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Examining Cultural Structures and Functions in Biology

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Synopsis Scientific culture and structure organize biological sciences in many ways. We make choices concerning the systems and questions we study. Our research then amplifies these choices into factors that influence the directions of future research by shaping our hypotheses, data analyses, interpretation, publication venues, and dissemination via other methods. But our choices are shaped by more than objective curiosity—we are influenced by cultural paradigms reinforced by societal upbringing and scientific indoctrination during training. This extends to the systems and data that we consider to be ethically obtainable or available for study, and who is considered qualified to do research, ask questions, and communicate about research. It is also influenced by the profitability of concepts like open-access—a system designed to improve equity, but which enacts gatekeeping in unintended but foreseeable ways. Creating truly integrative biology programs will require more than intentionally developing departments or institutes that allow overlapping expertise in two or more subfields of biology. Interdisciplinary work requires the expertise of large and diverse teams of scientists working together—this is impossible without an authentic commitment to addressing, not denying, racism when practiced by individuals, institutions, and cultural aspects of academic science. We have identified starting points for remedying how our field has discouraged and caused harm, but we acknowledge there is a long path forward. This path must be paved with field-wide solutions and institutional buy-in: our solutions must match the scale of the problem. Together, we can integrate—not reintegrate—the nuances of biology into our field.

Introduction

Biology is a broad field that systematically excludes all but a narrow group of systems, analytical approaches, researchers, students, and cultures. A genuine effort to reform biology requires examining intersections of structural, methodological, and societal practices on multiple levels. Organization structures like academic departments, funding proposal sections, and even the names of subfields, provide the foundation for content in training programs and the hierarchy of experimental or theoretical techniques (Bourke and Butler 1998; Whitley 2000, 2003). These organizational struc-

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tures are periodically interrogated and changed, resulting in departmental splits or mergers and new interdisciplinary programs (Mäkinen et al. 2020). The ways in which we motivate, reward, and recognize scientific advances prioritize individual glory over cooperative and equitable teaming and training. However, because the organizational infrastructure and interpersonal interactions within a scientific community are greatly informed by our society outside of science, we must critically examine and actively reshape our scientific processes to foster inclusive and integrative research. Without intervention, systems that were built by a racist society will inevitably reproduce racism. Current constraints suppress human and scientific potential by systematically excluding groups of people and ideas (Hackett 1990; Gaukroger 2008; National Center for Science and Engineering Statistics 2019; Chaudhury and Colla 2020; Cooper et al. 2020).

Our thoughts for reshaping biology arose during a 2019 workshop run by the National Science Foundation on reintegrating biology. Here, we describe the state of culture and ethics in biology by covering a wide breadth of intersectional issues impacting diversity, equity, and inclusion. We call for an overhaul of current practices in biology and provide starting points that can support movements toward equity and interdisciplinarity in the context of classrooms, research groups, manuscripts, departments, societies, and funding agencies.

Structure and function in research

Methods in the biological sciences

Scientific thinking is broader than the experiments themselves. In the process of experimentation, we sometimes oversimplify the problem and limit further inquiry. Often reducing of the scale of the problem is a methodological necessity that creates systemic biases. We have identified some methodological limitations of our current approach:

(*1*) Established methods provide quick and effective ways to generate new knowledge. Data are obtained by using samples, tools, and methods at hand. However, without questioning our assumptions or generating new approaches, the limitations of established practices greatly constrain scientific inquiry (see examples in Soldatova and King 2006; Laake et al. 2007; Dodick et al. 2009).

(*2*) Focus on particular systems makes less studied systems less visible and hence, less valued. For example, the majority of our understanding of terrestrial legged locomotion arises from "cursorial" animals that use steady-state locomotion (Jenkins 1971). As a result, researchers frequently assume that all legged locomotion is dynamically similar to cursorial locomotion, and that "variability" in more complex locomotion should be reduced so that preexisting tools can be applied.

(*3*) Focus on a handful of model organisms risks missing or minimizing important differences between organisms, such that "averaged" organismal characteristics minimize the nuances of biological systems (Hedges 2002). When the approaches become systematic, our understanding of the complexity of the biological system is diminished.

To overcome these limitations, we propose:

(*1*) Use the limitations of our methods and technologies to identify conceptual traps that currently constrain our thinking (Torres-Vila et al. 2004; Williams 2008).

(*2*) Use the lens of method development to identify cultural silos and narrowing of perspectives that has occurred in various sub-disciplines (Hull 2010).

(*3*) Use systematic approaches that acknowledge the weaknesses of systems studied and consider more holistic integration of sub-fields (Jose 2020).

(*4*) Put a higher value on complex and interdependent communities of organisms that need to be studied together rather than as independent species to be fully understood. We need to foster respect for the complex networks of interactions among organisms (Proulx et al. 2005).

Society informs culture in the biological sciences

Questions that we ask as scientists, the hypotheses we generate, and the data analyses we choose, determine the direction of science. How we approach these questions is shaped by cultural paradigms reinforced by societal upbringing and scientific indoctrination during training (Fountain 1998; Whitley 2000; Hull 2010; Hansson 2018). Some features that limit scientific progress by reinforcing existing cultural norms are as follows:

(*1*) Scientists are influenced by cultural paradigms in society and their scientific community as they build biological hypotheses (Milner 2007). For example, cultural misogyny predisposed Victorian scientists to dismiss the role of female choice in Anolis lizard mating (Kamath and Losos 2017). Additionally, the idea that a single gene that yields a single protein which exists to perform a single function fit the culture of individual exceptionalism at the time and place of its discovery (Crick 1958), but both genetics and theory have since been shown to be substantially more complex (Gould and Lewontin 1979).

(*2*) When the views of a few powerful individuals shape a field, high similarity in backgrounds (e.g., field of expertise, socioeconomic status, gender, ethnicity) of those individuals can limit new directions or alternative perspectives (e.g., Crick 1958; Hallgrímsson and Hall 2011; Hall 2012; see Lewontin 1982 for a related critique). This effect is especially evident when foundational theories are wrongly attributed to the "genius" of single individuals, upon which entire subfields are established—this erases the diversity present in the generation of any "great idea" and canalizes subsequent work as derivative of the founder.

(*3*) Recruitment and retention in our field, especially in leadership roles, are limited to a narrow demographic, which leads to a narrowing of the cultural lens (Clark and Ma 2005; Taylor et al. 2017; Kaplan et al. 2018). Individuals entering a field do not, and cannot, see themselves represented in the present culture, and therefore must conform, be silenced, or leave (Morley and Lugg 2009; Burke 2013). The few who attempt and/or succeed to broaden the cultural lens pay a significant personal and professional cost for disrupting cultural norms (Rodríguez et al. 2015; Burnett et al. 2020).

To identify these and other cultural limitations, we propose:

(*1*) Broadening training for all researchers—in philosophy, ethics, history, languages, along with a broader training in various aspects of biology. This training should address how to express appreciation for these learned diverse perspectives through not only acknowledgement but explicit incorporation into biological approaches (Kimmerer 2002; Schell et al. 2020).

(*2*) Building an equitable scientific community that broadens the perspectives of those involved in asking questions, building hypotheses, and analyzing data. A stronger focus on improving equity through retention, but also via promotion to leadership positions for later-stage career individuals, not just recruitment of early career individuals (Etzkowitz et al. 2000; Price et al. 2005; Trotman and Brown 2005; Stout et al. 2018; Barnard et al. 2021).

(*3*) Normalizing a career-long learning process to examine and value broad and multidisciplinary perspectives. This could include presenting science to a broader scientific audience; engaging and including the public in science and its implications for our society would help to deepen the questions we ask and the solutions we generate (Dahlstrom 2014; Barnard et al. 2019; Canfield et al. 2020).

(*4*) Training scientists to pay attention to persistent cultural paradigms in experimental design and subsequent data analyses, including at the molecular level. This would especially require moving away from the binary modes of thinking (e.g., genes are either "on" or "off") and will involve building multiple hypotheses at the onset (Reece et al. 2014; Spribille et al. 2016).

(*5*) Establish a framework that rewards valid opinions or analyses and resists the urge to narrow down perspectives too early in the process. Increasing seed funding for exploration of new ideas or for taking a wider view of a topic would provide incentives for creative thoughts.

Language in the biological sciences

Science is done by people and is communicated using language choices that impact scientific progress. For example, terms such as "fight" against diseases or "unraveling the secrets of Nature" (with nature being feminine) add cultural framing to the scientific question (Brewer and Gross 2005; Chong and Druckman 2007). However, most scientists and science communicators are unaware of the consequences of these language choices:

(*1*) The language we use has implications for hypothesis building, experimental design, and data analyses. Simplifying complex topics using metaphorical language simultaneously increases broad understanding and limits complex interpretations without the proper context (Kuhn 1979; Duit 1991; Gentner and Jeziorski 1993). For example, labeling DNA as a "master switch" serves to minimize the role of other cellular factors necessary for the formation of an organism and limits studies on these.

(*2*) The teaching of biology, its presentation in the media, and in popular culture all require an understanding and effective communication of the principles of biology (Horst 2013; Tang and Rappa 2020). For example, cultural biases about gender, sex, and sexuality shape scientific discussions and inquiries into spotted hyena (Crocuta crocuta) matriarchal social dynamics, which were originally described as "sex role reversal" but are in fact much more nuanced (Conley et al. 2020). Moreover, scientists participate in amplifying cultural narratives that are inaccurate (Nisbet and Scheufele 2009; Dahlstrom and Ho 2012). This can limit or prevent understanding of the underlying biological processes.

(*3*) Language plays an important role in the perception of science. During the COVID-19 pandemic we "suit up" with personal protective equipment to "battle" viruses—simplifying biological principles of infection as an "us against them" paradigm.

Furthermore, when certain health care workers are lauded as "heroes" while others are ignored, the potential contribution of individuals outside of the scientific or medical communities is minimized. (Maddux and Rogers 1983; O'Neill and Nicholson-Cole 2009).

(*4*) Language, including phrasing and jargon, creates barriers between sub-disciplines and restricts participation. Arguing the semantics of terminology has the potential to hold back clear comprehension and true collaborations in biology, as well as multidisciplinary understanding of diverse topics.

(*5*) Words like "stress," "adaptation," and "resilience" have literal meanings, which may differ according to scientific sub-discipline, as well as metaphorical significance (Giles 2017; Taylor and Dewsbury 2018).

We propose the following as a starting point for further conversations:

(*1*) Intentional use of words and phrases in describing scientific endeavors. Science communication research shows that the content of effective framing, or the intentional use of words/phrases, is dependent on intended outcome (Borah 2011; Lakoff 2014). There is no "one size fits all" approach to effective science communication and collaboration. Combative language (e.g., war, fight) produces outcomes where one side is "correct," which should be avoided when engaging diverse discourse (Hansen 2016). This can be in part addressed by intentional training of all scientists in rhetoric and critical communication (Druschke et al. 2018).

(*2*) We must include non-academic communities as partners to consider the multiple cultural and ethical impacts of terminology and nomenclature (Dahlstrom and Ho 2012; Canfield et al. 2020). This may, for example, require changing names of genes or organisms, with appropriate and generative upheaval to both the naming frameworks and the past literature.

(*3*) Examining the cultural contexts in which our understanding of molecular systems, cells, tissues, organisms, and ecosystems were originally described, while refraining from larger generalization based on a handful of model organisms (Hedges 2002). This will point to areas that have suffered canalization of thought because they were narrowly founded.

Ethics in the biological sciences

Considering the broader social and environmental consequences of scientific study ("ethics" in the colloquial sense) is an important aspect of doing biology, but rarely integrated into the practice of research (Lindell and Milczarek 1997). While there is a long history of bioethics in medical fields, ethical training and considerations in other subfields of biology is a much more recent development (Richie 2014). Moral and ethical dimensions of biology need to be discussed routinely both in classrooms and in presentations (Johansen and Harris 2000). Through training to consider the ethical implications of all forms of biology on a regular basis, the risk of widespread harm can be reduced. For example, unethical experimentation harms not only the individuals involved in the studies, but has engendered a justified and deep mistrust of medical professionals among the communities that are targeted for exploitative study (Armstrong et al. 2007). Ethical—and other—concerns of affected parties must be anticipated and welcomed at every stage of scientific experimentation.

Examples of biology study areas with urgent need for ethical considerations for researchers and trainees:

(*1*) Molecular cloning is now so routine that we have forgotten to address its ethical dimensions (Harris 1997; Häyry 2018). The public at large worries about genetically modified foods but students in our classrooms are not provided with complex conversations on these topics (Sadler et al. 2006). Scientists need to understand the ethical dilemmas embedded in our work and should be ready to discuss the complexity of these ethical dimensions with non-specialists. Disregarding ethical concerns as un-informed causes loss in trust, whether these be foods, medicines, climates, or vaccines (Frewer 1999; John 2018).

(*2*) Biology has inflicted unacknowledged harm on people from applications of research findings to policy, management and resource allocation. Specifically, biology research was instrumental in legitimizing eugenics historically and race "science"; there is ongoing concern about the parallels to environmental risk research in marginalized communities (Hasian 1996; Pidgeon and Fischhoff 2011).

(*3*) Tools for gene editing are now readily and cheaply available to alter the course of evolution of species due to rapid technological innovation. Yet researchers and students working with gene editing are not necessarily receiving rigorous ethical guidance (Krishan et al. 2016). For example, while biologists may want to eradicate disease through gene editing tools like CrisprCas9, what constitutes an illness is socially defined—and many disabled people with genetic disabilities are concerned the application of these tools will amount to a more modern form of eugenics (Boardman 2020).

We propose the following as a starting point for further conversations:

(*1*) Biology training should be grounded in ethics, more specifically bioethics (Johansen and Harris 2000; Childress 2020).
(*2*) Multiple perspectives on a problem need to be recognized and should be routinely discussed. Special attention should be paid to cultural and societal inequities. Different identities, perspectives and abilities should be represented in science and in discussions on ethics (Kimmerer 2002; Walter et al. 2020).
(*3*) Diverse collaborations (including non-scientists and non-specialists) should be normalized in generating questions, hypotheses and analyses of data (Hong and Page 2004).
(*4*) Our goals should include to "do no harm" as a basic tenet of training. Our current model of hyper-competitiveness and capitalistic mindset does not put ethics at the center of understanding biology and nature and can be exploitative of Earth's resources and communities (Koslowski and Buchanan 1996; Griffin et al. 2020).

Structure and function of research

Integrating biology programs

Creating integrative biology programs will require intentionally developing departments or institutes that allow overlapping expertise in multiple subfields of biology. Teaching, research and training at the interface will only flourish when an appropriate balance between specialized training and broadening of perspectives can be achieved. This will require carefully delineating the aspects that make a department or program be successful. Some universities and colleges are already developing such programs; the successes and failures (which should be expected with any new effort) of these efforts will need to be examined to create better integrative biology studies.

Some of the challenges we envision are as follows:

(*1*) Resources (including, equipment, spaces, and administrative support) need to vary drastically between different sub-fields of biology (Fitzgerald 1983).
(*2*) Currently, overlapping expertise causes competition between departments/programs when hiring faculty and filling teaching schedules. For integrative researchers, the efforts to satisfy multiple departments and their tenure and promotion requirements may distract from research and inhibit creativity (Bruhn 1997).
(*3*) The expectations for student training, course requirements, duration and compensation for postdoctoral work, and numbers of publications are different in each subfield of biology (Bunker and Clark 2010).
(*4*) Substantial changes to support and encourage interdisciplinary and integrative work likely requires a shift in a department's traditional strengths and goals. Departmental leadership may be reluctant to embrace such changes, especially if they are interpreted as a loss of control, self-determination, or identity (Bauder et al. 2018).

Some potential solutions for creating effective integrative fields are as follows:

(*1*) Cluster hiring of faculty with complementary disciplinary expertise and skill sets that meet the needs of integrative work. For example, some universities are experimenting with multiple departments pooling their resources to make new hires (Munyon et al. 2011).
(*2*) Internal reorganization of departments will require incentives from academic administrators and other external agencies, such as conversations with successful teams of researchers in integrative fields and funds to create multi-use spaces. Integrated programs will require new shared sets of expectations (Creaton and Heard-Lauréote 2019).
(*3*) Creating multidisciplinary institutes that are independent of university's tenure and promotion structures may incentivize collaborative and integrative work. For example, field stations often engage in integrative work and share their resources widely, even across universities (Tydecks et al. 2016). Recent NSF Research Coordination Networks also address this solution.
(*4*) Increasing independent support of students or projects in a way that allows for easier movement between laboratories to foster creative new partnerships.

Complex multidisciplinary research

Staggeringly large amounts of data are now available. Complex analyses of these data are needed to make informed decisions and require large and diverse teams of scientists working together (Wuchty et al. 2007; Börner et al. 2010; Nancarrow et al. 2013). No single individual is trained in the multiple fields that need to come together for these projects, including but not limited to mathematics, life science, social science, philosophy, history, ethics with additional expertise in managing large teams and effective communication. A multiplicity of perspectives are needed to make good decisions using vast datasets which will require including various stakeholders, including community partners (Yosso 2005).

Some challenges to large team-based multidisciplinary work are as follows:

(*1*) A lack of training to prepare members of diverse yet overlapping fields to work together, intentional development of leadership, and involving all relevant stakeholders (Boaz et al. 2018).
(*2*) A lack of understanding of the impact of data on multiple fields including but not limited to fields such as health care, economics, and environmental monitoring and remediation.
(*3*) Those holding power in decision making may not cede control; institutions—both academic and private sector—that currently place profit at the center of decision making will continue to perpetuate systems that entrench profit as the primary motivator (Ortiz et al. 2020).
(*4*) Identifying and dealing with the theoretical and ethical challenges presented by such studies (Tuck and Yang 2014; Tsosie et al. 2019).

Some potential solutions to these are as follows:

(*1*) Immediately developing bridging programs to build skills in areas adjacent to current training (Youngblood 2007). The goals of these programs should be to develop a diverse group of students from multiple disciplines to work on large datasets and pursue graduate work in these areas.
(*2*) Developing new types of graduate programs that depend on teams of students and faculty from multiple backgrounds (e.g., geographic, academic, cultural, linguistic, etc.) working together. Through such courses, participants learn to communicate across disciplinary boundaries. These experimental courses will then provide insights into developing functional research teams that involve multiple fields (Repko et al. 2019).
(*3*) Creating collaborative PhD theses which focus on students' ability to engage with the complexity of the project (Repko and Szostak 2021). Progression of the project by a team would be used for granting degrees instead of individual achievements.
(*4*) Incentivizing faculty professional development and willingness to engage in new methods of research and teaching (e.g., Pelletreau et al. 2018).

Open-access and equitable research practices

A philosophy of "open-access" was developed in an effort to make scholarly research available to those outside of elite academic institutions without access to similar resources. In principle, open-access should be unproblematic with multiple benefits (Eysenbach 2006). Shared datasets enable downstream meta-analyses and more effective training on real systems. Complementary analyses can enrich understanding of a system. For example, recent advances in data accessibility have increased the number of meta-analysis studies by 3.5-fold from 2010 to 2020 (33 studies in 2010; 117 studies in 2020; Web of Science search term "meta-analysis," refined by "biology" category).

Although the open-access concept ideally enriches all researchers, there are many concerns with the current open-access paradigm:

(*1*) The burden to fund open-access is placed on the researchers and institutions, limiting the creation of such material to elite academic institutions (Kamerlin et al. 2021).
(*2*) The current model incentivizes increased manuscript publications leading to monetary gains for for-profit journals. Professional editors are encouraged to accept research to improve the journal's impact factor (measured over the previous 2 years) rather than consider long-term impact on the progression of the field (Beall 2016; Teixeira da Silva et al. 2019).
(*3*) Tools and technology that facilitate research are often prohibitively expensive and unavailable to scientists who are not members of elite institutions, or who are outside of academia. This skews power in research (e.g., what research is done where, and by whom) away from the people that research most directly affects (Liboiron 2017).
(*4*) Open datasets are primarily serving interests of the researching bodies and do not take the perspectives of subjects/objects of study. The data can be extractive and may be used without the proper consent, which requires deeper understanding of the consequences of sharing. Marginalized communities need greater control of data and its usage (Harding et al. 2012; James et al. 2014; Beaton et al. 2017).
(*5*) Scientists disseminating open-access publications or datasets rarely share their resources outside of academia. Marginalized communities may not be aware of or know how to access and use datasets, even when they were involved in the study.

Even if data sharing were working optimally, many talented researchers, especially in less resourced communities, are unable to fully participate in science, which is to our collective detriment. Following suggestions provide better access to research along with providing access to data:

(*1*) Well-resourced researchers that work in remote areas or underfunded communities should collaborate with local scientists, include local students, and include all the stakeholders in that community. Ethical decisions regarding data, specimens or open-access that are made collectively with significant community input will improve the quality of science and its impact on the society (Tsosie et al. 2019).

(*2*) The high cost of specialized equipment can hinder advances in research in economically disadvantaged communities. Sharing the tools of science at a lower cost can make science more equitable, minimize the opportunity cost of interdisciplinary research, and may encourage the invention of new and customized scientific methods using open-access technology (Eriksen et al. 2018; Maia Chagas 2018).

(*3*) Well-resourced laboratories should aim to create tools that benefit all researchers. For example, open-access electronic devices and electronic Do-It-Yourself skills provide low-cost solutions (Liboiron 2017). Freely available programming languages, such as R or Python serve as good models. Freely available languages can further be supported with dedicated funding, as demonstrated by the NSF-funded National Evolutionary Synthesis Center developing tools for phylogenetic analysis in R. (https://www.nescent.org/cal/calendar_detail.php-id = 70.html).

(*4*) Accessibility should be of paramount concern throughout the research process, including collaboration and disseminating information. This includes creating and sharing media (such as video and audio) in multimodal forms, as detailed in access standards such as the Web Content Accessibility Guidelines (Caldwell et al. 2008) and the Universal Design for Learning (CAST 2018). Resources led by disabled scientists and scholars, such as "Nothing about us without us" (Charlton 2000) provide guidance for creating inclusive scientific communities and workflows. Large funding agencies can and should provide leadership to support this by requiring accessible deliverables from grantees and enhancing diversity/access supplements to enable full participation of scientists and trainees.

(*5*) Data must be presented in formats that are accessible and understandable by a diverse set of users beyond the experts in a particular field. Public data need to be collected and reported on shared platforms, perhaps funded and maintained by national organizations or well-established publishing platforms. For example, "The iDigBio" community seeks to facilitate digital specimen data sharing. Video data that have been collected in many different formats are being standardized for providing stable repositories (Brainerd et al. 2017).

Anti-racist biological sciences: addressing the function of the structure of research

Scientists too often want to believe that science can be objective and free of bias. However, science is a human endeavor, as evidenced by eugenics, Eurocentric human genome research, and unequal and discriminatory access to health care (Mackie and Hamilton 2014). The concept of science as pure and objective glosses over the racist history of biology, such as the intentional infection of Black men with syphilis (in the Tuskegee trials) or the theft and widespread use of HeLa cells without the consent of the Black woman whose cells they are, or remuneration of her family. Such cultivated ignorance does not allow for critical examination of who participates in science, who is included (and when), the questions we ask (or don't), whose voices are heard, and who benefits from publicly funded research (Hooks 1994; Wuchty et al. 2007; Glaude 2020). Systematic racism permeates the structures of academic science, the culture of which is based on success of privileged white men and has been only slightly updated since the 1800s. It is past time to examine the structures of science and make science more inclusive and humane (Schell et al. 2020).

Some challenges to this endeavor are as follows:

(*1*) Scientists' belief that science is objective despite the evidence to the contrary (Natorp and Kolb 1981; Andersen et al. 2019).

(*2*) It is difficult to give up unearned privileges, especially those which have been so long-present as to be invisible to the people who have them (McIntosh 1988; Pease 2013).

(*3*) There is always resistance to change that is perceived as inconvenient or not beneficial to the people who hold the most power (Ford et al. 2008; Kanter 2008).

Incremental steps can be taken to practice anti-racist science. Some solutions can be implemented more easily than others, but all will require intentionality and inclusion of diverse participants (Collins 2019). Many of the following solutions below will seem familiar from prior sections:

(*1*) To immediately increase the diversity of participants recruited and retained in science through targeted hires, fellowships, and admission to training programs, as well as comprehensive career-long support for the participants (Fournier et al. 2019).

(*2*) To examine mainstream perspectives and broaden our lens (see sections "Methods in the biological sciences," "Complex multidisciplinary research," and "Open-access and equitable research practices").

(3) To decrease the value placed on appearing "expert" instead of practicing science. People should have multiple entry points into scientific practice and discourse (Kerr et al. 2007; Ribeiro and Lima 2015).

(4) To use real-life problems in teaching and learning science along with genuine engagement with local communities to assist their efforts (e.g., no white saviors dictating what problems confront communities and then deciding how to best address them).

(5) To actively acknowledge, discuss and learn from past harms done by scientists in order to build trust in science. This includes accepting refusals of communities and individuals to participate in research and recognizing their right to bar researchers from accessing their data, resources, and knowledge (Walter et al. 2020).

(6) To broaden scientific training of science to include ethics, history, and philosophy of science.

(7) To decrease the use of jargon and increase public dissemination of science (Druschke et al. 2018).

(8) To increase holistic participation in the practice of science via increases in fellowships, internships, apprenticeship at all levels from early education to K-12 teachers to non-scientists (Fournier et al. 2019).

(9) To develop a framework that encourages multiple hypotheses and multiple analyses—opening spaces for various legitimate interpretations of data.

(10) To decrease focus on a single expert and their opinions in defining a field, which is accomplished by moving away from a competition-based mindset with an emphasis on solving problems over celebrating individuals (Larivière et al. 2016).

(11) To increase greater participation in problem solving; for example, crowd-sourced and game-based approaches have advanced protein and RNA folding research and been used to predict COVID-19 infections (Menni et al. 2020).

Conclusion

Integrative scientific inquiry is impossible without equity at every level of inquiry—from the recruitment, promotion and retention of research professionals to the choice of study systems, hypotheses, and analytical approaches. The systemic exclusion of people and perspectives impedes creativity and reduces the nuance present in our disciplines. Critically, justice efforts cannot be pursued solely to recuperate the productivity and innovation lost: science that does not represent society is inherently incomplete.

Current solutions are too little too late and fail to address the structural issues holding back the way we incorporate diverse peoples and ideas into biology. Recognizing how intersectional injustices manifest across our field is the first step in finding solutions that go beyond single issues. As a scientific community, we frequently highlight how resources are awarded to R1, white man-dominated non-interdisciplinary research groups and individuals (Payne 2000; Payne and Siow 2003; Ceci and Williams 2011), but institutions have changed nothing to address how the bulk of funding and university support structures are allocated. Targeted equity measures are not enough. They contribute to tokenization and represent a lack of commitment to anti-racism, anti-discrimination, and justice (Kelly et al. 2017; Ng et al. 2017). In this article, we have highlighted a variety of ways in which peoples and ideas are systematically and pointedly silenced by individuals and institutions in biology. We have identified starting points for remedying how biology has discouraged and harmed both scientists and non-scientists, while acknowledging there is a long path forward. **This path must be built using field-wide solutions and institutional buy-in: our solutions must match the scale of the problem.** Together, we can integrate—not reintegrate—the nuances of biology into our field.

Author contributions

All authors formed the initial ideas collectively; R.L.T., N.G., and T.Y.M. led the revisions; all authors edited the manuscript.

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