serving across multiple institutions) for license research and execution for intellectual property resulting from this effort, and create a model for more efficient licensing from universities more generally.
- One challenge that has been repeatedly identified in both synthetic biology and synthetic cell areas is the need for standardization of parts, both to facilitate design and address regulatory concerns. This is an area where approaches from large foundries could be scaled to the entire field with a potentially large impact. More work is needed to define the gaps in current supply chain and define needs of a synthetic cell foundry.

E.2 Advancing education and workforce development. A key challenge for the Convergence Accelerator is that existing and emergent bio-design foundries, as successful as they are, are still too few to significantly scale up the global rate of moving from the recognized problems and solutions found in biological systems to products ready for the marketplace. In addition to distilling, adapting, and disseminating process models of innovation from existing foundries, the accelerator should also invest in nurturing and connecting isolated clusters of bio-design training and education. For example, at least a dozen colleges and universities (including some that participated in the workshop – e.g., Berkeley, Syracuse, Akron, Northeastern, Minnesota, MIT, Georgia Tech, and UIUC, as well as others that have not – e.g., Arizona State, Fresno State, Mesa CC, NMSU, Cleveland State) have launched undergraduate courses and certificate/training programs in bio-inspired design, developed interdisciplinary bio-inspired design co-ops, fellowships, and internships at the undergraduate and graduate levels. Investment by the Convergence Accelerator will pay large dividends in propagating bio-inspired design among not only scientists, engineers, designers and other 'makers', but also more broadly to consumers who will welcome and expect rather than be ignorant to or afraid of new bio-inspired design products and technologies. The importance of such investments cannot be ignored because it is the critical human capital for both the supply and demand of what foundries will produce. Leveraging a **network approach** to connect clusters across the country can yield rapid results (within 3-5 years) commensurate with the time horizon of a Convergence Accelerator, producing curricula and pedagogy that can be exponentially amplified through expanding the network. Existing foundries will not only provide case study and ongoing inspiration, but they can also directly draw on new talent that is more diverse and distributed than any they currently have access to now. This vision is consistent with addressing some of the barriers and challenges identified in the workshop and in follow-up interviews of participants associated with multiple platforms:

- Dearth of training modes and models for students and faculty
- Successful, but isolated and limited sharing of best practices and approaches such as co-ops, classes, internship and fellowship platforms
- Lack of models for academic-industry partnership in training and education in areas such as
  - Intellectual Property Strategy
  - Technology translation, including technical and commercial de-risking
  - Interdisciplinary and cross-sector communication
  - Industrial R&D vs. Academic Research
  - Market research and market pull
  - Biological system inspiration and solutions in search of problems

E.3 Advancing Diversity, Equity, and Inclusion in Bio-inspired Design. The network approach described above in Section E.2 above can be leveraged to include a specific focus on recruiting additional institutional members to address gaps in representation in the field of bio-inspired design. Indeed, building and cultivating authentic, representative partnerships among the educational network would be key to achieving the desired impacts across an Accelerator track. Intentional outreach to bio-inspired programs or adjacent programs at Minority-Serving Institutions (MSIs) will both grow the network and–because diverse teams are more likely to explore more diverse solutions to issues–expand the scope of problems identified and addressed by Bio-Inspired Design practitioners. Examples of MSIs with research interests that intersect with our theme include Hampton University (strength in Biomaterials, partnerships with Brandeis University's BioInspired Soft Materials Center and Syracuse University's BioInspired Institute), North Carolina A&T (Strength in physics and materials, Partner with SU BioInspired).

Overall efforts would aim to solve documented systemic problems of recruitment, retention, graduation, and placement for domestic Black, Indigenous, and Latina/o students by creating pathways between Primarily-White Institutions (PWI), and MSIs. We would seek to break down well-documented policies/practices that prevent Black, Indigenous and Latina/o students from accessing and persisting in STEM undergraduate and graduate programs. Barriers include lack of pre-college experiences in which students can form a STEM identity (Carlone and Johnson 2007, Robinson, Perez et al. 2018, Chen, Binning et al. 2021), academic admissions policies rooted in exclusionary practices that fail to account for students' unique strengths and circumstances (President's Council of Advisors on Science and Technology (PCAST) 2012, Chen 2015, Castellanos 2018), and lack of coordinated campus-based supports available to students through their undergraduate and graduate-level education (Morganson, Major et al. 2015, Provencher and Kassel 2017), in particular a supportive cohort of peers and research and classroom experiences with faculty who are trained in inclusive pedagogical and mentoring practices (Kates 2011, Ceyhan, Thompson et al. 2019, Sto Domingo, Sharp et al. 2019). The proposed theory of change for this track integration activity is based on leveraging the insights afforded by institutional theory as applied to higher education to disrupt standards and processes within organizations, to study and remedy commonalities, to identify and learn from those barriers that are in fact institution or PWI/MSI specific, and to simultaneously forge lasting, equitable scholarly, educational, and workforce relationships between MSIs, PWIs, and industry partners.

Activities must not increase the flow of younger students into a broken Bio-Inspired Design pipeline, but rather must fix the pipeline itself beginning with undergraduate matriculation through training and into successful careers. A nationwide, convergent approach would (1) re-envision and redesign the pipeline from K-12 to higher education to ensure equity in the preparation and retention of students for undergraduate and, eventually, graduate programs; (2) redefine admissions policies; (3) create career-supporting, career-spanning mentoring and peer networks for students independent of their major program, department, and institution; and (4) build stronger and sustainable research collaborations between MSIs and PWI faculty so that they can effectively engage students in research and professional development, leading to an increase in student motivation, retention, and advancement in STEM fields, including bio-inspired design.

Periodic feedback mechanisms (annual meetings, quarterly updates, pedagogical publications, etc.) among Educational Network participants would ensure that best practices are shared broadly. Beyond pedagogy, a bio-inspired design Accelerator would prioritize the dissemination of methods for inclusive recruitment, retention, and teaching among its partners. These would include those from industry who host interns and co-op trainees. One example effort could be a specific focus on recruitment efforts on conferences for URM researchers (e.g. Annual Biomedical Research Conference for Minority Students, SACNAS NDiSTEM, National Society of Black Physicists Annual Conference, etc.).

E.4 Exploring Bioethics and enhancing science communication. Several bio-inspired design platforms involve subjects that are potentially sensitive to negative public perception. The broad rejection of genetically-modified organisms in foodstuffs in Europe, for example, shows the public's general squeamishness of "playing God" with biology, at least when it involves a product so intimately linked to the end user as food. Several applications described in Section D, above, potentially push this limit even further. For example, designed organoids, or especially artificial organs grown exogenously on host animals (Nagashima and Matsunari 2016, Lu, Zhou et al. 2019), present acute challenges to a public skeptical of engineered biological systems. Even greater concerns may apply with synthetic cells, if they have the ability to self-replicate. There is potential public concern with the entire concept of creating life, as well as concerns about containment.

This presents an opportunity for the Bio-Inspired community to focus on public outreach and science communication strategies, areas already emphasized by the public health discourse during the last several years of the COVID pandemic. Besides integrating outreach activities into the organizations participating in an Accelerator track, science communication could play an additional key role in the educational and pedagogical outputs in the Section E.2. Too few educational programs across virtually any STEM fields emphasize communication with the public. This is despite an increasing recognition that scientific experts must play a larger role in the public discourse about science, medicine, and society. Thus, bio-inspired design educational network programs would include content specifically related to science communication. Importantly, this focus area would help drive convergence of disparate fields by equipping specialized practitioners the tools needed to communicate with others across disciplines.

In addition, the network would provide opportunities for sustained discussions with bioethicists to identify issues in bio-inspired design that may raise bioethics concerns and develop a framework for addressing them. We envision collaborations with foundations that support bioethics research (e.g. Greenwall Foundation, Pew, Templeton) to develop workshops, panel discussions, and reports pertinent to specific platforms and technologies.

E.5 Explore creation of a national policy office to develop public policies and regulations. Like the National Nanotechnology Coordination Office (NNCO), bio-inspired design may need a central, federally-operated office to coordinate policy, regulatory authorities, and core user facility networks across the country. Like the NNCO, a bio-inspired design coordinator would employ a set of informal mechanisms to support interagency discussions, stakeholder engagement, and/or the development of activities focused on specific bio-inspired design topics. Communities of interest would support and build interagency engagements in priority areas. Designated liaisons would interface with related Federal groups to share information across activities and connect synergistic activities. Coordinators in key areas would serve as points of contact both inside and outside of the Government, and to actively coordinate interagency efforts. Additional Federal stakeholders would include:

- National Institutes of Health: basic research, translation and clinical expertise, biological characterization tools
- FDA: medical regulatory
- NIST: standards (where appropriate), materials characterization tools
- NSF: basic research, characterization tools
- DoD: basic and applied research, use-case needs
- DOE: basic and applied research, characterization tools
- EPA: environmental regulatory, basic research
- Small Business Administration: SBIR/STTR, technology transfer
- Commerce: technology transfer, business regulatory
- State: international regulatory
- OSTP, NSTC: Federal-wide priorities
- USPTO: intellectual property policy

This possible coordination office is given additional impetus from the recent Executive Order on enhancing biotechnology and biomanufacturing in America (Office of the President of the United States of America 2022). Though the phrase "bio-inspired design" does not appear in the EO, many platforms and applications identified in this report are directly related to issues raised by it, including synthetic biology, biomanufacturing, ethics, training, and improving the National ecosystem for translating research into societal impact.

F. Conclusions. Bio-inspired design – *the process of developing concepts, approaches and technologies that build and control the way nature does* – is convergent and primed for acceleration into translation and commercialization. While some Convergence Accelerator tracks focus attention on a specific societal need, this document demonstrates that bio-inspired design encompasses a coherent and evolving set of science and technology platforms that have a unique power to address a host of our most pressing societal and national security needs. We highlight how a Convergence Accelerator track in bio-inspired design could bring products to market in a short timeframe that address needs such as sustainable food systems, manufacturing, and energy sources, carbon footprint reduction and pollution remediation, novel therapeutics for disease and novel materials for defense and improved quality of life. To emphasize feasibility of translation, we also highlight recent examples where bio-inspired design has already led to commercialized products, and emphasize that there is vast untapped potential that could be unlocked by targeted initiatives to drive translation.

Appendix 1. Convergence Accelerator Workshop Participants

First name	Last name	Institution	Title	In-Person	Virtual Session	Survey
Kate	Ademala	University of Minnesota	McKnight Land Grant Professor Assistant Professor of Genetics, Cell Biology, and Development	x	x	
Marianne	Alleyne	University of Illinois Urbana-Champaign	Assistant Professor of Entomology	x		
Josh	Bongard	University of Vermont	Professor of Computer Science			x
David	Breslauer	Bolt Threads	Chief Technology Officer and co-founder			x
Howie	Choset	Carnegie Mellon University	Professor of Robotics, Biomedical Engineering, and Electrical & Computer Engineering			x
James	Collins	Massachusetts Institute of Technology	Termeer Professor of Medical Engineering and Science	x		
Noah	Cowan	Johns Hopkins University	Professor of Mechanical Engineering			x
Hugh	Crenshaw	Physcient Surgical	Chief Executive Officer and co-founder			x
Bianxiao	Cui	Stanford University	Job and Gertrud Tamaki Professor of Chemistry		x	
Jamie	Davies	University of Edinburgh	Professor of Experimental Anatomy & Dean of Education			x
David	Deamer	University of California Santa Cruz	Research Professor of Biomolecular Engineering		x	
Douglas	Densmore	Boston University	Professor of Electrical and Computer Engineering and Biomedical Engineering		x	
Leila	Deravi	Northeastern University	Assistant Professor of Chemistry and Chemical Biology, Barnett Institute for Chemical & Biological Analysis	x	x	
Michael	Dickey	North Carolina State University	Camille and Henry Dreyfus Professor of Chemical and Biomolecular Engineering		x	
Shawn	Douglas	University of California San Francisco	Associate Professor of Cellular and Molecular Pharmacology		x	
Steven	Evans	BioMADE	Senior Technical Fellow	x		
Frank	Fish	West Chester University	Professor of Biology			x
Brooke	Flammang	New Jersey Institute of Technology	Associate Professor of Biological Sciences	x		x
Elisa	Franco	University of California Los Angeles	Associate Professor of Mechanical and Aerospace Engineering and Bioengineering	x		

Robert	Full	University of California Berkeley	Professor of Integrative Biology			x
Deborah	Fygenson	University of California Santa Barbara	Professor of Physics and Biomolecular Science & Engineering	x	x	
Kate	Galloway	Massachusetts Institute of Technology	W. M. Keck Career Development Professor in Biomedical Engineering	x		
Oleg	Gang	Columbia University	Professor of Chemical Engineering and of Applied Physics and Materials Science	x	x	
Austin	Garner	Syracuse University	Assistant Professor of Biology		x	
Mattia	Gazzola	University of Illinois Urbana-Champaign	Assistant Professor of Mechanical Science & Engineering	x		
John	Glass	J. Craig Venter Institute	Professor and Leader of the Synthetic Biology Group		x	
Wendy	Goodson	Gingko Bioworks	Senior Director of Business Development - Government	x		
Karmella	Haynes	Emory University School of Medicine and Georgia Institute of Technology	Associate Professor of Biomedical Engineering			x
Amy	Herr	Chan Zuckerberg Initiative and University of California Berkeley	John D. & Catherine T. MacArthur Professor of Bioengineering	x		
Manju	Hingorani	National Science Foundation	Program Manager	x		
India	Hook-Barnard	Engineering Biology Research Consortium (EBRC)	Executive Director	x		
Donald E.	Ingber	Harvard University	Judah Folkman Professor of Vascular Biology at Harvard Medical School and the Vascular Biology Program at Boston Children's Hospital	x		
Duncan	Irschik	University of Massachusetts Amherst	Professor of Biology	x		
Daniel	Koditschek	University of Pennsylvania	Alfred Fitler Moore Professor of Electrical & Systems Engineering			x
George	Lauder	Museum of Comparative Zoology, Harvard University	Henry Bryant Bigelow Professor of Ichthyology			x
Luke	Lee	Brigham and Women's Hospital	Professor of Medicine	x		
Tim	Liedl	Ludwig-Maximilians Universität Münich	Professor of Experimental Physics		x	
Allen	Liu	University of Michigan	Associate Professor of Mechanical Engineering and Biomedical Engineering		x	
John	Long	Vassar College	John Guy Vassar Chair and Professor of Biology and Cognitive Science			x
Zan	Luthey-Schulten	University of Illinois Urbana-Champaign	Murchison-Mallory Endowed Chair in Chemistry		x	

Nikhil	Malvankar	Yale University	Associate Professor of Molecular Biophysics and Biochemistry	x		
Lisa	Manning	Syracuse University	William R. Kenan, Jr. Professor of Physics	x		
Wallace	Marshall	University of California San Francisco	Professor of Biochemistry and Biophysics	x		
Ibrahim	Mohedas	National Science Foundation	Program Manager	x		
Mary Beth	Monroe	Syracuse University	Assistant Professor of Biomedical and Chemical Engineering	x	x	
David	Mooney	Harvard University	Robert P. Pinkas Family Professor of Bioengineering	x		
Talia	Moore	University of Michigan	Assistant Professor of Robotics			x
Leonardo	Morsut	University of Southern California	Assistant Professor of Stem Cell Biology and Regenerative Medicine, Keck School of Medicine; and of Biomedical Engineering, Viterbi School of Engineering	x		x
Richard	Murray	California Institute of Technology	Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering		x	
Peter H.	Niewiarowski	University of Akron	Professor of Biology	x	x	
Luisa	Ruge-Jones	University of Dayton	Assistant Professor of Communication	x		
Rebecca	Schulman	Johns Hopkins University	Associate Professor of Chemical and Biomolecular Engineering		x	
Shashank	Shekhar	Emory University	Assistant Professor of Physics		x	
William	Shih	Harvard Medical School	Professor of Biological Chemistry and Molecular Pharmacology; and of Cancer Biology, Dana-Farber Cancer Institute	x	x	
Pam	Silver	Harvard University	Elliott T. and Onie H. Adams Professor of Biochemistry and Systems Biology	x		
Emilie	Snell-Rood	University of Minnesota	Associate Professor of Ecology, Evolution, and Behavior	x		
Simon	Sponberg	Georgia Institute of Technology	Dunn Family Associate Professor of Physics and Biological Sciences			x
Jeremy	Steinbacher	Syracuse University	Director of Operations, BioInspired Institute	x	x	
Hannah	Stuart	University of California Berkeley	Don M. Cunningham Endowed Professor of Mechanical Engineering			x
Devi	Stuart-Fox	University of Melbourne	Associate Professor of Biosciences			x
Cynthia	Sung	University of Pennsylvania	Gabel Family Term Assistant Professor of Mechanical Engineering and Applied Mechanics			x
Alison	Sweeney	Yale University	Associate Professor of Physics and of Ecology and Evolutionary Biology	x	x	

Rebecca	Taylor	Carnegie Mellon University	Associate Professor of Mechanical Engineering	x		x
Michael	Travisano	University of Minnesota	Distinguished McKnight University Professor of Ecology, Evolution, and Behavior		x	
Amy	Wissa	Princeton University	Assistant Professor of Mechanical and Aerospace Engineering	x		
Peng	Yin	Harvard Medical School	Professor of Systems Biology	x		
Teng	Zhang	Syracuse University	Assistant Professor of Mechanical and Aerospace Engineering			x
Marika	Ziesack	Circe Bioscience	Chief Technology Officer and co-founder			x
Laurie	Zoloth	University of Chicago	Margaret E. Burton Professor of Religion and Ethics		x	

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