© 2024. Published by The Company of Biologists Ltd | Development (2024) 151, dev202342. doi:10.1242/dev.202342

PERSPECTIVE

Pluripotency of a founding field: rebranding developmental biology

Crystal D. Rogers[1,*], Chris Amemiya[2], Swathi Arur[3], Leslie Babonis[4], Michael Barresi[5], Madelaine Bartlett[6], Richard Behringer[3], Blair Benham-Pyle[7], Dominique Bergmann[8], Ben Blackman[9], C. Titus Brown[10], Bill Browne[11], Jasmin Camacho[12], Chiswili Yves Chabu[13], Ida Chow[14], Ondine Cleaver[15], Jonah Cool[16], Megan Y. Dennis[17], Alexandra Jazz Dickinson[18], Stefano Di Talia[19], Margaret Frank[20], Stewart Gillmor[21], Eric S. Haag[22], Iswar Hariharan[23], Richard Harland[23], Aman Husbands[24], Loydie Jerome-Majewska[25], Kristen Koenig[26], Carole Labonne[27], Michael Layden[28], Chris Lowe[29], Madhav Mani[27], Megan Martik[23], Katelyn McKown[30], Cecilia Moens[31], Christian Mosimann[32], Joyce Onyenedum[33], Robert Reed[4], Ajna Rivera[34], Dan Rokhsar[23], Loic Royer[35], Flora Rutaganira[36], Rachel Shahan[37,38], Neelima Sinha[39], Billie Swalla[40], Jaimie M. Van Norman[41], Daniel E. Wagner[42], Athula Wikramanayake[11], Sophia Zebell[43] and Siobhán M. Brady[44,*]

[1]Anatomy, Physiology, and Cell Biology, School of Veterinary Medicine, University of California Davis, Davis, CA 95616, USA. [2]University of California, Merced, Department of Molecular and Cell Biology and Quantitative and Systems Biology Program, 5200 N. Lake Road, SE1 262, Merced, CA 95343, USA. [3]The University of Texas, MD Anderson Cancer Center, Houston, TX 77030, USA. [4]Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, NY 14853, USA. [5]Smith College, Northampton, MA 01063, USA. [6]Biology Department, University of Massachusetts Amherst, Amherst, MA 01003, USA. [7]Stem Cell and Regenerative Medicine Center, Baylor College of Medicine, Department of Molecular and Cellular Biology, Baylor College of Medicine, Houston, TX 77030, USA. [8]Department of Biology and HHMI, Stanford University, Stanford, CA 94305, USA. [9]University of California, Berkeley, Berkeley CA 94720, USA. [10]Population Health & Reproduction, School of Veterinary Medicine, University of California Davis, Davis, CA 95616, USA. [11]Department of Biology, University of Miami, Coral Gables, FL 33146, USA. [12]Stowers Institute for Medical Research, Kansas City, MO 64110, USA. [13]Biological Sciences, University of Missouri, Columbia MO 65211, USA. [14]Society for Developmental Biology, Rockville, MD 20852, USA. [15]Department of Molecular Biology, Center for Regenerative Science and Medicine, UT Southwestern Medical School, Dallas, TX 75390, USA. [16]Chan Zuckerberg Initiative, Redwood City, CA 94063, USA. [17]Genome Center, MIND Institute, and Department of Biochemistry & Molecular Medicine, University of California, Davis, CA 95616, USA. [18]Department of Cell and Developmental Biology, School of Biological Science, University of California San Diego, La Jolla, CA 92093, USA. [19]Department of Cell Biology, Duke University Medical Center, Durham, NC 27710, USA. [20]School of Integrative Plant Science, Cornell University, Ithaca, NY 14853, USA. [21]Unidad de Genómica Avanzada, CINVESTAV-IPN, Irapuato, Guanajuato 36824, Mexico. [22]Department of Biology, University of Maryland, College Park, MD 20742, USA. [23]University of California Berkeley, Department of Molecular and Cell Biology, Berkeley, CA 94720, USA. [24]Department of Biology, University of Pennsylvania, Philadelphia, PA 19104, USA. [25]Department of Pediatrics, Human Genetics, Anatomy and Cell Biology, McGill University and Research Institute of the McGill University Health Centre at Glen Site, Montreal, QC H4A 3J1, Canada. [26]Harvard University, Cambridge, MA 02138, USA. [27]Department of Molecular Biosciences, Northwestern University, Evanston, IL 60208, USA. [28]Department of Biological Sciences, Lehigh University, Bethlehem, PA 18015, USA. [29]Hopkins Marine Station, Department of Biology, Stanford University, 120 Oceanview Blvd., Pacific Grove, CA 93950, USA. [30]Department of Biology and Stanford Introductory Studies, Stanford University, Stanford, CA 94305, USA. [31]Fred Hutchinson Cancer Center, Seattle, WA 98109, USA. [32]Children's Hospital Colorado, Department of Pediatrics, Section of Developmental Biology, University of Colorado School of Medicine, Anschutz Medical Campus, 12801 E. 17th Avenue, RC1 South, 12114, Aurora, CO 80045, USA. [33]School of Integrative Plant Sciences and L. H. Bailey Hortorium, Cornell University, Ithaca, NY 14853, USA. [34]University of the Pacific, Stockton, CA 95211, USA. [35]Chan Zuckerberg Biohub, San Francisco, CA 94158, USA. [36]Departments of Biochemistry and Developmental Biology, Stanford University, Stanford, CA 94305, USA. [37]Department of Biology, Duke University, Durham, NC 27708, USA. [38]Howard Hughes Medical Institute, Duke University, Durham, NC 27708, USA. [39]Department of Plant Biology, University of California, Davis, CA 95616, USA. [40]Biology Department and Friday Harbor Labs, University of Washington, Seattle, WA 98195, USA. [41]Department of Botany and Plant Sciences, University of California, Riverside, Riverside, CA 92521, USA. [42]Department of Obstetrics, Gynecology and Reproductive Science, University of California, San Francisco, CA 94143, USA. [43]Cold Spring Harbor Laboratory, Cold Spring Harbor, NY 11724, USA. [44]Department of Plant Biology and Genome Center, University of California, Davis, CA 95616, USA.

*Authors for correspondence (crdrogers@ucdavis.edu; sbrady@ucdavis.edu)

C.D.R., 0000-0002-9549-1089; S.M.B., 0000-0001-9424-8055

ABSTRACT

The field of developmental biology has declined in prominence in recent decades, with off-shoots from the field becoming more fashionable and highly funded. This has created inequity in discovery and opportunity, partly due to the perception that the field is antiquated or not cutting edge. A 'think tank' of scientists from multiple developmental biology-related disciplines came together to define specific challenges in the field that may have inhibited innovation, and to provide tangible solutions to some of the issues facing developmental biology. The community suggestions include a call to the community to help 'rebrand' the field, alongside proposals for additional funding apparatuses, frameworks for interdisciplinary innovative collaborations, pedagogical access, improved science communication, increased diversity and inclusion, and equity of resources to provide maximal impact to the community.

Introduction

Developmental biology, the integrative study of change in multicellular organisms across space and time, is a foundational field of science that has seeded many new disciplines, leading to the emergence of diverse research fields, analogous to a pluripotent stem cell in a developing embryo (Gilbert, 2017). Despite its continued successes, many researchers in the field feel that it is – or is at least perceived to be – in decline (St Johnston, 2015; Stern, 2022; Wallingford, 2019; Zon, 2019). This suggestion, beyond perception, also creates inequity in opportunities for discovery. Two significant challenges facing the community are: (1) articulating the broad spectrum of science that should be considered developmental biology and (2) integrating the researchers who are studying developmental biology but do not necessarily identify themselves as doing so. The concepts of unity and diversity are equally important sides of the same coin when accessing opportunities in academic spaces. Expensive '-omic', imaging and other technologies have created inequalities between labs, and we need to ensure that all in our community have the opportunity to contribute, regardless of their funding situation and their choice of experimental approach.

At the 'Envisioning the Future of Developmental Biology' workshop, in Napa, California, USA, in March 2023, 50 developmental biologists convened to discuss these issues. Together, and as discussed in this Perspective, the group proposed

Development (2024) 151, dev202342. doi:10.1242/dev.202342

creative solutions to help achieve equity of access to resources and maximize impact across the field of developmental biology.

Moving forward as a community

Now is the time for all developmental biologists to take ownership of our love for this field of research. *We are one community*. Despite the differences in our scientific questions, the organisms we study to understand life, and the tools we employ, we are united in our study of organismal change across space and time. Developmental biology, among all disciplines, is uniquely positioned to define how life forms and changes. However, many of us could be more flexible in our approaches. By definition, developmental biology studies evolve as the foundational concepts, both concrete and abstract, evolve. In light of this flexibility, we should demonstrate an eagerness to change with the times. We need to create a more diverse community that embraces and supports the inclusion of those with different expertise and those who are historically excluded. We need to support potential future developmental biologists with pedagogical approaches that incorporate developmental biology as early as possible in the undergraduate curriculum, not only in a wide variety of biology courses, but also in other scientific classes, including physics, chemistry, engineering, environmental sciences, and food security. We need to take advantage of the beauty and wonder of our systems and communicate the power of our approaches by employing hands-on research, engaging funding agencies, sharing our findings through media that attracts a broad audience, and advocating for the inherent importance of description as a foundation for elucidation of novel scientific paradigms. We can expand our reach by communicating the wonders of developmental biology in our daily lives and by straightforward conversations about relevant concepts with family, children and friends. What could be more impactful than understanding how organisms change over time? Our field is necessary to understand evolution, aging, stem cells, disease progression, congenital anomalies, plant and animal responses to climate change, and the natural world in general. We must come together to fight for our field, our researchers, our well-studied model organisms, and the vast diversity of understudied organisms that inhabit our planet and may unlock new answers.

Where we are

Developmental biology has launched some of the most exciting and dynamic fields in biomedical research, including stem cell and regenerative biology, and has made seminal contributions to understanding the causes of congenital and pathological diseases. With cultivation, developmental biology's continued influence on fundamental knowledge with translational societal impact can be tremendous. In addition, at its core, developmental biology research harnesses techniques and concepts from other fields, including cell and molecular biology, genetics, computer science, biochemistry and physics, to answer questions about how organisms develop. Complementing our traditional tools and techniques to 'observe and perturb' the mechanisms that regulate how an organism grows and lives, we now have a suite of novel technologies at our disposal. For example, our ability to generate organoids and embryoids can be used to tackle questions related to early human development, as well as the identification of potential causes of disease – and their cures. An excellent case of how expanding the research toolkit can identify unifying principles of development is in the rapid growth of transcriptomic approaches that visualize gene expression at unprecedented spatial and temporal resolution. For example, we can now combine data from single-cell RNA sequencing, advanced *in situ* techniques such as hybridization chain reaction (HCR), and live imaging to gain unprecedented insights into cellular trajectories through development, as exemplified in the recently preprinted Zebrahub dataset (Lange et al., 2023 preprint). We can identify every gene expressed in a cell at a given time and compare it directly to other individuals within or across species. Such studies have revealed that the transcriptomes of some cell types have diverged more rapidly than others, including via the 'repurposing' of gene circuits from other cell types, for example in grasses (Guillotin et al., 2023).

Our evolving understanding of the developmental dynamics underlying plant form and function, combined with advanced genome-editing technologies, has driven advances in crop breeding and agricultural improvement (Boden and Ostergaard, 2019). A rich exploration of structure and function has fueled research into environmental impacts on whole organisms. We, as a field, need to ensure that developmental principles and concepts remain at the center of conversations about the discoveries made in these and other applied fields.

Although we, as a society in general, are more connected now than ever before, communication amongst developmental biologists remains limited across the perceived chasms of research organisms, technological approaches, institutional types, career stages, and professional networks. We need more support for cross- and interdisciplinary collaborations across specialties, organizations and species. Although small, broad-scope meetings for the field do exist, our discussions are too often limited to our professional echo chambers. There can be a tendency to opt out of conference sessions and seminars focusing on organisms, processes or fields other than those we study, reflecting our disconnect. However, we should spend our time on these efforts because novel collaborations and discoveries come from new interactions and ideas.

Where we want to be

Developmental biology has its roots in the detailed observation of dynamic biological systems, but these studies have not always been well integrated with other fields. New interdisciplinary collaborations, bringing together developmental biologists and computer scientists, biochemists, physicists, population geneticists, ecologists and engineers, are starting to emerge, providing original ideas, approaches and technologies that will help us to understand the full complexity of developmental systems and how this complexity informs our natural world. Developmental biology can further guide studies inspired by biological systems, including material sciences, engineering, and even biomimicry in architecture. To increase the visibility and power of developmental biology research, we need to become more effective communicators within and between all fields that touch developmental biology so that there is a broader recognition of our transformative potential. We must communicate the novel biological questions that remain unanswered, challenge our rules, and reveal new paradigms.

Discoveries in developmental biology, from the identification of key signaling pathways to the reprogramming of cellular identity, have been foundational for other fields, particularly in the medical sciences. Many of these discoveries have been driven by powerful genetic approaches in model organisms, and modern technologies now allow such approaches to be used in many more and varied organisms. These technologies will undoubtedly result in more fundamental (and surprising) discoveries. The future of developmental biology will be powered by the detailed exploration of unique traits and the identification of unifying principles through comparative efforts, particularly by using traditionally understudied organisms. To achieve these goals, we

Development (2024) 151, dev202342. doi:10.1242/dev.202342

need to increase the accessibility of new technology, and also to provide a detailed understanding of 'wild type', necessitating high-quality descriptive studies in a wide range of diverse systems. The overarching aim to define the conserved and divergent mechanisms of development will require collaborations between researchers working on divergent species and will also require us to integrate advances in our understanding of the origins of multicellularity and the evolution of complex body plans from the fungal and protist lineages in the tree of life.

We must envision and design experiments that have the potential to reveal paradigm-shifting discoveries using cellular-resolution epigenetic, transcriptomic, proteomic and metabolomic studies in the context of evolutionarily diverse species. As discussed further below, such efforts will require us to expend significant efforts in improving our ability to process, manage and share data, both to take full advantage of the rich wealth of information contained in these datasets, and to reduce inequities across the field. We will also gain significantly from collaborating with computational and data scientists – not just as an afterthought, but by including them at the earliest stages of project planning.

In summary, we should cultivate the notion that research in diverse, emerging research organisms can be as crucial as a deep dive into a small number of model organisms. Promoting the use of each organism for its strengths in a complementary way should be the way forward. Incorporating intuitive public access to data resulting from new technologies in both non-traditional and 'model' organisms will help enable the results of these technologies to be more easily accessible. The extensive resources generated for a handful of organisms serve as a base for nearly all comparative studies, and projects that develop such resources should continue to be fostered.

How we get there: a community call to action

Action Item 1: Identify new paradigms and increase the diversity of studied organisms

As a field, we have largely focused in recent decades on a small number of experimentally tractable organisms. However, advances in sequencing and genome-editing technology now facilitate our return to exploring biological diversity, comparative studies, and the characterization of novel biology. We are poised to 'zoom out' and understand the diverse and complex mechanisms driving development in many more plant and animal representatives from the tree of life. Although our traditional models will continue to provide value and enhance discovery for years to come, we can now pick the best model system to answer key developmental questions rather than fitting our questions onto a limited number of models. Moreover, research into understudied organisms allows us to probe some of the global challenges we face – such as how plants and animals can adapt to changing external environments – and provide insights to underpin medical advancements. For example, *Astyanax mexicanum* (cave fish) morphs have lost their eyes and adapted their metabolism to survive in extreme environments that would cause starvation or disease in other organisms (Riddle et al., 2018). Emerging models such as the liana *Paullinia* can help us understand the evolutionary developmental origin of the woody plants that make up our forests (Chery et al., 2020). Research into continuous stem cell renewal in species such as the freshwater polyp *Hydra vulgaris*, which are essentially immortal, can give us clues into the conserved and divergent mechanisms controlling regeneration, aging, and diseases such as cancer (Cazet et al., 2023; Moltzahn et al., 2008; Pillai et al., 2021).

We propose an integrated community-driven and community-supported approach that leverages available funding and technology and combines with our collective knowledge. One solution might be the creation of an international committee whose goal is to understand where the gaps are, and which organisms should be studied, to understand the evolution of development. This committee should consider the phylogenetic position, the exhibition of novel traits, and the capacity for genetic manipulation or transformation, and provide informed recommendations to funding agencies and societies. From a practical perspective, this should be accompanied by efforts to define and bring together a community of scientists who work on such new representatives to share the practical challenges of this work and provide training opportunities. A recent example of a meeting of this sort (organized by Development and The Company of Biologists) is the 'Unconventional and Emerging Experimental Organisms in Cell and Developmental Biology' conference held in Surrey, UK, in 2023. Another highly successful example of training developmental biologists to consider a broader range of model systems is the Marine Biological Laboratory (MBL) Embryology Course in Woods Hole, Massachusetts, USA, which uses a pure discovery approach to study organisms randomly sampled from a natural environment or provided by experts. We propose to use these as frameworks to expand initiatives focused on the adoption of new organisms for study. To make these opportunities available to as many in the community as possible, workshops could be added to key developmental biology meetings. Communities could also collectively seek funds to support the development of facilities for housing new research organisms and identify collaborators to mentor new scientists as they adopt these systems.

Action Item 2: Increase funding for projects that incorporate developmental biology and decrease gatekeeping of funding opportunities

Acquisition of funding for purely developmental biology-focused projects is challenging as more funding institutions require translational or technological impact in funded projects. Although there are multiple public and private funders of science (for a list of funding opportunities available to US-based researchers, see Table S1), many are moving away from discovery-based science on the premise that our knowledge of biological processes is sufficiently impactful. The difficulty in securing funding is perhaps emblematic of the challenges we face in communicating the importance and societal impact of our research – we need to do better in selling the 'big picture'. Moreover, we have become conditioned to prioritize projects that focus on molecular mechanisms in a few select organisms to answer developmental questions rather than assessing the importance of the questions and the approach in general. Thus, grant applications for research in less well-established systems are often unsuccessful, and papers are often rejected from high-profile journals for being insufficiently 'mechanistic'.

It is challenging to secure reviewers of grants and manuscripts in every scientific field, and developmental biology is no exception. We propose that the community generates and maintains a database of potential willing reviewers who recognize the importance of descriptive and discovery-based science and who commit to providing constructive review. In this way, we can reduce the gatekeeping that prevents funding of developmental biology grants and papers from being accepted into key journals. We can additionally capitalize upon the strength and generosity of our community by sharing success stories – this database could include examples of successful grants to help others seeking similar funding. We propose that inviting members of national (and international) societies to join such a database could be a mechanism to achieve this goal.

Development (2024) 151, dev202342. doi:10.1242/dev.202342

In Box 1, we propose a number of changes to our funding mechanisms to better support our community. There are examples of the kinds of innovative funding mechanisms we propose. For example, in the context of climate change, a recent program solicitation from the National Science Foundation (NSF) seeks to create a 'Synthesis Center for Understanding Organismal Resilience' and fund six to ten 'Organismal Responses to Climate Change' projects. More opportunities like this, which link organismal biology with environmental changes, would clearly benefit our society.

Action Item 3: Increase the diversity of our scientists

In addition to diversity in the organisms we study, we must actively diversify our scientific community. This effort could be accomplished using multiple methods. First, we need to recruit outside of our majors and departments to seek out students who do not already have existing interests in developmental biology. To capture the interest of new students, we can market the societally relevant aspects of developmental biology, such as food insecurity (developing climate change-resistant crops or the importance of nutrition in embryonic development), environmental justice (the adverse effects of exposure to toxins and toxicants during pregnancy, particularly in poor and marginalized communities), reproductive rights (in-depth knowledge from fertilization through fetal development to birth), and congenital diseases (hereditary and environmental causes). Faculty need to be willing and flexible to allow students to follow their curiosities and share their research with their peer community to capture emerging talent.

In addition, paid training or mentorship opportunities can increase the recruitment and retention of students from historically excluded communities. Programs that recruit students from historically black colleges and universities (HBCUs), primarily undergraduate institutions (PUIs), or low-resourced public institutions focus on expanding the reach of the field to groups that may not have prior knowledge of it. At the undergraduate level, programs such as the Society for Developmental Biology (SDB) 'Choose Development!' (Unguez et al., 2021) and the 'Developing Future Biologists' (DFB) (Graniel et al., 2023) programs provide resources in the form of hands-on laboratory research and interactions with current trainees and faculty in developmental biology. Additionally, the NSF and National Institutes of Health (NIH) provide funding for undergraduates to gain research experience, but these are limited because US citizenship or permanent residency is required of the participants for the majority of them. Expanding such initiatives in an international context would provide opportunities for many young people who would not currently consider research as a potential career.

Graduate students and their advisors can apply for the Howard Hughes Medical institute (HHMI)-funded Gilliam Fellows Program, which supports pairs of scientists who are committed to building an equitable and inclusive scientific culture. For postdoctoral fellows, current programs such as the Leading Edge Fellows program supported by HHMI and the Tara Health Foundation, as well as the GetHIRED! course created by the SDB provide professional growth opportunities and training that can better prepare developmental biologists to climb the career ladder (with the former providing support specifically to women and non-binary scientists). These well-trained scientists should be invited to give talks at conferences and in departmental seminars to extend their reach.

Action Item 4: Integrate developmental biology concepts in education

Teaching is a crucial part of communicating science, and we need to adapt our methods to revitalize the field of developmental biology. A significant challenge is capturing the interest of first- and second-year undergraduates, as developmental biology is often only offered in elective courses at later stages. We advocate for the incorporation of developmental biology within the core curriculum for biology majors. Indeed, developmental biology is the root from which novelty in multicellular organisms arises and should be a base for all biological studies taught at the undergraduate level. If incorporating developmental biology in these earlier courses is not feasible, one can use a 'stealth' approach to sneak concepts from our field into relevant courses such as genetics, molecular biology, and botany, as has worked for other topics in the past (Alberts, 2022; Haga, 2006; Korf, 2002; Lee, 2016). Communication of the importance of developmental biology to college advisors is also a crucial tool: if we can convince them, they have the power to convince their advisees of the same.

We need to take advantage of the beauty of development when teaching undergraduates. Simply observing development in real

Box 1. Improving the funding climate in developmental biology

- Given few funding opportunities, developmental biologists are forced to compete with each other for a limited pool of money. Having more and diverse funding opportunities may help guide scientists to apply only to the most relevant calls. Scientists must be educated about these opportunities, as the funding sphere is often opaque, particularly for those from first-generation or historically excluded populations.
- Creating new funding opportunities for multi- or interdisciplinary approaches that explicitly include developmental biology will expand the scope of discovery and potential impact of findings. Mechanisms to fund approaches that integrate developmental biology with translational or applied research themes could be achieved through integrated support across multiple government agencies or private funders.
- We should advocate for the creation of funding opportunities specific to exploratory or descriptive work – essential groundwork for innovation. Importantly, review panels must be educated on the importance of such funding mechanisms, how scoring these grants differs from traditional methods, and on ensuring more equitable funding.
- Funding agencies should also consider providing explicit financial support for experts in modeling, statistics, or computational biology at the beginning of the project to assist in experimental design. This inclusion will improve the efficiency and use of research funds with a more streamlined experimental methodology.
- Public funds should continue to support model organism databases, which are essential for continued discovery at the current rate of progress. Currently, multiple databases, including FlyBase (Gramates et al., 2022), UCSC Genome Browser (Kent et al., 2002), WormBase (Davis et al., 2022) and ZFIN (Bradford et al., 2022), among others, are supported by public funds through the US-based National Human Genome Research Institute, but these projects are at risk (Cheng et al., 2022).
- To provide expanded opportunities for US-based developmental biologists to apply for NSF funding, we recommend changing the focus of NSF Biology from 'Understanding the structure and function of organisms' to 'Understanding the structure, development and function of organisms', and changing the descriptor to 'We support research aimed at understanding how organisms develop and function as units of biological organization'.
- By generating more publicly funded service centers, with sliding scale costs, we can increase accessibility of new technology to institutions with limited financial resources.

Development (2024) 151, dev202342. doi:10.1242/dev.202342

time using microscopy can be a way to 'hook' students on the wonder of the field (and in a very cost-effective way). Students also want to learn and embrace new technologies they have heard about in the news, such as CRISPR. We advocate for 'teaching like a chef': showing the final product and then demonstrating piece-by-piece how the hierarchal scales of organization work together to build an organism. For example, we can use this approach to compare the embryos of a deuterostome versus a protostome. Show students the final form – a human versus an insect – and then take them through the developmental processes that give rise to these distinct body plans. In doing so, teach them what it feels like to be a scientist – how to look, think, inquire and test – and, as part of this, teach the innovative methodologies (such as CRISPR) that underlie that testing.

As discussed above, technology has radically transformed our ability to answer previously unsolved biological questions and to generate massive amounts of data that can be mined to formulate new questions and hypotheses. We advocate for the teaching of computational literacy at the earliest stages and propose that training in computational biology should be mandatory within the graduate student curriculum.

Finally, developmental biology should also be a component of core curricula within additional science courses, including microbiology, ecology, physiology, environmental toxicology, physics, chemistry, math and engineering. As a community, we can support this effort by curating case studies of the intersections between developmental biology and these diverse fields. For example, integrating development and microbiology allows us to understand the influence of the microbiome on organismal health and behavior, and integrating developmental biology, genetics and physiology would allow us to explain the relevance of the newly approved CRISPR-mediated sickle cell anemia treatment. Organoid culture technologies rely on principles from physics and engineering. Environmental pollutants have enormous effects on organismal development, and we can learn how particular chemicals cause disease by studying their impacts on development. These examples and others will enrich courses across a wide range of scientific disciplines.

Action Item 5: Improve data sharing and access to new technology

In addition to educating biologists in computational literacy at an early career stage, we need training and support for scientists to ensure good data management in research projects, with a particular focus on data accessibility. With the expansion of open-access publishing methods, preprint servers and open-access databases, restricting access to data or training methods can no longer be justified as the practice expands and prolongs inequities. Those generating publicly available datasets must ensure rigorous data curation, employ the FAIR (Findability, Accessibility, Interoperability and Reuse of digital assets) principles for data management (Wilkinson et al., 2016) and, ideally, develop accessible web interfaces for exploring the data. Moreover, we have a responsibility to set and uphold standards for statistics and rigor to ensure reproducibility and to campaign for public funding to maintain databases and repositories, ensuring accessibility.

We must also address the inherent financial barriers to adopting new technology. These limitations will ultimately stifle their adoption and reinforce inequity in the field. Whereas some labs can spend $20,000 on a single-cell or spatial transcriptome sequencing project for an individual trainee, others are limited by a lack of funding, infrastructure, resources, or technical knowledge. Data accessibility will bridge some of these barriers and reduce inequities, but we also need to increase access and reduce gatekeeping for technology. We cannot ignore the importance of universities with fewer resources, including PUIs, HBCUs, other minority-serving institutions (MSIs), and those that educate students from underserved and rural communities. Regional service centers can help enable access to new technologies, but we should bear in mind that by the time technology is affordable for all, it is often no longer considered cutting edge. Many scientists who develop new technology face the problem of maintaining these exciting technical advances, and we could do more to provide mechanisms to make new (non-commercial) techniques generally accessible.

Action Item 6: Improve communication between scientists and the general public

Communicating the worth, impact and significance of our scientific endeavors is crucial to achieving greater relevance and opportunity within the scientific community and the public (for a list of actions individuals can take to support this action, see Box 2). Legislators often need help understanding the integral societal importance of funding mechanistic and basic research (Safford and Brown, 2019; Smith et al., 2022), as was overtly demonstrated during the 2008 USA Presidential race when Vice Presidential candidate Sarah Palin suggested that research using fruit flies had 'little or nothing to do with the public good' (https://www.science.org/content/article/french-fruit-fly-fracas).

Scientists are highly trained to follow protocols, use field-specific jargon and discuss their work with colleagues, but many of us struggle to communicate what we do in our labs to our family and friends. One targeted mechanism to fix this issue is the use of explicit training to communicate with the public. We propose

Box 2. Suggestions for individual developmental biologists to increase visibility and impact

- Make yourself findable – are you Googleable? Are your Google Scholar and lab/personal websites up to date? Are you on social media sites? Are you open to collaboration?
- Invest in setting up working relationships (socially) before actually working together – this can be done virtually. Do not limit yourself to those in your direct or adjacent research fields; cultivate interactions with those in distant fields (e.g. physics, chemistry, structural biology, and computer science).
- Value the expertise of others and the potential synergy in collaborations. It is vital to remain open to learning and be willing to learn a new scientific language.
- Be concise in communication and use everyday language, avoiding jargon. Recognize and accept that telling a good story that makes your research accessible may mean sacrificing details that are important to you, but that may be unnecessary to communicate with a collaborator.
- Bring people together by collaborating with peers to apply for workshop funding (such as the workshop that resulted in this document).
- Communicate the advantages of your system(s) with the public and with your colleagues. Learn how best to articulate why your model is particularly suitable for addressing your question of interest (and why that question is important).
- Be available for comment. We are experts in biological change across time and scale, and our opinions would be informative to the media, university communications teams, and to people across all echelons of society.
- Take advantage of any media/communication training offered by your institution or society.

Development (2024) 151, dev202342. doi:10.1242/dev.202342

creating workshops led by marketing/communication professionals to train developmental biologists at all levels in communicating their research in the news and how to impart zest for the field. An ideal forum for this training would be via academic societies, such as the SDB or British Society for Developmental Biology (BSDB), or at field-specific conferences.

A second idea is based on the adage, 'a picture is worth a thousand words'. Developmental biology arguably produces some of the most beautiful, award-winning, scientific images and movies, scaling from the cellular to the organismal (Fig. 1). Broadly advertising these images to the public is an effective way to communicate what we do, demonstrate the power of this research field, and build enthusiasm. For example, an exhibition coordinated by the American Society for Cell Biology (ASCB) and the National Institute of General Medical Sciences displayed large scientific images in the Gateway Gallery at Washington Dulles airport, a two-level walkway through which about 2.5 million passengers pass each year, allowing non-scientists to enjoy the wonder of life as we see it (https://www.scientificamerican.com/gallery/dulles-airport-shows-beautiful-images-of-mouse-brain-and-zebra-fish-embryo/). A developmental biology conference recently hosted in Strasbourg, France, incorporated developmental biology images in bus stops, trains, and even an interactive video-mapping event in the city center (Masayuki and Reymann, 2023).

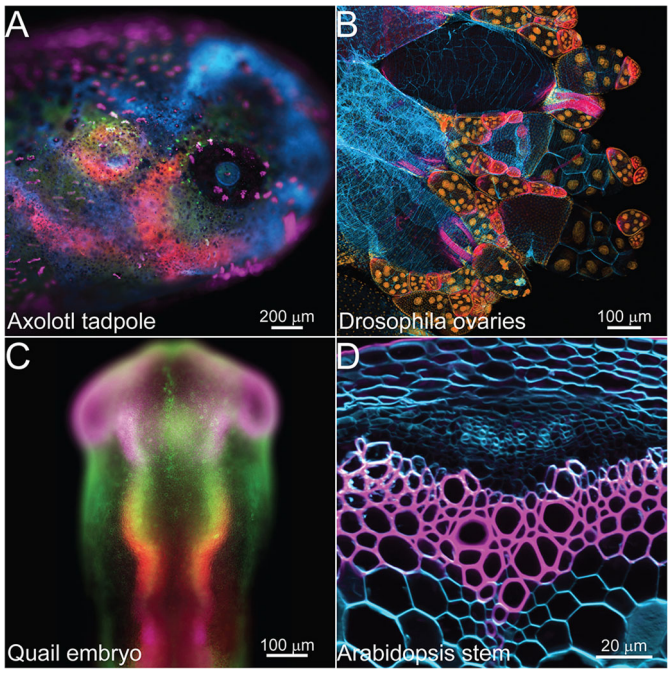

Fig. 1. Developmental biologists create true scientific art. (A) A lateral view wholemount image of an *Ambystoma mexicanum* (axolotl) stage 45 tadpole shows cartilage (red) and sensory cells (pink and green) visualized with immunohistochemistry and stained with DAPI to show nuclei (credit to Emma Marshall, Rogers Lab at UC Davis). (B) *Drosophila melanogaster* (fruit fly) ovary stained for cytoskeleton (blue), DNA (orange) and STAT-responsive cells expressing GFP (magenta). This image was a winner of the 2018 FASEB BioArt competition (credit to Rogers Lab at UC Davis). (C) A wholemount immunohistochemistry image of a 13-somite stage *Coturnix japonica* (Japanese quail) embryo stained for E-cadherin (cadherin 1; green), PAX6 (magenta) and PAX2 (orange), anterior to the top (credit to Rogers Lab at UC Davis). (D) A cross-section of an *Arabidopsis thaliana* (thale cress) stem stained with Basic Fuchsin to visualize lignin in the secondary cell walls (pink) and Direct Yellow-96, which shows cellulose (credit to Mona Gouran at UC Davis).

Developmental biology has a remarkable capacity to stimulate wonder and transform society. To bring this wonder to a broader audience, the community needs to know what developmental biology is. We propose that one way to support the field would be to produce accessible documentaries focused on the beauty and wonder of embryos, development, and regeneration of plants and animals. There are current efforts towards this type of communication. HHMI has created 'Films to Inspire', which are engaging and award-winning short science documentaries. The Science Education wing of HHMI could look for opportunities to collaborate with media companies to produce documentaries or to get involved with more creative projects. Currently, the BSDB is creating a documentary-style video focused on developmental biology labs and topics. Additionally, websites such as 'the Node' (https://thenode.biologists.com) host movies, images and blogs, which expand the footprint of scientists in the fields of cell and developmental biology and provide a public location that is free to access for the general public. Some societies provide training or funds to enhance scientific communication. The SDB has a Science Communication Internship where trainees learn about scientific writing and social media posting, and the ASCB offers a COMPASS Outreach Grant, which funds scientists who do public engagement. As an aspirational example, a collaboration between film-makers and botanists created the world depicted in Disney's Encanto (Adamo, 2022). How better to reach a wide audience than to promote visually stunning images and movies, charismatic scientists, and novel information about life to the public?

Science communication can improve the way our peers and the public engage with our research. To this end, improved science communication can also have positive societal impacts and can influence important decisions. For example, as developmental biologists, we can have significant societal impact on how the public understands reproductive health. Basic knowledge of developmental biology would help to improve equity in human rights across multiple spectra. Communicating our knowledge should plant seeds of the potential of our approaches and the value in our decades of community-generated knowledge, including to funding agencies. Thus, by improving the way we present our science to the public, we can hope to influence those who hold the purse strings for funding our research.

An eye towards the future: Moonshot thinking

The long-term future of our field relies on a healthy funding environment that ensures longevity, increases innovation, and supports discovery in developmental biology. As a group of active scientists, most of our thoughts are focused on upcoming papers we need to publish before the next grant cycle. Since the pandemic emergency, our concerns about grant funding are even more acute owing to supply chain issues, inflation, and cost-of-living increases. Given these concerns, how can public and private funders help us thrive in the short term? Then, with thoughts of the future, what bold and adventurous ideas can we propose to synergize across existing funding agencies, to take advantage of all that developmental biology has to offer, and to improve the prospects for the next generations of developmental biologists? Any ideas proposed should include a particular eye towards supporting those from historically excluded backgrounds who obtain significantly less funding (Chen et al., 2022; Ginther, 2022; Ginther et al., 2011). Here, we guide our potential funders and supporters to ideas that could lead to our 'best-case' scenarios. We note that these ideas should benefit all fields of research, but that some may be particularly impactful in our field, where the timescale of

Development (2024) 151, dev202342. doi:10.1242/dev.202342

experiments can often be very long. When funding agencies seek feedback from the community regarding their activities, we call on the community to provide input that can support our field going forwards. Our specific suggestions for funders are listed below.

- Increase funding lengths (from 4-5 years) to 7 years for all investigators. The time we spend constantly writing grants (particularly for historically excluded investigators, who spend two to four times more time on this activity because of lower success rates; Ginther, 2022; Ginther et al., 2011), could be spent engaging in scientific discovery, mentoring, and communicating our research to the greater community and society.
- Increase NIH (and other) budgets to reflect inflation rates. For example, annual budgets of $250,000, which have not increased at the NIH for 20 years, are worth approximately 55% of their original value due to inflation. Buying power is reduced and principal investigators cannot keep up with personnel costs, which inevitably reduces the productivity of single labs (https://drugmonkey.scientopia.org/2020/12/16/updating-the-erosion-of-the-purchase-power-of-the-modular-nih-r01/). We also encourage the adoption of flexible budgets by other funding agencies. Increased freedom in spending money for research will free up time spent with grant analysts and encourage creativity and novelty.
- In 2022 and 2023, more than ten universities in the USA (including, for example, University of California, University of Michigan and University of Washington) experienced staff and student walkouts and strikes to fight for better compensation. University employee strikes have also occurred in the UK, as members of the University and College Union went on strike between 2018 and 2023. We call on governments, universities and funding agencies that have not already done so to increase faculty and postdoctoral salaries and graduate student stipends to reflect inflation and ensure that we can recruit the best and the brightest to our field.
- As discussed above, create multidisciplinary, cross-institutional/directorate, or cross-funding agency grant mechanisms and programs with forward-thinking calls, and ensure the review structures are appropriate to promote innovation.
- Change the bar set for assessment of investigators during grant review. Open science is the way of the future and by embracing preprints, community peer review initiatives and Open Access journals, we can ensure rapid and widespread dissemination of our science. However, there is extreme bias in journal prestige and impact factors. Even considering the Declaration on Research Assessment (https://sfdora.org/), a worldwide initiative to focus on scientific quality rather than impact factors, scientists have created new gatekeeping mechanisms to prevent access to funding, advancement and retention of those who do not meet their bar of success. Assessment of the potential and success of future generations needs to change from the top. If funding agencies and their reviewers require that the quality of science, rather than the number of publications and impact of journals, are assessed, we can promote innovation.

Concluding thoughts

Diversity of experience, ideas and interests brings new scientific adventures and challenges that will push our field forward into the future. Fifty scientists from diverse backgrounds, career stages, scientific focuses, and institutions, came together to share their passion for the field of developmental biology, and to provide suggestions and guidance for the greater community about how we can work together to ensure a long-term productive and impactful future for our community. Rather than differentiating into multiple related fields, we hope to bring people back to the pluripotent state and sustainable core of the community, which has significant potential. Although many of the suggestions can broadly be applied to any scientific discipline, we hope to inspire everyone who has ever considered themselves a developmental biologist to visualize the future of the field. We envision a future that fosters inclusion, enables discovery, produces amazing imagery, and has less gatekeeping (Cleaver et al., 2023), and we call on all members of the developmental biology community – in its broadest sense – to join us in pushing for this goal.

Acknowledgements

We are grateful to Anna Allen and JD Swanson from the NSF for attending the meeting and for their support of the developmental biology community. We thank Mona Gouran for provision of the image of an *Arabidopsis* inflorescence stem.

Funding

The workshop from which these ideas originated was funded by a National Science Foundation (NSF) conference grant: 'Envisioning Developmental Biology for the Future' (NSF IOS-2310253 to S.M.B. and C.D.R.). C.D.R. is also supported by an NSF CAREER award (2143217) and by the National Institutes of Health (R03DE032047-01).

References

Adamo, M. (2022). *UCLA botanist brings biodiversity of Colombia to Disney's 'Encanto'*. UCLA Newsroom.

Alberts, B. (2022). Why science education is more important than most scientists think. *FEBS Lett.* **596**, 149-159. doi:10.1002/1873-3468.14272

Boden, S. A. and Ostergaard, L. (2019). How can developmental biology help feed a growing population? *Development* **146**, dev172965. doi:10.1242/dev.172965

Bradford, Y. M., Van Slyke, C. E., Ruzicka, L., Singer, A., Eagle, A., Fashena, D., Howe, D. G., Frazer, K., Martin, R., Paddock, H. et al. (2022). Zebrafish information network, the knowledgebase for Danio rerio research. *Genetics* **220**, iyac016. doi:10.1093/genetics/iyac016

Cazet, J. F., Siebert, S., Little, H. M., Bertemes, P., Primack, A. S., Ladurner, P., Achrainer, M., Fredriksen, M. T., Moreland, R. T., Singh, S. et al. (2023). A chromosome-scale epigenetic map of the Hydra genome reveals conserved regulators of cell state. *Genome Res.* **33**, 283-298. doi:10.1101/gr.277040.122

Chen, C. Y., Kahanamoku, S. S., Tripati, A., Alegado, R. A., Morris, V. R., Andrade, K. and Hosbey, J. (2022). Systemic racial disparities in funding rates at the National Science Foundation. *Elife* **11**, e83071. doi:10.7554/eLife.83071

Cheng, K. C., Burdine, R. D., Dickinson, M. E., Ekker, S. C., Lin, A. Y., Lloyd, K. C. K., Lutz, C. M., MacRae, C. A., Morrison, J. H., O'Connor, D. H. et al. (2022). Promoting validation and cross-phylogenetic integration in model organism research. *Dis. Model Mech.* **15**, dmm049600. doi:10.1242/dmm.049600

Chery, J. G., Pace, M. R., Acevedo-Rodriguez, P., Specht, C. D. and Rothfels, C. J. (2020). Modifications during early plant development promote the evolution of nature's most complex woods. *Curr. Biol.* **30**, 237-244.e2. doi:10.1016/j.cub.2019.11.003

Cleaver, O., Prince, V. E. and Wallingford, J. B. (2023). We have seen the gatekeepers, and they are us. *Dev. Biol.* **501**, A15-A17. doi:10.1016/j.ydbio.2023.06.016

Davis, P., Zarowiecki, M., Arnaboldi, V., Becerra, A., Cain, S., Chan, J., Chen, W. J., Cho, J., da Veiga Beltrame, E., Diamantakis, S. et al. (2022). WormBase in 2022 – data, processes, and tools for analyzing Caenorhabditis elegans. *Genetics* **220**, iyac003. doi:10.1093/genetics/iyac003

Gilbert, S. F. (2017). Developmental biology, the stem cell of biological disciplines. *PLoS Biol.* **15**, e2003691. doi:10.1371/journal.pbio.2003691

Ginther, D. K. (2022). Reflections on race, ethnicity, and NIH research awards. *Mol. Biol. Cell* **33**, ae1. doi:10.1091/mbc.E21-08-0403

Ginther, D. K., Schaffer, W. T., Schnell, J., Masimore, B., Liu, F., Haak, L. L. and Kington, R. (2011). Race, ethnicity, and NIH research awards. *Science* **333**, 1015-1019. doi:10.1126/science.1196783

Gramates, L. S., Agapite, J., Attrill, H., Calvi, B. R., Crosby, M. A., Dos Santos, G., Goodman, J. L., Goutte-Gattat, D., Jenkins, V. K., Kaufman, T. et al. (2022). FlyBase: a guided tour of highlighted features. *Genetics* **220**, iyac035. doi:10.1093/genetics/iyac035

Graniel, J. V., Teitel, J., Glineburg, M. R., Cohen, E., Buttitta, L. A., Barolo, S. and Allen, B. L. (2023). Developing Future Biologists: developmental biology for undergraduates from underserved communities. *Development* **150**, dev201337. doi:10.1242/dev.201337

Guillotin, B., Rahni, R., Passalacqua, M., Mohammed, M. A., Xu, X., Raju, S. K., Ramirez, C. O., Jackson, D., Groen, S. C., Gillis, J. et al. (2023). A pan-grass

transcriptome reveals patterns of cellular divergence in crops. *Nature* **617**, 785-791. doi:10.1038/s41586-023-06053-0

Haga, S. B. (2006). Teaching resources for genetics. *Nat. Rev. Genet.* **7**, 223-229. doi:10.1038/nrg1803

Kent, W. J., Sugnet, C. W., Furey, T. S., Roskin, K. M., Pringle, T. H., Zahler, A. M. and Haussler, D. (2002). The human genome browser at UCSC. *Genome Res.* **12**, 996-1006. doi:10.1101/gr.229102

Korf, B. R. (2002). Integration of genetics into clinical teaching in medical school education. *Genet. Med.* **4**, 33s-38s. doi:10.1097/00125817-200211001-00007

Lange, M., Granados, A., VijayKumar, S., Bragantini, J., Ancheta, S., Santhosh, S., Borja, M., Kobayashi, H., McGeever, E., Solak, A.C. et al. (2023). Zebrahub – multimodal zebrafish developmental atlas reveals the state transition dynamics of late vertebrate pluripotent axial progenitors. *bioRxiv* . doi:10.1101/2023.03.06.531398

Lee, C. M. (2016). Speaking up for science. *Trends Immunol.* **37**, 265-268. doi:10.1016/j.it.2016.02.003

Masayuki, O. and Reymann, A. C. (2023). Meeting report: third Franco-Japanese developmental biology meeting 'New Frontiers in developmental biology: celebrating the diversity of life'. *Genesis* **61**, e23527. doi:10.1002/dvg.23527

Moltzahn, F. R., Volkmer, J. P., Rottke, D. and Ackermann, R. (2008). 'Cancer stem cells' – lessons from Hercules to fight the Hydra. *Urol. Oncol.* **26**, 581-589. doi:10.1016/j.urolonc.2008.07.009

Pillai, A., Gungi, A., Reddy, P. C. and Galande, S. (2021). Epigenetic regulation in hydra: conserved and divergent roles. *Front. Cell Dev. Biol.* **9**, 663208. doi:10.3389/fcell.2021.663208

Riddle, M. R., Aspiras, A. C., Gaudenz, K., Peuss, R., Sung, J. Y., Martineau, B., Peavey, M., Box, A. C., Tabin, J. A., McGaugh, S. et al. (2018). Insulin resistance in cavefish as an adaptation to a nutrient-limited environment. *Nature* **555**, 647-651. doi:10.1038/nature26136

Safford, H. and Brown, A. (2019). Communicating science to policymakers: six strategies for success. *Nature* **572**, 681-682. doi:10.1038/d41586-019-02372-3

Smith, N. R., Mazzucca, S., Hall, M. G., Hassmiller Lich, K., Brownson, R. C. and Frerichs, L. (2022). Opportunities to improve policy dissemination by tailoring communication materials to the research priorities of legislators. *Implement Sci. Commun.* **3**, 24. doi:10.1186/s43058-022-00274-6

St Johnston, D. (2015). The renaissance of developmental biology. *PLoS Biol.* **13**, e1002149. doi:10.1371/journal.pbio.1002149

Stern, C. D. (2022). Reflections on the past, present and future of developmental biology. *Dev. Biol.* **488**, 30-34. doi:10.1016/j.ydbio.2022.05.001

Unguez, G. A., Bennett, K. L., Domingo, C. and Chow, I. (2021). Increasing diversity in developmental biology. *Front. Sociol.* **6**, 762836. doi:10.3389/fsoc.2021.762836

Wallingford, J. B. (2019). We are all developmental biologists. *Dev. Cell* **50**, 132-137. doi:10.1016/j.devcel.2019.07.006

Wilkinson M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J. W., da Silva Santos, L. B., Bourne, P. E. et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* **3**, 160018. doi:10.1038/sdata.2016.18

Zon, L. (2019). Improving the visibility of developmental biology: time for induction and specification. *Development* **146**, dev174631. doi:10.1242/dev.174631