Integrative and Comparative Biology

Integrative and Comparative Biology, volume 62, number 5, pp. 1147–1152
https://doi.org/10.1093/icb/icac143

Society for Integrative and Comparative Biology

SYMPOSIUM INTRODUCTION

Best Practices of Bioinspired Design: Key Themes and Challenges

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From the symposium "Best practices for bioinspired design education, research and product development" presented at the annual meeting of the Society for Integrative and Comparative Biology annual meeting, January 3-7, 2022.

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Synopsis Bioinspired design (BID) is an interdisciplinary research field that can lead to innovations to solve technical problems. There have been many attempts to develop a framework to de-silo engineering and biology and implement processes to enable BID. In January of 2022, we organized a symposium at the 2022 Society of Integrative and Comparative Biology Annual Meeting to bring together educators and practitioners of BID. The symposium aimed to (a) consolidate best practices in teaching bioinspiration, (b) create and sustain effective multidisciplinary teams, (c) summarize best approaches to conduct problem-based or solution-driven fundamental research, and (d) bring BID innovations to market. During the symposium, several themes emerged. Here we highlight three critical themes that need to be addressed for BID to become a truly interdisciplinary strategy that benefits all stakeholders and results in innovation. First, there is a need for a usable methodology that leads to proper abstraction of biological principles for engineering design. Second, the utilization of engineering models to test biological hypotheses is essential for the continued engagement of biologists in BID. Third, there is a necessity of proven team-science strategies that will lead to successful collaborations between engineers and biologists. Accompanying this introduction is a variety of perspectives and research articles highlighting best practices in BID research and product development and guides that can highlight the challenges and facilitate interdisciplinary collaborations in the field of BID.

Introduction

Academic institutions and funding agencies are increasingly aware that interdisciplinary research is essential for solving society's most intractable research and engineering problems. A prominent example of interdisciplinary research is bioinspired design (BID), also referred to as bioinspiration, biomimicry, or bionics. Over the past few decades, there have been several definitions for BID (reviewed in Fayemi et al. 2017). Common to most of these definitions are extracting natural principles and building analogies between biological and engineering processes and structures. Given the long history of studies focused on defining and developing processes for bioinspiration and BID (Helms et al. 2009; Lepora et al. 2013; Helms and Goel 2014; Snell-Rood 2016; Ng et al. 2021; Wanieck and Beismann 2021; Graeff et al. 2022), we wanted to organize a symposium with a different scope: a symposium focused on practitioners and best practices rather than formal definitions and processes. The goal of the symposium was to discover common themes and new perspectives in BID and identify challenges that can aid in forming and maintaining successful and productive BID collaborations.

Over the past 5 years, a multi-disciplinary team from the University of Illinois at Urbana-Champaign and Princeton University has worked to develop best practices to facilitate BID projects that benefit all participants. The authors of this paper comprise the core group within the team and include two biologists, one mechanical engineer, and two social scientists. Collabora-

Advance Access publication September 17, 2022

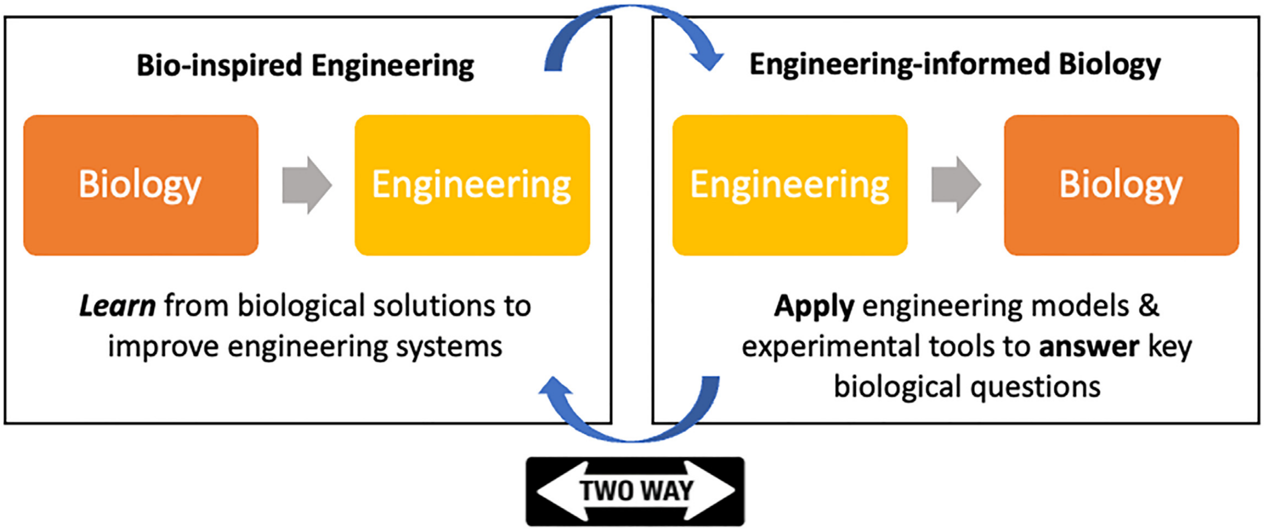

Fig. 1 Schematic of the BID method used by the authors in their research and teaching.

tions across knowledge boundaries are necessary to create successful innovations and to better understand biological processes. These boundary-crossing BID activities need to be studied, evaluated, and appropriately incentivized at all institutional levels.

In our own research labs, and in the courses we teach, we identify biological solutions that can be used to improve engineering systems (BID). We also apply engineering models and experimental tools to answer key biological questions (engineering-informed biology). This is ideally a mutually reciprocal relationship (Fig. 1).

Our symposium at the 2022 Society of Integrative and Comparative Biology Annual Meeting brought together educators and practitioners of BID, with the goals of

(1) consolidating best practices in teaching bioinspiration;
(2) creating and sustaining effective multidisciplinary teams;
(3) identifying best approaches to problem-based or solution-driven fundamental research;
(4) bringing BID innovations to market.

Recent advances in imaging, computation, and fabrication have engineering activities that match the scales where nature excels, which in turn has enabled opportunities for innovation via BID. Also, from experience, we know that BID is especially relatable to the general public and K–12 students since it shows an application for fundamental biological research. In this time when fundamental science and its applications are devalued, it is important to create educational and outreach experiences, like those based on BID, that speak to a broader audience.

This special issue collects a sample of perspectives on BID. We present perspectives on teaching and product development in BID (Loudon 2022), BID research (Bolmin et al. 2022; Flammang 2022; Larabee et al. 2022; Pennick et al. 2022; Saro-Cortes et al. 2022), and several examples of recent studies that foreground the dynamics by which BID can lead to fundamental insights into core biological principles (Barley et al. 2022; Hu 2022). Below, we detail the structure of the symposium and associated proceedings and highlight the themes and new perspectives that emerged from the symposium and the papers submitted by its participants to this journal issue.

Symposium overview

The symposium was divided into three major sections related to BID and one section related to team science. The BID portions focused on education, research, and product development. While preparing for the symposium, we invited speakers and authors to discuss best practices and challenges in one specific area, namely education, research, and product development. We requested that each speaker address the following questions. Questions marked with an [R] were only sent to speakers asked to speak about BID research or BID product development, while questions marker with an [E] were only sent to speakers asked to speak about BID education.

- What is the most useful definition for bioinspiration or bioinspired design?
- How did bioinspiration affect the solutions you designed? Did it help you reach these solutions faster or easier and was it constraining at times?

- [R] What are some of the most significant results that you believe were only possible because of nature's inspiration?
- [R] What are some of the most significant results that you believe were only possible because of an interdisciplinary collaboration?
- [E] What advantages does bioinspired design have in educating better designers, engineers, or biologists?
- What is a collaboration tactic that results in productive interdisciplinary teams?
- In your experience, are there certain signs that signal early on that an interdisciplinary collaboration will not be successful or enjoyable?
- Was working in interdisciplinary teams more productive than others in your experience? If so, why?

During the best practices in BID education, we invited BID practitioners at the K–12 education level (Ms. Aubrey Mikos), undergraduate-serving institutions (Prof. Clint Penick), and those involved in developing education, assessment, and outreach programs across multiple institutions (Prof. Robert Full) speakers. For best practices in BID research, we invited speakers to discuss BID work in swimming (Prof. Brooke Flammang), legged locomotion (Prof. Mark Cutkosky), flight (Prof. Aimy Wissa), and BID across scales (Prof. David Hu). Finally, for BID product development, we invited Prof. Cate Loudon to present her experience of developing and commercializing a product inspired by a biological solution. The symposium concluded with two presentations focused on addressing the challenges of BID collaborations founded on research in team science (Prof. William Barley), and summarizing the role of organizations in supporting interdisciplinary collaboration (Dr Luisa Ruge-Jones). Similar topics are also present in the special issue associated with our symposium. In both the symposium presentations and associated publications, common themes and exciting perspectives were shared, highlighted, and discussed. The next section summarizes these common themes and perspectives.

Themes and perspectives

Abstraction of biological principles for engineered systems

A biological design framework that can quickly and reliably zoom in on the appropriate optimal solutions will require the user to use analogical reasoning. Correct analogies can be made in three steps: retrieval, mapping, and abstraction. During the symposium and in the related papers, best practices were discussed to facilitate each analogy step. Exploiting biodiversity, or looking at many species, has been proposed to ensure the retrieval of the correct functionality. Penick et al. (2022) propose a comparative method that leverages biodiversity by drawing inspiration across a broad range of species. Mapping or extracting biological connections and elements to engineering designs is challenging because of the complexity of biological organisms. It is often difficult to isolate a single biological component, structure, or mechanism for engineering design. Several mapping methods and models have been proposed and published in the literature and were outlined in Barley et al. (2022). However, these models often assume that core biological principles are known, well understood, and documented, which is often not the case. Instead, the mapping step should rely on careful observations and simple model extraction from biological studies. For example, Bolmin et al. (2022) show that studying multiple species of click beetles across a wide range of scales helps derive simple dynamic models for the click beetle jump. Also, Larabee et al. (2022) show that careful observation of the mandible strike of trap-jaw ants can guide design principles for ultrafast systems by decoupling muscle activity from movement, thus reducing the effect of muscle fatigue during high-acceleration maneuvers. The final step of creating an analogy is abstraction. Distilling the most relevant biological details to a solution-neutral principle that can be transferred and implemented in an engineered solution is often the most challenging yet critical step of analogy creation. Abstraction usually requires multiple iterations and careful evaluation of the abstracted principle to assess its accuracy and relevance. The proper abstraction of biological principles allows for creative engineered designs that are expansive across multiple problems and transferable beyond basic research. For example, Loudon (2022) shows the development and intellectual property process of a product that suppresses bed bugs inspired by leaf microstructures. Such a transfer from basic research to a marketable product is possible because of proper retrieval, mapping, and abstraction but also requires other skills and knowledge, such as awareness of IP laws and commercialization practices.

Engineering for biological hypothesis

Engineering in BID has been traditionally viewed as a "recipient" instead of a contributor. Recipient here refers to the idea that an engineered system is often thought of as the output of the BID process that received and used biological knowledge to solve an engineering challenge. There are several examples of bioinspired engineering systems that revolutionized mechanical systems but made little contribution to biological knowledge. More recently, a theme that emerged in the field of bioinspiration is that engineered models, physical or numerical, can be used to test biological hypotheses that are difficult to test on natural organisms. These hypotheses might be related to behavior not observable in nature (Ito et al. 2019; Harvey et al. 2022), and morphologies that are unachievable in living organisms (Saro-Cortes et al. 2022) or surface features that are hard to alter in living systems (Oh et al. 2019, 2020).

Unlike biological systems, engineering systems are repeatable and controllable

In engineering systems, parameters can be modulated one at a time and across a wide range of values. In contrast, biological systems are often coupled, and each component may have more than one function. Therefore, isolating one effect or relating a feature to a function or behavior is often prohibitive and inconclusive. Even more apparent, studies on biological organisms in the field or the lab are often time-consuming. For example, it is often difficult to solicit a desired and repeatable behavior from an animal. Even when the desired behavior is achieved, repeating the experiments several times might yield different results due to fatigue or wear. Conversely, an engineering system is repeatable, and wear and tear are more easily identifiable.

This theme of engineering-enabled biology was apparent in the papers and presentations of our symposium. Engineered models of honeycomb structures, robotic fish, and insect-inspired gliders were presented to test hypotheses about topologies, biomechanics, and even evolutionary constraints. Of course, engineering models and experimental prototypes will not replace or substitute experiments on biological organisms, but they can supplement, simplify, and expedite such studies. At the same time, experiments on biological organisms can inform and validate the design of engineered prototypes.

The necessity of interdisciplinary collaborations

Another clear theme that emerged during the symposium is the importance of interdisciplinary collaborations during BID projects. However, such collaborations have multiple challenges when compared with single-discipline collaborations. Interdisciplinary collaboration takes a longer time to form, and productivity might initially be slow as teams develop nomenclatures and break technical communication barriers. Barley et al. (2022) discuss some of these challenges found on research in team science. The authors present institutional structures and policies that hinder interdisciplinary collaborations and discuss how diverse motivations between the researchers impact what is valued and prioritized during the collaboration. These challenges are common to all interdisciplinary collaborations.

Challenges specific to BID collaborations are the perception of (a) the contributions of biology and biologists by engineers and (b) the value of engineered analogies and studies to the biologists (Barley et al. 2022). Recently, some published work on BID processes suggested that collaboration with biologists is unnecessary beyond understanding preliminary biological principles, rendering long-term collaborations pointless. We dispelled this line of thinking during our symposium, as it assumes that either the biology is fully understood or a limited amount of biological knowledge is necessary to form good analogies for design. We discussed that biological discoveries are necessary and critical for the success of collaborations, and engineered models can be used to test biological hypotheses related to morphology (Saro-Cortes et al. 2022), evolution (Flammang 2022), and scaling (Bolmin et al. 2022), to mention a few. Therefore, long-term collaborations can be productive and beneficial for engineers and biologists alike. We also discussed how the over-abstraction of biological principles to simplify the engineered implementation might sometimes render the engineered model useless for studying biological hypotheses. We concluded that this could be resolved by clearly distinguishing between engineered prototypes designed to solve a specific problem and those built to represent model organisms or biological components for testing hypotheses. We concluded the discussion on collaborations by pointing out that the success of a BID collaboration depends on the team. As a community, we should leverage the wealth of knowledge in the team science field to improve our collaborations, enhance the creativity of our solutions, and discover new biological principles in ways that are difficult to achieve through single-discipline efforts.

Symposium perspectives

The first exciting perspective to emerge from the symposium presentations and articles is that the themes detailed above are common across all presenters and publications. The speakers and authors associated with our symposium presented work at research-intensive institutions, undergraduate-serving institutions, and K–12 schools. Also, the work presented during the symposium ranged from basic research to viable products in the commercialization stage. Another clear perspective was the role of evolutionary biology in BID. Several presenters and authors discussed that by considering multiple species and understanding evolutionary history, constraints, and relations, one could distill nature's principles more accurately, enabling stronger analogies and more successful BIDs and systems. One can also test evolutionary hypotheses that would otherwise take years to test on natural systems using synthetic or mechanical systems. Finally, while presenters were asked to present best practices and challenges of BID research, education, and product development, most of the challenges identified were related to working in interdisciplinary teams and were common to other interdisciplinary teams beyond BID. Thus, a refreshing perspective of this symposium calls for the involvement of team science and scientists within BID teams to help establish and maintain strong and productive collaborations.

Challenges and outlook

There are challenges that BID collaborations may encounter. Whereas interdisciplinary teams can enable effective decision making and are more resilient, innovative, and productive (Uzzi et al. 2013; Graef et al. 2021; Martins and Sohn 2021; Yan et al. 2021), life at the disciplinary boundary does require flexibility, familiarity, respect, equity, trust, reliability, and thus clearly stated agreements (de Dreu et al. 2008; Lu et al. 2012; Nowotny 2017). It will come down to incentives that will benefit all parties involved. And these incentives cannot just be working toward understanding biological systems better or getting a BID prototype built. Successful BID programs will require flexibility in academic programs and cultures that reward interdisciplinary work, especially at the hiring and promotion stages. There will need to exist a funding structure that makes resources available for those, even junior researchers, who want to work collaboratively across disciplinary boundaries. And researchers should be rewarded for non-traditional products, for instance, biologists obtaining patents and engineers publishing in biology journals.

BID has the potential to improve engineering systems, and the application of engineering models and experimental tools can help answer key biological questions. However, meaningful collaborations are required to make BID successful. Successful collaborations require the involvement of social scientists and biologists at all stages of design, something that the three themes mentioned above support.

Acknowledgments

We gratefully acknowledge support from the Society of Integrative and Comparative Biology, as well as the symposium participants.

Funding

This work was supported by the National Science Foundation, Division of Biological Infrastructure (2022129), the Society for Integrative and Comparative Biology's Divisions of Comparative Biomechanics (DCB), Vertebrate Morphology (DVM), Animal Behavior (DAB), and Comparative Endocrinology (DCE), and the American Microscopical Society (AMS).

Conflict of Interest

The authors do not have any conflicts of interest to declare.

Data availability

No new data were generated or analyzed in support of this research.

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