



SYMPOSIUM INTRODUCTION

Biology Beyond the Classroom: Experiential Learning Through Authentic Research, Design, and Community Engagement

Alexandria K. Hansen ^{*,1}, Patrice Connors [†], Dermot Donnelly-Hermosillo [‡], Robert Full [§], Alisa Hove [¶], Hayley Lanier ^{||}, David Lent ^{*}, Jasmine Nation [#], Kimberly Tucker ^{**}, Jennifer Ward ^{††}, Lisa Whitenack ^{‡‡} and Erika Zavaleta ^{§§}

^{*}Department of Biology, California State University, Fresno, CA 93740, USA; [†]Department of Biological Sciences, Colorado Mesa University, 1100 North Avenue Grand Junction, CO 81501, USA; [‡]Department of Chemistry and Biochemistry, California State University, 2555 E. San Ramon Ave., Fresno, CA 93740, USA; [§]Department of Integrative Biology, U.C. Berkeley, 3040 Valley Life Sciences Building # 3140 Berkeley, CA 94720, USA; [¶]Biology Department, Warren Wilson College, PO Box 9000 Asheville, NC 28815, USA; ^{||}Sam Noble Oklahoma Museum of Natural History and Department of Biology, University of Oklahoma, 730 Van Vleet Oval, Room 314 Norman, OK 73019, USA; [#]Liberal Studies, California State University, San Luis Obispo, CA 93407, USA; ^{**}Department of Biological Sciences, Stevenson University, 1525 Greenspring Valley Road Stevenson, MD 21153, USA; ^{††}Department of Biology, University of North Carolina at Asheville, 1 University Heights Asheville, NC 28804, USA; ^{‡‡}Department of Biology, Allegheny College, 520 N. Main St., Meadville, PA 16335, USA; ^{§§}Department of Biology, University of California, 1156 High Street, Santa Cruz, CA 95064, USA

¹E-mail: akhansen@mail.fresnostate.edu

Synopsis This paper introduces the collection of manuscripts from the symposium, “Biology Beyond the Classroom: Experiential Learning through Authentic Research, Design, and Community Engagement,” presented at the 2021 annual meeting of the Society for Integrative and Comparative Biology. The following papers showcase innovative approaches for engaging undergraduate students in experiential science learning experiences. Specifically, we focus on three high-impact practices that allow students to take their learning outside of the classroom for increased relevance and authenticity: (1) Course-Based Undergraduate Research, (2) Digital Fabrication in Makerspaces, and (3) Service or Community-based Learning Opportunities. Although each topic is unique, all provide an alternative approach to the traditional lecture and have proven effective at appealing to diverse groups of students who are traditionally underrepresented in the Science, Technology, Engineering, and Mathematics workforce.

Current evidence suggests that, in the next decade, the US workforce will need *1 million more* STEM professionals than it is expected to produce (National Academy of Sciences, Engineering, and Medicine 2019). Moreover, the diversity of the STEM workforce is vastly unrepresentative of the US population in terms of gender and ethnicity, signaling concerns regarding the equity of current educational systems and practices. For example, women comprised 52% of the overall US workforce in 2017, but only 29% of STEM jobs were held by women (National Science Board 2020). Similarly, the number of underrepresented minorities (URM) in STEM careers continues to lag behind the overall pop-

ulation: only 13% of individuals who identified as Black, Hispanic, American Indian, or Alaska Native were employed in a STEM career compared to 28% of the total US population (National Science Board 2020). With these concerns in mind, it follows that special attention should be paid to expanding the overall quantity and diversity of individuals who pursue STEM careers.

Institutions of higher education are poised to address potential workforce needs; however, the STEM disciplines face additional challenges. Many individuals who are initially interested in and/or declare a STEM major do not graduate with that degree; this attrition problem is often referred to as the “leaky pipeline” (Berryman

1983; Alper 1993; Metcalf 2010). Reasons for this leaky pipeline and resulting underrepresentation are complex and can vary across demographic groups (e.g., McGee and Bentley 2017) and specific STEM sub-disciplines (e.g., Chesler et al. 2010). While some reports indicate women are persisting in STEM majors at a higher rate than previously documented (e.g., Miller and Wai 2015), disparities still clearly exist for specific ethnic groups (National Science Board 2020). Further, the STEM pipeline metaphor itself may fail to “describe the experience for nearly half of those who go on to become scientists or engineers, masks meaningful differences in trajectories by subfield, and informs policies that do little to diversify or increase the size of the STEM workforce” (Cannady et al. 2014). Although the reasons underlying student decisions to abandon their pursuits of STEM degrees vary (Wu and Uttal 2020), the leaky pipeline disproportionately affects women and other URM (Blickenstaff 2005; Asai, 2020).

One factor that consistently links to students’ decisions to leave STEM majors is ineffective teaching practices, particularly those that prioritize the presentation of content knowledge over fostering connections between content and students’ lives (Seymour and Hewitt 1997; Watkins and Mazur 2013). Lecture is still the primary teaching method used in STEM disciplines (Jaschik 2018), despite evidence that it negatively influences students’ STEM persistence (Berrett 2012). Lecture-based teaching methods conceptualize “teaching as telling,” and feature the instructor conveying the bulk of information to students from textbooks and lecture notes (Mazur 2009). There are many reasons why STEM instructors often default to lecture-based teaching methods. For instance, research in educational sociology shows that individuals often teach how they were taught; this is known as the apprenticeship of observation (Lortie 1977). If faculty have not experienced other modes of instruction as learners, it may be difficult to implement other methods when teaching. Further complicating this problem, many faculty members in STEM disciplines lack formal training in education, teaching, or learning, which has been cited as one primary reason that STEM faculty rely on lecture-based methods (Sunil et al. 2001). While institutions of higher education cannot control many antecedents associated with the leaky pipeline issue in STEM, they can shape the subsequent learning environment and support faculty in effectively implementing active learning and other student-centered pedagogies; for an example of a successful multi-institutional initiative to improve STEM faculty teaching practices see Borda et al. (2020).

Active learning is an effective lecture alternative that increases the likelihood students will persist and perform well in a STEM major during college (Haak et

al. 2011; Freeman et al. 2014). While operationalized definitions of active learning vary, the underlying justification for this approach is found in the learning theory of constructivism (Cooperstein and Kocevar-Weidinger 2004). Constructivism emphasizes student-centered approaches to teaching that provide opportunities for learners to actively make sense of novel information through the lens of their past experiences. It recognizes learners as having unique experiences and ideas that influence how they perceive and make sense of new information, rather than being a blank slate (*tabula rasa*). Good and Brophy (1994) described four key aspects of constructivist teaching: (1) Learners construct their own meaning, (2) New learning builds on prior learning, (3) Learning is enhanced by social interaction, and (4) Meaningful learning occurs through authentic tasks. This view on learning shares similarities to many approaches recommended by educational theorists throughout the twentieth century, specifically Dewey’s (1938) focus on experiential learning, Bruner’s (1961) discovery-based learning, and Schwabb’s (1960) inquiry-based learning.

Further, recent research on undergraduate education has proposed the concept of a “high-impact practice”—a teaching and learning practice that has been widely tested and shown to be beneficial for undergraduate students from many different backgrounds (Kuh 2008). While these practices can vary based on content, context, and instructor approach, they share common themes of creating meaningful connections and deep learning (Watson et al. 2016). Common examples of high-impact practices include first-year seminars to help with the transition to college life, integrated coursework (e.g., Technology and Society) that helps students make connections across disciplines, writing-intensive courses, collaborative assignments and projects, undergraduate research, internships, and service or community-based learning (Kuh 2008; Sandeen 2012; Finley and McNair 2013; Soria and Johnson 2017). Each of these practices align with active-learning recommendations derived from constructivist learning theories, and each has been shown to increase student retention and engagement.

The symposium, *Biology Beyond the Classroom: Experiential Learning through Authentic Research, Design, and Community Engagement* was hosted by the Society of Integrative and Comparative Biology (SICB) and highlighted three high-impact practices that have demonstrated effectiveness at retaining students who are often underrepresented in the STEM fields (Gregerman et al. 1998; Jones et al. 2010; Chang et al. 2014). The associated papers specifically focus on the following pedagogical approaches: (1) Course-based undergraduate research (CUREs), (2) Digital

fabrication in makerspaces, and (3) Service or community-based learning. While these practices differ in their approaches, each pedagogy: (1) provides an arena for experiential learning outside the traditional classroom construct, (2) explicitly considers the broad relevance of course content, and (3) actively engages students in authentic, collaborative work that requires the acquisition and application of knowledge and skills spanning multiple disciplines. Furthermore, these practices are feasible to implement in a typical undergraduate STEM course; these spaces are accessible to *all* individuals, unlike other exclusive high-impact practices, such as research internships or apprenticeships, that many students will self-select out of due to perceived competition (National Academy of Sciences, Engineering & Medicine 2019). In the following sections, we briefly describe each pedagogical approach.

Course-based undergraduate research (CUREs)

CUREs provide opportunities for students to conduct research in their coursework to experience the process of scientific inquiry. Unlike other types of undergraduate research experiences (e.g., research internships), CUREs are accessible to more individuals because they occur in the context of a standard course (National Academy of Sciences, Engineering & Medicine 2017) and thus do not require students with time or work constraints to take on additional commitments (Bhattacharyya et al. 2020). Rather than completing a pre-fabricated laboratory assignment created by an instructor or based on an educational kit, CUREs provide the opportunity for authentic scientific investigation under the supervision of their instructor (Auchincloss et al. 2014). By immersing students in collaborative, iterative, and relevant research, CUREs can increase student motivation to pursue research careers (Corwin et al. 2018) and enhance student communication skills (Thu et al. 2021). CUREs also align with recommendations for inquiry-based and experiential learning opportunities and provide a more inclusive learning environment for students who are traditionally underrepresented in STEM (Banger and Brownell 2014).

In this issue, Hernandez et al. (2021) describe a CURE that asks students to conduct authentic research connected to their local zoo. Students work in small groups to ask a scientific question about a specific exhibit or enclosure, design methods for investigation, collect and analyze data, as well as communicate their findings at a symposium in the format of an academic poster at the end of the semester. For instance, for one

laboratory in this course, students investigated ideal salinity ranges for the zoo's stingray exhibit and generated actionable recommendations for zoo staff to ensure the stingray population's health. This specific project has demonstrated improved science interest for enrolled female students who failed a traditional format version of the course in a previous semester, indicating the importance of this approach for students underrepresented in the STEM disciplines.

Other successful CURE designs provide opportunities to engage in field research. Field-based CUREs in disciplines like ecology and the geosciences, which rely heavily on outdoor data collection, have demonstrated value in closing demographic gaps (O'Brien et al. 2020). Moreover, field-based CUREs can build students' confidence and sense of belonging across broader STEM disciplines because they lend themselves to community-building through shared experiences (Beltran et al. 2020; Zavaleta et al. 2020). Another paper included in this issue (Race et al. 2021) examines how a relatively low-cost field course aimed at early career undergraduates is especially effective for retention in STEM, helping students build relationships, confidence, and outdoor skills before they navigate the series of large lecture classes required for biology majors. Through student journals and participant-observation, authors examine the formation of stronger self-efficacy and belonging during the field-based CURE class, which involved a series of short, student-designed field research projects, introduction to research opportunities across campus, and two overnight field trips.

Building collaboration and promoting undergraduate course-based research in field ecology is also a focus of the Squirrel-Net CUREs (Connors et al. 2021). This set of CUREs is supported by a collaborative network of faculty across multiple institutions whose classes follow the same protocols for data collection in order to develop a shared resource for student research (Dizney et al. 2020). Addressing questions ranging from tradeoffs in foraging and vigilance (Connors et al. 2020), to habitat usage (Duggan et al. 2020; Yahnke et al. 2020), to estimating population density (Varner et al. 2020), these flexible CURE modules increased student self-efficacy and confidence in their abilities. The approach of working across institutions in shared scientific pursuits not only better mirrors many faculty research pursuits, a largely collaborative enterprise, but also elevated student perceptions of their contributions to the broader scientific community.

Place-based CUREs, focused on regional ecosystems and issues, have the potential to connect experiential learning and collaborative research with student interests and affinity for a particular area. In this issue, Hiatt et al. (2021) report on a series of plant-focused

laboratory and field CUREs centered on the southern Appalachian region of the USA. CUREs were aligned around a single theme: understanding ecological responses of southern Appalachian plant communities to global change. For example, ecology students applied biological concepts related to climate change by monitoring plant phenology in the field, sharing data with the USA National Phenology Network Nature's Notebook program, and analyzing associations between climate and the timing of plant and animal life history events. Genetics students gained research skills and experience through the analysis of regional species with cultural and economic significance (e.g., American ginseng, *Panax quinquefolius*) and considered the broad implications of their findings. These CUREs were associated with gains in plant awareness and in some cases student sense of identity in STEM, and highlight the potential for active learning practices connected to regional biodiversity to engage students in biology.

Digital fabrication in makerspaces

Another experiential learning approach receiving attention for its potential to broaden perceptions of STEM experiences and, in turn, make STEM more welcoming is digital fabrication—the process of designing objects for the purposes of fabricating with machinery such as three-dimensional (3D) printers, laser cutters, and Computer Numerical Control (CNC) machines (Hansen et al. 2019). Historically, these types of tools have been exceptionally costly and difficult to access; however, recent advancements in technological design have been accompanied by decreasing prices. Blikstein (2013) refers to this as the *democratization of invention*: as prices drop and access increases, anyone can now make the transition from consumer to producer.

Making through digital fabrication also holds potential for its ability to reframe what counts as science and who sees themselves as capable of becoming a scientist (Birmingham et al. 2017). Students majoring in STEM, especially first generation and underrepresented students, often confront challenges in motivation and self-confidence (Anderson and Kim 2006). Making can provide an entry point to develop a STEM identity and increase the likelihood of joining the STEM workforce (Chu et al. 2015). Additionally, fabrication projects that tackle real-world problems can provide a sense of belonging and community connection (Holbert 2016; Birmingham et al. 2017).

In the context of higher education, many institutions are creating makerspaces (or fabrication labs) that allow students to gain hands-on design experience using cutting-edge technology (Barrett et al. 2015). These spaces are sometimes connected to specific depart-

ments (e.g., engineering, studio art), but are increasingly being housed in public spaces such as libraries. Moreover, the evidence for the value of this approach is clear in the educational literature: when students are actively creating an artifact for the public, something with a larger purpose, motivation and engagement increase (Papert and Harel, 1991; Blikstein, 2013). Further, learning the STEM content becomes a means to an end: students learn the content to fabricate the object, not simply to ace the test (Hansen et al. 2019). Maker and digital fabrication projects can apply the approach of “just-in-time STEM”, where science and engineering content are introduced as they become relevant (Calabrese Barton et al. 2017). Previous research has positively connected making to learning gains in mathematics (Garneli et al. 2013), art (Peppler 2013), writing (Cantrill and Oh 2016), computing (Papert 1980), and spatial reasoning abilities (Leduc-Mills and Eisenberg 2011). It has also been associated with an increase in twenty-first century skills, such as creative confidence (Barron and Martin, 2016), self-efficacy and perseverance in problem solving (Peppler 2013), and resourcefulness (Sheridan and Konopasky 2016). However, the extent of the impact of student-driven making and creation in biology education is relatively understudied in the higher education setting (Hansen et al. 2020), and biology undergraduate programs rarely provide interdisciplinary learning experiences for students (Lent et al. 2021).

This symposium and associated papers highlight several examples of successful digital fabrication projects in the context of higher education and the larger community. For instance, Staab (2021) describes the use of fabrication as a pedagogical tool in undergraduate vertebrate anatomy courses. Given the increased availability of online computed tomography (CT) data repositories, anatomy students can download, analyze, and 3D-print skeletal models of both common and endangered vertebrate animals. Students reported increased motivation to study intricate skeletal anatomy simply by manipulating the bones using 3D-software. Specifically, in an introductory biomechanics course, students build models of animal anatomy using simple materials (e.g., crafting supplies) and/or 3D-printing, enhancing understanding of the basic physical principles of animal movement (e.g., lever mechanics). The use of simple materials reduces the barrier to entry for students who have minimal experience with technology and ensures the feasibility of implementation with university budget constraints.

Finally, makerspaces can show diverse students the path from authentic biological discovery to bio-inspired devices with societal benefit. One symposium speaker and author of this paper (RF) described a bio-inspired

design program in the context of a large research university called *i⁴s Toward Tomorrow*. Using culturally sustaining connections, students envision a future where their voice is urgently needed for *i*nvolve*m*ent, *i*magination, *i*nvention, and *i*nnovation. The program connects two recent revolutions by integrating BioDesign with the Maker Movement and its democratizing effects empowering anyone to innovate. Its goal is to expand the STEM workforce with an early, inspirational, and interdisciplinary experience for 200 students that fosters inclusive excellence. The program removes artificially created disciplinary boundaries to extend beyond STEM by including students from over 40 different majors collaborating in diverse teams using scientific discoveries to create inventions that lead to seeing new careers, benefiting society, and shaping our future. For example, students make a gecko-inspired adhesive for novel health applications and an origami insect-inspired robot for search-and-rescue. Assessment shows significant increases in student self-efficacy as well as interdisciplinary thinking and collaboration for students who are underrepresented in the STEM disciplines.

Community-based learning

The final topic for this symposium is community-based learning. This approach generally involves partnering courses with local community organizations (e.g., hospitals, schools, non-profits, etc.) to identify and design solutions for their pressing problems in collaboration. There are many different models of community-based learning (Mooney and Edwards, 2001). For instance, students might engage in a service-learning project with a community partner, work as a research intern at a local company, or engage in a community science research project to investigate an issue important to their local community alongside scientists. Community-based learning typically involves some public benefit that simultaneously enhances the student learning connected to course content. This approach to teaching has been shown to positively increase undergraduate students' academic performance (or GPA), interest in the content area, retention of female-identifying students in STEM, self-efficacy, leadership skills, and a desire to pursue service-related career opportunities after college (Astin et al. 2000; Hunter and Brisbin 2000; Tannenbaum and Berrett 2005; Diekman et al. 2015). Community-based learning also fosters civic engagement and connects a student's education to real and current issues. Over the years, many institutions have focused on job market preparation as opposed to graduating engaged citizens (Evans et al. 2019), with some STEM fields focusing solely on workforce development. Making these impor-

tant community connections in STEM courses raises awareness of societal issues and prepares future scientists to respond to those grand challenges (Ballou 2012; SENCER).

The grand challenges our world faces require interdisciplinary solutions, yet our traditional academic structure does not typically allow for deep, interdisciplinary connections among or within courses (Lent et al. 2021). By participating in well-designed service-learning, students can immediately observe how necessary it is to form productive, interdisciplinary partnerships in order to address real challenges (Culhane et al. 2018). Another manuscript in this symposium issue (Marx et al. 2021) reviews the importance of interdisciplinary learning and describes how faculty at Stevenson University have created a model for interdisciplinary service-learning. The model was developed, piloted, and refined over multiple semesters by partnering genetics and design courses to create educational games in partnership with the Education and Community Involvement Branch of the National Human Genome Research Institute. Students involved in these projects enhanced their learning of a subject while also learning important facets of another discipline's approach and how real challenges cannot be solved in disciplinary silos. The authors share the framework for this model and how it was applied to another course collaboration among design, literature, and conservation biology students.

Further, many community-oriented approaches at the undergraduate level connect to and serve K-12 students. These approaches largely draw from community partnerships and seek to inspire an early interest in the STEM fields for young students. One paper in this issue (Nation and Hansen, 2021) describes the Community STEM Framework as an approach for enacting partnerships with youth-serving organizations and describes examples of effective programs that have successfully partnered youth with scientists, researchers, and other community groups. Similarly, Yep and Nation (2021) describe a specific outreach program where Spanish-speaking undergraduates design and implement microbiology activities for children at a bilingual elementary school to learn foundational science ideas and address misconceptions. This program also positions the undergraduate students as role models for the young children and seeks to motivate and inspire the next generation of scientists and engineers.

Conclusion

The diversity of the current STEM workforce fails to represent the larger US population. While reasons for this underrepresentation are complex,

ineffective teaching methods consistently dampen a student's motivation in and desire to pursue STEM. Despite a growing body of evidence from education research about what qualifies as effective and equitable teaching, the STEM fields often still rely on traditional lecture-based approaches that fail to actively engage students' diverse interests and life experiences. This symposium and associated manuscripts provide alternative teaching approaches that have effectively engaged diverse students in STEM. It is our hope that these papers inspire STEM faculty and instructors to reflect on and reevaluate their teaching practices to create more equitable learning spaces, thus broadening student conceptions of STEM and building a stronger, more diverse STEM workforce in the years to come.

Acknowledgments

AKH, PC, RF, HL, and LBW thank all symposium presenters and presenters at the contributed sessions for their presentations and manuscripts.

Funding

Funding for this symposium was provided by the Society for Integrative and Comparative Biology (DCB, DCPB, DEDB, DIZ, DEDE, DVM, DNNSB, DCE, DOB) and the National Science Foundation [NSF-IOS award number 2031887].

Data availability

There are no data associated with this article.

References

- Alper J. 1993. The pipeline is leaking women all the way along. *Science* 260:409–11.
- Anderson E, Kim D. 2006. Increasing the Success of Minority Students in Science and Technology. Washington, DC: American Council on Education.
- Asai D. 2020. Excluded. *J Microbiol Biol Edu* 21:10.
- Astin AW, Vogelgesang LJ, Ikeda EK, Yee JA. 2000. How service learning affects students. *High Edu* 1:144.
- Auchincloss LC, Laursen SL, Branchaw JL, Eagan K, Graham M, Hanauer DI, Lawrie Gwendolyn McLinn Colleen M Pelaez Nancy Rowland Susan et al. 2014. Assessment of course-based undergraduate research experiences: a meeting report. *CBE—Life Sci Edu* 13:29–40.
- Ballou J. 2012. Reshaping how educators view student STEM learning. *Sci Edu Civic Engag: Int J Winter* 2012:27–36.
- Bangera G, Brownell SE. 2014. Course-based undergraduate research experiences can make scientific research more inclusive. *CBE—Life Sci Edu* 13:602–6.
- Barrett T, Pizzico M, Levy BD, Nagel RL, Linsey JS, Talley KG, Forest Craig R., Newstetter WC. 2015. A Review of University Maker Spaces. Georgia Institute of Technology. Seattle, Washington: American Association for Engineering Education. (<https://peer.asee.org/a-review-of-university-maker-spaces>).
- Barron B, Martin CK. 2016. Making matters: a framework for assessing digital media citizenship. In: Peppler K, Halverson E, Kafai YB, editors. *Makeology: Makers as learners*. New York, NY: Routledge. p. 45–71.
- Beltran RS, Marnocha E, Race A, Croll DA, Dayton GH, Zavaleta ES. 2020. Field courses narrow demographic achievement gaps in ecology and evolutionary biology. *Ecol Evol* 10:5184–96.
- Berrett D. 2012. Lectures still dominate science and math teaching, sometimes hampering student success. *The Chronicle of Higher Education*. (<http://chronicle.com/article/article-content/135402/>).
- Berryman SE. 1983. Who will do science? Minority and female attainment of science and mathematics degrees: trends and causes. Rockefeller Foundation. New York, NY: Rockefeller Foundation.
- Bhattacharyya P, Chan CWM, Duchesne RR, Ghosh A, Girard SN, Ralston JJ. 2020. Course-based research: a vehicle for broadening access to undergraduate research in the twenty-first century. *Schol Prac Undergrad Res* 3:14–27.
- Birmingham D, Calabrese Barton A, McDaniel A, Jones J, Turner C, Rogers A. 2017. But the science we do here matters: Youth-authored cases of consequential learning. *Sci Edu* 101:818–44.
- Blickenstaff JC. 2005. Women and science careers: leaky pipeline or gender filter? *Gen Edu* 17, 369–86.
- Blikstein P. 2013. Digital fabrication and 'making' in education: the democratization of invention. In: Walter-Herrmann J, Büching C, editors. *FabLabs: Of Machines, Makers and Inventors*. Bielefeld: Transcript Publishers. p. 203–22.
- Borda E, Schumacher E, Hanley D, Geary E, Warren S, Cassidy I, Lauren S. 2020. Initial implementation of active learning strategies in large, lecture STEM courses: lessons learned from a multi-institutional, interdisciplinary STEM faculty development program. *Int J STEM Edu* 7:1–18.
- Bruner JS. 1961. The act of discovery. *Harvard Edu Rev* 31:21–32.
- Cannady MA, Greenwald E, Harris KN. 2014. Problematizing the STEM pipeline metaphor: is the STEM pipeline metaphor serving our students and the STEM workforce? *Sci Edu* 98:443–60.
- Cantrill C, Oh P. 2016. The composition of making. In: Peppler K, Halverson E, Kafai YB, editors. *Makeology: Makerspaces as Learning Environments* New York, NY: Routledge. p. 107–20.
- Chang MJ, Sharkness J, Hurtado S, Newman CB. 2014. What matters in college for retaining aspiring scientists and engineers from underrepresented racial groups. *J Res Sci Teach* 51:555–80.
- Chesler NC, Barabino G, Bhatia SN, Richards-Kortum R. 2010. The pipeline still leaks and more than you think: a status report on gender diversity in biomedical engineering. *Ann Biomed Eng* 38:1928–35.
- Chu SL, Quek F, Bhangaonkar S, Ging AB, Sridharamurthy K. 2015. Making the Maker: A Means-to-an-Ends approach to nurturing the Maker mindset in elementary-aged children. *Int J Child-Comput Interact* 5:11–9.
- Connors PK, Lanier HC, Erb LP, Varner J, Dizney L, Flaherty EA, Duggan JM, Yahnke CJ, Hanson JD. 2021. Connected while distant: networking CUREs across classrooms to create community and inspire students. *Integr Comp Biol* (<https://doi.org/10.1093/icb/icab146>).

- Connors PK, Varner J, Erb LP, Dizney L, Lanier HC, Hanson JD, Yahnke CJ, Duggan JM, Flaherty EA. 2020. Squirreling around for science: observing sciurid rodents to investigate animal behavior. *Course Source* 7:1.
- Cooperstein SE, Kocevar-Weidinger E. 2004. Beyond active learning: a constructivist approach to learning. *Ref Serv Rev* 32:141–8.
- Corwin LA, Runyon CR, Ghanem E, Sandy M, Clark G, Palmer GC, Reichler S, Rodenbusch SE, Dolan EL, Hewlett J. 2018. Effects of discovery, iteration, and collaboration in laboratory courses on undergraduates' research career intentions fully mediated by student ownership. *CBE-Life Sci Edu* 17:1–11.
- Culhane J, Neiwołny K, Clark S, Misyak S. 2018. Exploring the intersections of interdisciplinary teaching, experiential learning, and community engagement: a case study of service learning in practice. *Int J Teach Learn High Edu* 30:412–22.
- Dewey J. 1938. *Experience and Education*. New York, NY: Kappa Delta Pi.
- Diekman AB, Weisgram ES, Belanger AL. 2015. New routes to recruiting and retaining women in STEM: policy implications of a communal goal congruity perspective. *Soc Iss Pol Rev* 9:52–88.
- Dizney L, Connors PK, Varner J, Duggan JM, Lanier HC, Erb LP, Flaherty EA, Yahnke CJ, Hanson JD. 2020. An introduction to the Squirrel-Net teaching modules. *Course Source* 7:1–7.
- Duggan JM, Varner J, Lanier HC, Flaherty EA, Dizney L, Yahnke CJ, Connors PK, Erb LP, Hanson JD. 2020. Squirrels in space: using radio telemetry to explore the space use and movement of sciurid rodents. *Course Source* 7:1–11.
- Evans BJ, Marsicano CR, Lennartz CJ. 2019. Cracks in the bedrock of American democracy: differences in civic engagement across institutions of higher education. *Edu Res* 48:31–44.
- Finley A, McNair T. 2013. Assessing underserved students' engagement in high-impact practices Association of American Colleges and Universities. Washington, DC: Association of American Colleges and Universities. (https://aacu.org/sites/default/files/files/assessinghips/AssessingHIPS_TGGrantReport.pdf).
- Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP. 2014. Active learning increases student performance in science, engineering, and mathematics. *Proc Natl Acad Sci* 111:8410–5.
- Garneli B, Giannakos MN, Chorianopoulos K, Jaccheri L. 2013. Learning by playing and learning by making. In: Ma M, Oliveira MF, Petersen S, Hauge JB, editors. *Serious Game Development and Applications* Berlin: Springer. p. 76–85.
- Good TL, Brophy JE. 1994. *Looking in Classrooms*. New York, NY: HarperCollins College Publishers.
- Greggerman SR, Lerner JS, Von Hippel W, Jonides J, Nagda BA. 1998. Undergraduate student-faculty research partnerships affect student retention. *Rev High Edu* 22:55–72.
- Haak DC, Hillerislambers J, Pitre E, Freeman S. 2011. Increased structure and active learning reduce the achievement gap in introductory biology. *Science* 332:1213–6.
- Hansen AK, McBeath JK, Harlow DB. 2019. No bones about it: how digital fabrication changes student perceptions of their role in the classroom. *J Pre-Coll Eng Edu Res (J-PEER)* 9:95–116.
- Hansen AK, Langdon TR, Mendrin LW, Peters K, Ramos J, Lent DD. 2020. Exploring the Potential of 3D-printing in Biological Education: a Review of the Literature. *Integr Comp Biol* 60:896–905.
- Hernandez T, Donnelly-Hermosillo D, Person E, Hansen A. 2021. “At least we could give our input”: under-represented student narratives on conventional and guided inquiry-based laboratory approaches. *ICB* (<https://doi.org/10.1093/icb/icab014>).
- Hiatt A, Hove AA, Ward JR, Ventura L, Boyd AE, Clarke D, Horton JL, Murrell Z, Neufeld HS. 2021. Authentic research in the classroom increases self-efficacy and appreciation for plants in undergraduate biology students. *Integr Comp Biol* (<https://doi.org/10.1093/icb/icab08>).
- Holbert N. 2016. The powerful ideas of making: Building beyond the curriculum. *Int J Entrepreneurship Innov* 5:1–7.
- Hunter S, Brisbin RA. 2000. The impact of service learning on democratic and civic values. *PS: Polit Sci Polit* 33:623–6.
- Jaschik S. 2018. Lecture Instruction: Alive and Not So Well. Inside Higher Education. (<https://www.insidehighered.com/news/2018/04/02/study-finds-lecture-remains-dominant-form-teaching-stem>).
- Jones MT, Barlow AE, Villarejo M. 2010. Importance of undergraduate research for minority persistence and achievement in biology. *J High Edu* 81:82–115.
- Kuh GD. 2008. Excerpt from high-impact educational practices: what they are, who has access to them, and why they matter. *Ass American Coll Univ* 14:28–9.
- Leduc-Mills M, Eisenberg M. 2011. The UCube: a child-friendly device for introductory three-dimensional design. *Proceedings from IDC '11: The Tenth International Conference on Interaction Design and Children*. New York, NY: ACM.
- Lent D, Estes K, Hansen A. 2021. Making the interdisciplinary learning experiences continuous throughout education. *ICB* (<https://doi.org/10.1093/icb/icab109>).
- Lortie DC. 1977. *Schoolteacher: A Sociological Study*. Chicago, IL: The University of Chicago Press.
- Marx M, Glaser R, Moran C, Tucker KP. 2021. A Creative Model for an Interdisciplinary Approach to Service-Learning. *ICB* (<https://doi.org/10.1093/icb/icab136>).
- Mazur E. 2009. Farewell, lecture?. *Science* 323:50–1.
- McGee EO, Bentley L. 2017. The troubled success of Black women in STEM. *Cogn Instr* 35:265–89.
- Metcalfe H. 2010. Stuck in the pipeline: a critical review of STEM workforce literature. *InterActions: UCLA J Edu Infor Stu* 6 (<https://doi.org/10.5070/D462000681>).
- Miller DI, Wai J. 2015. The bachelor's to Ph.D. STEM pipeline no longer leaks more women than men: a 30-year analysis. *Front Psych* 6:1–10.
- Mooney LA, Edwards B. 2001. Experiential learning in sociology: service learning and other community-based learning initiatives. *Teach Socio* 29:181–94.
- Nation J, Hansen A. 2021. Perspectives on community STEM: learning from partnerships between scientists, researchers, and youth. *ICB* (<https://doi.org/10.1093/icb/icab092>).
- National Academies of Sciences, Engineering, and Medicine. 2017. *Undergraduate Research Experiences for STEM Students: Successes, Challenges, and Opportunities*. Washington, DC: The National Academies Press.
- National Academies of Sciences, Engineering, and Medicine. 2019. *Minority Serving Institutions: America's Underutilized Resource for Strengthening the STEM Workforce*. Washington, DC: The National Academies Press.

- National Science Board. 2020. The state of U.S. Science and Engineering 2020. Alexandria, VA: National Center for Science and Engineering Statistics (NCSES). (<https://nces.nsf.gov/indicators/>).
- O'Brien LT, HL B, Garcia DM. 2020. Why are there so few ethnic minorities in ecology and evolutionary biology? Challenges to inclusion and the role of sense of belonging. *Soc Psych Edu* 23:449–77.
- Papert S. 1980. *Mindstorms: Children, Computers and Powerful Ideas*. New York, NY: Basic Books.
- Papert S, Harel I. 1991. Situating constructionism. *Constructionism* 36:1–11.
- Peppler K. 2013. STEAM-powered computing: using e-textiles to integrate the arts and STEM. *Comput Edu* 46:38–43.
- Race A, Beltran RS, Zavaleta ES. 2021. How and why does a field course close demographic gaps in ecology and evolutionary biology? *ICB* (<https://doi.org/10.1093/icb/icab121>).
- Sandeen C. 2012. High-impact educational practices: what we can learn from the traditional undergraduate setting. *Cont High Edu Rev* 76:81–9.
- Schwab J. 1960. Enquiry, the science teacher, and the educator. *Sci Teach*: 6–11.
- Seymour E, Hewitt NM. 1997. *Talking About Leaving*. Boulder, CO: Westview Press.
- Sheridan KM, Konopasky A. 2016. Designing for resourcefulness in a community-based makerspace. In: Peppler K, Halverson E, Kafai YBm editors. *Makeology: Makerspaces as Learning Environments*. New York, NY: Routledge. p. 30–46.
- Soria KM, Johnson M. 2017. High-impact educational practices and the development of college students' pluralistic outcomes. *Coll Stu Aff J* 35:100–16.
- Staab K. 2021. Implementing fabrication as a pedagogical tool in vertebrate anatomy courses: motivation, accessibility, and lessons. *ICB* (<https://doi.org/10.1093/icb/icab147>).
- Sunal DW, Hodges J, Sunal CS, Whitaker KW, Freeman LM, Edwards L, Johnston RA, Odell M. 2001. Teaching science in higher education: faculty professional development and barriers to change. *Sch Sci Math* 101:246–57.
- Tannenbaum SC, Berrett RD. 2005. Relevance of service-learning in college courses. *Acad Exch Quart* 9:197–201.
- Thu YM, French LB, Hersh BM, Nelson MK, Whitenack LB. 2021. FSBio 201: a successful CURE-based course that scaffolds research and scientific communication. *ICB* (<https://doi.org/10.1093/icb/icab128>).
- Varner J, Lanier HC, Duggan JM, Dizney L, Flaherty EA, Connors PK, Erb LP, Yahnke CJ, Hanson JD. 2020. How many squirrels are in the shrubs? A lesson plan for comparing methods for population estimation. *CourseSource* 7:1–8.
- Watkins J, Mazur E. 2013. Retaining students in science, technology, engineering, and mathematics (STEM) majors. *J Coll Sci Teach* 42:36–41.
- Watson CE, Kuh GD, Rhodes T, Light TP, Chen HL. 2016. ePortfolios – The eleventh high impact practice. *Int J ePortfolio* 6:65–9.
- Yahnke CJ, Dizney L, Varner J, Duggan JM, Lanier HC, Erb LP, Flaherty EA, Connors PK, Hanson JD. 2020. Sorry to eat and run: a lesson plan for testing trade-offs in Squirrel Behavior Using giving up densities (GUDs). *Course Source* 7:1–10.
- Yep A, Nation J. 2021. *ICB* (<https://doi.org/10.1093/icb/icab117>).
- Zavaleta ES, Beltran RS, Borker AL. 2020. How field courses propel inclusion and collective excellence. *Trends Ecol Evol* 35:953–6.