Integrative and Comparative Biology

Integrative and Comparative Biology, volume 62, number 5, pp. 1192–1201
https://doi.org/10.1093/icb/icac041
Society for Integrative and Comparative Biology

SYMPOSIUM

Addressing Diverse Motivations to Enable Bioinspired Design

William C. Barley[*,1], Luisa Ruge-Jones[*], Aimy Wissa[†], Andrew V. Suarez[‡§] and Marianne Alleyne[‡]

[*]Department of Communication, University of Illinois at Urbana-Champaign, 3001 Lincoln Hall MC-456, 702 S. Wright St., Urbana, IL 61801, USA; [†]Mechanical & Aerospace Engineering, Princeton University, 59 Olden St. Princeton, NJ 08544, USA; [‡]Department of Entomology, University of Illinois at Urbana-Champaign, 320 Morrill Hall, 505 S. Goodwin Ave., Urbana, IL 61801, USA; [§]Department of Evolution, Ecology, and Behavior, University of Illinois at Urbana-Champaign, 515 Morrill Hall, 505 S. Goodwin Ave., Urbana, IL 61801, USA

From the symposium "Best Practices in Bioinspired Design" presented at the annual meeting of the Society for Integrative and Comparative Biology, January 2022 at Phoenix, Arizona.

[1]E-Mail: barley@illinois.edu

Synopsis Bioinspired design (BID) is an inherently interdisciplinary practice that connects fundamental biological knowledge with the capabilities of engineering solutions. This paper discusses common social challenges inherent to interdisciplinary research, and specific to collaborating across the disciplines of biology and engineering when practicing BID. We also surface best practices that members of the community have identified to help address these challenges. To accomplish this goal, we address challenges of bioinspiration through a lens of recent findings within the social scientific study of interdisciplinary teams. We propose three challenges faced in BID: (1) complex motivations across collaborating researchers, (2) misperceptions of relationships and benefits between biologists and engineers, and (3) institutionalized barriers that disincentivize interdisciplinary work. We advance specific recommendations for addressing each of these challenges.

Introduction

There is an increasing necessity and value for building interdisciplinary teams to tackle the pressing questions in science (National Research Council 2014). Influential scientific papers are increasingly characterized by novel contributions from varying fields (Xiaolin et al. 2009; Uzzi et al. 2013), and are often produced by diverse teams (Wuchty et al. 2007; Larivière et al. 2015). However, interdisciplinary work is not without its challenges. Differences among fields in motivation, terminology, methods, and even values can inhibit the successful formation and implementation of team-based interdisciplinary science. A growing field of the "science of team science" has begun to catalog these challenges (McBee et al. 2017; Hall et al. 2018), and to develop tactics designed to address them in practice (Hall et al. 2019). We propose that bioinspired design (BID) is a particularly apt exemplar and case study of the potential to be gained from implementing tactics grounded in an understanding of the social challenges of interdisciplinary research.

BID has long served as an important area of interdisciplinary research positioned at the intersection between biology and engineering. Growing from its roots in bionics (Harkness 2004; Vincent 2009), bioinspiration has enabled advancements of issues important to both the biological sciences and engineering (from our own work: Bolmin et al. 2021a, 2021b; Román-Kustas et al. 2020; Alvarez and Wissa 2021; Duan and Wissa 2021). A growing array of scholars have called for expanding this discipline because of its applied and conceptual approaches, and its potential to turn to nature for inspiration advancing materials, robotics, and medicine (Sanchez et al. 2005; Snell-Rood 2016; Broeckhoven and du Plessis 2022).

Despite BID's promise, scholars and institutions face real challenges as they seek to promote this mode of biological inquiry. In this manuscript, we argue that many of the central challenges to enabling BID re-

Advance Access publication May 19, 2022

Table 1. A selection of published definitions of bioinspiration, biomimetics, biomimetics, and bioinspired design (with added emphasis foregrounding commitments to interdisciplinarity)

Term	Definition	Source
Bioinspiration and biomimetics	The study and distillation of ***principles and functions found in biological systems*** that have been developed through evolution and application of this knowledge ***to produce novel and exciting basic technologies*** and new approaches to solving scientific problems	Scope statement for the journal *Bioinspiration and Biomimetics* (last accessed January 2022)
Bionics	Examining ***biological phenomenology*** in the hope of gaining insight and inspiration ***for developing physical or composite bio-physical systems*** in the image of life	(Schmitt 1963)
Biomimicry	Innovation inspired by nature	(Benyus 1997)
Bioinspiration	The application of ***nature's*** lessons to ***engineered robots***	(Full 2001)
Biomimicry and bioinspiration	To select ideas and inventive ***principles from nature*** and apply them to ***engineering products***	(Sanchez et al. 2005)
Bioinspired design	The use of ***analogies to biological systems*** to develop ***solutions to engineering problems***	(Helms et al. 2009)
Bioinspired design	The ***use of nature*** to inspire solutions ***to engineering problems***	(Glier et al. 2011)
Biomimetics	Applying principles and strategies ***abstracted from biological systemsto engineering and technological design***	(Fayemi et al. 2017)
Biomimetics	Interdisciplinary ***cooperation of biology and technology or other fields of innovation*** with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution	(ISO 2015)

search stem from its core commitment to pursing research that crosses significant disciplinary boundaries. Social science research in organization studies, team science, and communication studies have long recognized that while epistemic boundaries (those connecting individuals with differing knowledge) can enable innovation, they also produce communication challenges that stymie success. Given this tension, we propose that the challenges of BID may not only be scientific or methodological, but socio-relational in nature. We turn to research on interdisciplinary teams and our own experiences building research programs, courses, and conferences to enable BID to identify three challenges we see as central to enabling the relationships needed for successful BID: (1) researchers are likely to come to interdisciplinary work with complex and varying motivations for project outcomes; (2) BID is often characterized as a directed relationship of applying concepts *from* biology *to* engineering, rather than as a reciprocal relationship between both disciplines; and (3) disciplines and institutions uphold structures that disincentivize work across disciplines. We propose a series of questions, with tentative answers, that we think will be important to consider as we build structures and practices to grow the BID endeavor. Specifically, we ask: What are some practical challenges to be considered as we support BID work?

Conceptualizing BID as an effort of interdisciplinarity

BID, the term that we use in this paper, is an interdisciplinary field that has a history connected at least back to research on bionics in the 1960s (Schmitt 1963; Harkness 2004). We focus on the term BID as the process of engaging in activities termed bioinspiration, biomimetics, or biomimicry. Even though there are some differences between the terms (Table 1), the challenges addressed in this paper are common to all these practices since they all involve interdisciplinary teams. In addition, the most critical step of the BID process is building appropriate analogies between biology and engineering or design (Helms et al. 2009). In this article, we thus focus on challenges that face interdisciplinary teams working at the intersection of biology and engineering, especially those engaged in building meaningful analogies.

Table 1 presents a selection of definitions of bioinspiration and closely aligned concepts. As the emphasis in definitions demonstrates, a common feature of *all* these definitions is a recognition of BID's core commitment to interdisciplinarity. Each definition emphasizes the potential for producing meaningful contributions via a relationship between fundamental biological knowledge and engineering principles; BID requires collaboration between these two disciplines.

Biology and engineering are not necessarily the most obvious partner disciplines. Engineering knowledge tends to emphasize a practical design orientation toward solving established problems (Kunda 2006; Gainsburg et al. 2010; Leonardi 2011, 2012). In contrast, biology is grounded in fundamental research of complex biological systems (Mayr 2004).

BID scholars acknowledge that differences between the disciplines of engineering and biology can be the source of meaningful challenges to success (Full 2001; Ng et al. 2021; Broeckhoven and du Plessis 2022). One of the prime sources of challenges to BID work is identifying biological processes that can relate to engineering challenges. BID has been characterized as a process of analogy, whereby scholars must engage in complex reasoning to connect, adapt, and extrapolate, which is a notoriously difficult process (Vattam et al. 2009; Cheong et al. 2014; Linsey and Viswanathan 2014; Hashemi Farzaneh 2020).

Prior work has attempted to address the challenge of matching known biological principles with established engineering design challenges through structured interventions and techniques (for a recent review see: Fayemi et al. 2017). One set of tools has focused on issues of translation, by producing glossaries and thesauruses with terms from biology and engineering (Nagel et al. 2010), or using a natural language processing approach to identify and apply analogies between biological and engineering systems (Shu 2010). Another set of solutions has attempted to address the challenges of finding interfaces between biology and engineering by collecting and categorizing interesting natural mechanisms into databases so that engineers may search biological solutions with the potential to inspire novel engineering designs (e.g., Vincent et al. 2006; Kaiser et al. 2014; Chechurin and Borgianni 2016). Others have sought to build automated systems to help identify and analogize biological systems for particular design contexts (Vattam et al. 2010; Goel et al. 2014).

Although these strategies have been effective in addressing some of the immediate challenges in BID collaboration, they are centered on the issue of managing the knowledge and fact, which emphasizes challenges of search (finding relevant biological solutions to a particular problem) and translation (abstracting biological processes via analogy to create engineering applications). We believe this emphasis overlooks another major challenge that emerges in BID work: the labor involved in building the social relationships that are necessary to collaborate on interdisciplinary teams. To address this, we now turn to the literature on interdisciplinarity.

Applying learnings from research on interdisciplinarity

We conceptualize BID as a process of building interdisciplinary relationships among scholars who identify with potentially widely variant disciplines, and consider the practical challenges faced as we seek to systemically support BID. We propose three sets of challenges: (1) navigating complex motivations across collaborating researchers, (2) managing misperceptions of relationships and benefits between biologists and engineers, and (3) addressing institutionalized barriers that disincentivize interdisciplinary work. In the following sections, we address each of these challenges in turn in by grounding them within our own experiences attempting to enable BID research, conceptualizing the challenge through a lens of team science, and mobilizing this connection to propose initial implications for furthering BID work. Collectively, the authors have worked to facilitate and support BID in several contexts. First, we have co-designed and offered undergraduate courses on BID that are cross-listed between biology and engineering departments. Second, we have co-organized multiple professional events gathering researchers with experience and interest in BID to solicit perspectives faced in growing BID scholarship. And, finally, we have drawn on our own experiences as scholars who have sought to build interdisciplinary collaborations in BID over the past decades. Table 2 summarizes our three challenges, alongside brief statements of their potential impact on BID research and practice, and outlines of our practical recommendations.

Challenge 1: addressing the presence of complex motivations

When individuals seek to work across disciplinary boundaries, they bring their individual motivations with them. In the case of BID work, the motivations driving researchers to engage in this work vary. In late summer 2021, the authors co-organized a workshop at their home institution designed to assemble scholars from across the university who self-identified as interested in identifying opportunities to grow the presence of BID on our campus. A total of 31 participants joined

Table 2. Summary of practical challenges to BID and applied implications

Challenge	Brief description	Implications if left unaddressed	Guiding question for future work, and initial recommendations
1. Addressing the presence of complex motivations	• Biologists and engineers are often driven by fundamentally differing objectives when considering engaging in BID work.	• When unaddressed, these differences can produce conflict, and disengagement in BID collaborations.	*How can we design processes to surface, acknowledge, and respect complex motivational differences on BID teams?* • Prioritize discussions about individual motivations at the outset of collaborations • Ensure collaborations involve plans to create products that will benefit each participating member • Explicit efforts to focus on building cross-understanding among BID practitioners involved in collaborations
2. Addressing (mis)perceptions of directionality	• Dominant discourses about BID reify perceptions of unidirectional relationship whereby engineering knowledge is extended through the application of pre-existing biological knowledge.	• If this discourse perpetuated, biologists may be especially reticent to engage in BID scholarship and practice.	*How can we foreground the reciprocal relationship between biology and engineering in BID work?* • Seek further visibility of BID efforts that have led to developing fundamental knowledge about biological principles • Communication efforts that foreground engineers' commitments to building projects that will contribute to knowledge of biology • Potential value in reframing BID as Engineering-enabled biology
3. Addressing institutional disincentives	• Multiple factors within disciplines, universities, and funding environments disincentivize scholars from engaging in cross-disciplinary work such as BID.	• BID will face difficulties growing as an inter-discipline without structures rewarding researchers for performing BID, and providing practical support for enacting BID research and teaching.	*How can we institutionalize policies and structures that support and reward the interdisciplinary labor of BID?* • Seed funding to support initial dialog in potential BID projects • Venues that encourage and reward biologist-engineer interactions • Personnel support to help administer BID teaching and research • Undergraduate curricula dedicated to skill-development for interdisciplinary collaboration

the workshop from 11 departments across the campus. Before the workshop, we asked each participant to share an exemplar of a past research product that they saw as a strong exemplar of their interests in BID research. We reasoned that we could use these documents to facilitate a conversation about the variety of motivations driving participants to engage in BID work.

We engaged in a thematic coding process to identify commonalities and differences in how participants conceptualized the value of their BID work (Tracy 2020). First, the co-authors parsed each manuscript for concrete statements for the conceptual motivation and justification for the contribution of the work. We extracted these statements into a separate document for review and analysis. Each of the co-authors examined the statements using a line-by-line level of analysis, and assigned open thematic codes to highlight recurring features across the corpus (such as "statements about target audiences" and "claims to contribution"). Next, the authors re-read the corpus in full, alongside the initial codes to engage in a process of constant-comparison combining open codes by similarity to reveal emergent themes (e.g., "scale of Analysis—cell/organism/biome," "Target Audience—engineers/biologists," and "conceptual motivation—practical/technical/conceptual"). When completed, the thematic analysis revealed multiple axes upon which the participants' submissions varied. We validated our categories by inviting workshop participants to perform a pile sorting of anonymized excerpts of these statements (Bernard 2011). During the workshop, we encouraged participants to collectively sort these motivation statements into groupings, and then to name and explain those groupings to the larger group. The participants' categorizations aligned with those that the organizers had identified beforehand, thus providing qualitative support for the validity of our thematic analysis.

Motivations statements varied on three dominant axes. First, contributions varied in terms of conceptual motivation, ranging from explanatory works that sought to know how an organism or process operated (i.e., fundamental research) to application works seeking to design and test the efficacy of a potential solution to a known practical problem (i.e., applied research). Second, topics of analysis ranged in scale of interest from cellular, to organismal, to ecological processes. Third, the disciplinary target audiences for the works submitted varied dramatically between engineering and biology outlets. Even among our 31 workshop participants, from the same institutions, there were many different primary motivations for the work they were doing related to BID.

Differing motivations are quite normal when conceptualized through a lens of team science. Groups researchers, for example, have long recognized that most collaborations are characterized by complex motivational dynamics. Even when team members agree that they share a global set of objectives (e.g., engaging in a specific BID project), their individual level goals often vary depending upon their disciplinary and organizational affiliations (Cartwright and Zander 1960; Stadtler and Van Wassenhove 2016). Yet, these seemingly subtle differences can be the source of meaningful challenges when groups seek to accomplish shared work (Keyton et al. 2008; Börner et al. 2010). For example, accountabilities to multiple disciplines can lead to tensions when teams seek to decide which journal or conference venues they should publish. If left unaddressed, divergent motivations can be sources of conflict, coordination challenges, and ultimately failure on interdisciplinary teams (Cummings and Kiesler 2005; Lewis et al. 2010; Wilson et al. 2020).

Acknowledging the presence and challenges associated with divergent motivations, however, surfaces implications that may inform policy for enabling BID. Research from team science has shown that diverse teams are more successful when they take the time to understand each other's knowledge and perspectives (Faraj and Sproull 2000; Huber and Lewis 2010; Janardhanan et al. 2019). Developing cross-boundary understandings requires making the time for dialog (Barley 2015; Barley et al. 2020; Wilson et al. 2020). To truly enable BID, we propose that policy makers and practitioners should consider the following question: How can we design processes to surface, acknowledge, and respect the complex motivational differences that drive biologists and engineers to engage in BID? Recognizing the importance differing motivations requires BID scholars to conceptualize cross-disciplinary collaborations as more complex than an exercise in connectivity and transfer. Even though we lack team research that specifically confirms the transferability of past team science research to BID collaborations, we believe there is much ground to be gained by foregrounding the importance of relationship building as a *necessary* component to realizing successful BID projects.

Recommendation 1: Facilitate early and regular discussions that identify, acknowledge, and respect different motivations that drive biologists and engineers to engage in BID.

Challenge 2: addressing (mis)perceptions of directionality

Our second challenge addresses a common misperception about the benefits garnered from the biology–engineering relationship embedded within BID. Namely, we believe it is common for scholars to conceptualize BID as an exercise that draws from a base of knowledge in biology for the benefit of applications in engineering. This conceptualization creates a one-way relationship in BID in which biologists give concepts to engineers rather than one, where both disciplines engage in a reciprocal knowledge building process. We invite the reader to return to the definitions of BID provided in Table 1. Note the recurring structure of these definitions that places biology as an antecedent of benefits in engineering. When taken literally, this framing positions biology and, by extension, the biologists involved in BID as standing to gain less than engineers from engaging in this work. These problems are particularly acute, given observations that biologists may be excluded from BID work once an analogical connection of a biological process establishes the possibility of informing an engineering solution (Ng et al. 2021).

It is important to mark that established BID scholars understand that engaging in this mode of inquiry can offer meaningful advancements in *both* biology and engineering (Snell-Rood 2016; Graeff et al. 2019; Hashemi Farzaneh 2020). For example, Full's BID work on adhesion developed fundamental knowledge of the mechanisms by which Geckos adhere to surfaces (Autumn et al. 2000; Gillies et al. 2014). Helmut Schmitz' multi-disciplinary work on infrared receptors in pyrophilous beetles has broadened our understanding of how biological systems detect heat (Schmitz and Bleckmann 1997; Hammer et al. 2001). Three of this article's co-authors have an active trajectory of multi-disciplinary research by which they have contributed fundamental knowledge to the mechanisms by which trap-jaw ants bite (Patek et al. 2006), click-beetles jump (Bolmin et al. 2019), and cicada wings achieve superhydrophobicity (Román-Kustas et al. 2020).

Even though BID research provides compelling examples of the mutually beneficial relationship between biology and engineering, research from organization studies shows that *perceptions matter* when seeking to enlist support for new collaborative work efforts. Social theorists have long recognized that people make decisions about how they will act based upon their personal understandings of issues at hand (Mead 1925; Goffman 1983). Empirical work has shown that individualized understandings of a collaboration, which are often called "frames," can influence individuals' intentions and motivations for engaging and supporting new work arrangements (Edmondson 2003; Leonardi 2011; Treem et al. 2021). Thus, this research suggests that if individuals *perceive* that BID involves a unidirectional relationship that will primarily benefit engineering, we expect this to affect the growth of BID collaborations by making it less likely that biologists, especially those who are not already exposed to BID, will see value in exploring potential BID research.

Our experiences demonstrate that this perception of unidirectionality is present, and suggest it is a key barrier to growing BID, especially to increasing the number of biologists who are interested in engaging in BID projects. We have seen evidence of this perception in several places. First, we have observed this when seeking to recruit biologists to participate in a cross-listed BID course at the University of Illinois. For years, two of our co-authors have offered this course and repeatedly found most registered students come from engineering departments. When we sought feedback from prospective biology students, the response has been uniform: those students do not immediately perceive how taking a course on BID will further their education in a manner that would outweigh the benefits of another, more traditional, biology elective.

Second, we observed evidence of this frame challenge via the contents of participant discussion and feedback in our BID workshop. When our conversations shifted to discussing practical directions for moving toward growing the presence of BID research on our campus, the engineers who were present engaged enthusiastically with the prospects of these resources. Multiple biologists, however, expressed explicit concerns about where they would fit into such a center stating that they were unsure as to how the center would contribute to the development of fundamental biological knowledge. In their written feedback, multiple participants from biology departments stated that they were unable to see what they would gain from participating in these types of efforts, and thus, were reticent to commit further to developing this work. Some biologists commented with concerns that engineers tended to abstract biological principles so much that the collaborative work became irrelevant to studying biological systems. Moreover, some engineers at the workshop commented that the biological literature often included all the information necessary to design a bioinspired engineering product, which meant they saw little need to engage biologists directly in BID work. Engineers also stated that ongoing collaborations with biologists beyond learning some preliminary principles often tend to be unnecessary or do not benefit the biologist or the engineer.

These perceptions of a unidirectional relationship suggest the need to both acknowledge BID misconceptions and to foreground the ***reciprocal*** relationship between biology and engineering within bioinspiration work. We believe one promising direction in addressing this challenge is to engage in counter-framing against misconceptions of unidirectional benefits. Practitioners and policymakers would do well to anticipate the potential hesitance of biologists by foregrounding specific examples and mechanisms by which biologists can expect benefits from this work. BID scholars can also play an important role in addressing this issue. Established BID scholars who are embedded within biology should do more work to highlight the ways their BID collaborations have led to developing fundamental knowledge about biological principles. Finally, we might consider using reframed terminology to describe our BID work to biologists. Perhaps rather than discussing bioinspired design when engaging with prospective collaborators, we might do well to discuss our work as engineering-enabled biology.

Recommendation 2: Engage in discussions that foreground intersections and reciprocal relationships between biologists and engineers.

Challenge 3: addressing institutional disincentives

Our final challenge positions BID research within a broader institutional context of universities and higher education. Despite increased discourse about the essential nature of cross-disciplinary research, team science and science policy scholarship has observed that many aspects of the organizational and policy structures in contemporary universities discourage interdisciplinary research. For example, many of the metrics upon which scientists are measured strongly incentivize scholars to maintain work within their own disciplinary fields (Jacobs and Frickel 2009). Promotion and tenure procedures often face difficulties assessing researchers whose work spans multiple disciplines (Klein and Falk-Krzesinski 2017). Funding opportunities for science often reward independent scholarship and provide minimal support for enabling scientific teams (Cooke and Hilton 2015). These challenges are accentuated by findings from research examining the effectiveness of interdisciplinary research for producing novel knowledge. Despite strong evidence that interdisciplinarity is an important driver of novelty in science from a macro-level perspective (Uzzi et al. 2013; Larivière et al. 2015; Wu et al. 2019), micro-level research has shown that collaborative work tends to fail more frequently than independent work (Fleming and Singh 2010). Individual interdisciplinary researchers are less productive, on average, than disciplinarians (Leahey et al. 2017; McBee et al. 2017). Thus, there are many reasons why individual researchers face institutional barriers as they consider engaging in interdisciplinary research. At the researcher level, there are strong warrants to support the argument that *doing* cross-disciplinary work is a losing strategy at an individual level.

As an area inquiry that is fundamentally committed to interdisciplinarity, BID is particularly influenced by these disincentives. Examples from our own experiences illustrate this. For instance, we faced serious practical challenges after we received funding to co-teach an undergraduate course on BID. Would the course be listed in the engineering, biology, or communication department? Which departments would receive credit for the instructional units incurred by the class? Which department's administration would support the course? We had to navigate these local bureaucratic questions on our own and advocate for the value of the course to multiple groups of stakeholders.

Another source of serious tactical challenges centers on where we choose to publish our work. Some engineering subdisciplines, for example, publish their work primarily within archival conference proceedings and view these outlets as a primary means for publishing current scholarly knowledge. Yet, biology departments frequently do not consider these publications as legitimate for purposes of considering promotion and tenure.

Similar challenges extend to our experiences seeking and administering funding for BID work. It is often unclear which funding programs are amenable to supporting BID work. We have received feedback from funders targeting engineering opportunities that discount the value of devoting resources to understanding fundamental biological principles, and similar feedback from funders in biology minimizing the value of contributions associated with building robots inspired by biology. Further, when a grant involves investigators from multiple departments, it incurs additional administrative loads such as coordinating across business offices. Whose staff coordinates investigators' travel? Which department supports purchases and reporting duties? Again, in our experiences, the answers to these questions are subject to local politics and policies. And, the burden of their resolution falls upon the investigators.

As with our other challenges, acknowledging the practical challenges of BID engenders an important question: How can we institutionalize policies and structures that support and reward the interdisciplinary labor required for successful BID scholarship? We believe the answers to this challenge will lie at the same level of analysis as the problem—within the institutions where we work and their policies for scientific collaboration. Doing BID involves much more labor than transferring and translating knowledge, and universities would do well to institutionalize support for this labor. To support BID, universities might consider building dedicated programs or centers to cultivate BID collaborations. Programs of these sorts might offer multiple forms of resources to spark BID research including: (1) seed funds to support the dialog necessary to germinate initial research projects, (2) physical and virtual spaces where engineers and biologists can interact, (3) personnel support to enable funding applications and administration, (4) training and coursework to teach undergraduates in biology and engineering about the labor involved in interdisciplinary work, and (5) process support to help nascent BID teams surface and manage the social tensions that we expect to be present in their work.

Recommendation 3: Evaluate and revise policies and organizational structures to reward interdisciplinary labor.

Recommendation 4: Inventory and establish multiple forms of resources, including funding, interactive spaces, personnel support, and training and courses to enable interdisciplinary work.

Conclusion and next steps

BID offers a unique possibility for advancing creative solutions to some of the most pressing challenges in biology and engineering. Despite its promise, we believe that significant social challenges are currently hindering the formation and growth of BID research. By highlighting these challenges, we hope to begin an action-oriented conversation about how to cultivate our community.

We do not claim that the challenges we have identified will be simple to address. To the contrary, we anticipate that efforts to address these issues may result in failures at multiple levels: in terms of teams who decide *not* to collaborate as a result of recognizing differing motivations, or institutions who attempt to build resources to enable BID only to discover new impediments to enacting interdisciplinary practice. But, making these challenges visible offers an important step toward progress. Scholars of innovation have long recognized that failures on diverse teams often afford opportunities to learn (Hargadon and Sutton 1997; Hargadon 2003; Edmondson 2011). Taking explicit efforts to experiment with mechanisms for growing BID, even if they fail, will increase our understanding of the impediments to growing this field of study.

It is also important to mark that we our arguments here have not addressed the wide diversity of subdisciplines and specialties within the disciplines of engineering and biology. It is reasonable to expect that certain subdisciplines of these fields may be prone to building effective BID collaborations or characterized by unique challenges and opportunities that we have not identified in this paper. Clearly, efforts to understand which subdisciplines of these fields have compatible cultures, practices, and research interests is a potentially fruitful venue for future development.

Most of our discussion has centered on the challenges faced by current researchers. But we will close with yet another observation. If we succeed, we will need to consider how we will train new scholars differently within a BID world—teaching, math and physics for biologists, biology for engineers, and cultivating cross-disciplinary incentives (as mentioned above). We conclude that there is much work to do, but addressing the complex embedded nature of BID research through communication, counter-framing, and institutional reform will enable us to move toward cultivating the real benefits we know are possible through BID research.

Funding

This material is based upon work supported by the National Science Foundation under Grant No. 2022129. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Acknowledgments

The authors are grateful for Elizabeth Bello and Valeria Saro-Cortes' support coordinating the workshops discussed in this manuscript. We would also like thank our anonymous reviewers for their thoughtful comments and suggestions on this work.

Data Availability

Supporting data for this manuscript are available in anonymized form upon request from the corresponding author.

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