Integrative and Comparative Biology
Integrative and Comparative Biology, volume 61, number 3, pp. 1002–1012
doi:10.1093/icb/icab109
Society for Integrative and Comparative Biology

SYMPOSIUM

Increasing Faculty Involvement in the Undergraduate Interdisciplinary Learning Experience

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From the symposium "SICB-Wide Symposium: Biology beyond the classroom: Experiential learning through authentic research, design, and community engagement" presented at the virtual annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2021.

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Synopsis More and more, we see that advances in life sciences are made because of Interdisciplinary collaborations. These collaborations are the future—they are necessary to solve the world's most pressing problems and grand challenges. But are we preparing the next generation of scientists and the community for this future? At the University level, a number of initiatives and studies have suggested the need to reintegrate biology education and have made arguments that for students to build core competencies in biology, their education needs to be interdisciplinary. At the K-12 level, progress is being made to make learning interdisciplinary through the implementation of the *Next-Generation Science Standards* (NGSS). As NGSS is implemented, it will fundamentally change life sciences education at the K-12 level. However, when seeing the effect these initiatives and studies have had on the courses offered to students for their undergraduate biology degree, they still appear to be often siloed, with limited integration across disciplines. To make interdisciplinary biology education more successful, we need biologists, who for one reason or another have not been part of these conversations in the past and are more involved. We also need to increase communication and collaboration between biologists and educational researchers.

Introduction

Biological research is becoming increasingly interdisciplinary and there are a growing number of problems that society is facing that require interdisciplinary approaches and collaboration. These are common themes that have been echoed in several reports, studies, and initiatives over the last 20 years (National Research Council 1999, 2003; Pfirman et al. 2007; National Research Council 2009; Pfirman and Martin 2010; American Association for the Advancement of Science 2011). In the early 20th century, interdisciplinarity in academia began to be promoted by social scientists as an important part of undergraduate education (Broudy et al. 1964; Stember 1991). It was recognized that academia had become increasingly specialized and disciplines and subdisciplines increasingly siloed. Similar to the physical sciences and biology after them, they released many studies, reports, and started initiatives in support of integration (Stember 1991).

When characterizing the integration of disciplines and subdisciplines for research and teaching in the biological sciences, we would think that we would already have consistent operational definitions of the different types of integration. However, interestingly, terms like multidisciplinary, interdisciplinary, and transdisciplinary have not been agreed upon (Stember 1991; National Research Council 2005; Tripp and Shortlidge 2019). As biologists, we may often define the extent of integration in our research and maybe in the courses we teach. We may put ourselves anywhere from intradisciplinary, or even subdisciplinary (i.e., molecular and cellular biology, ecology, microbiology), to transdisciplinary, combining biology with social sciences, economics, politics, etc. (National Research Council 2005; Pettibone et al. 2018). But what does this mean? The term

Advance Access publication May 29, 2021

interdisciplinary is widely thrown around and not consistently used. Do we actually have much integration in our teaching? Do we often reach the interdisciplinary level of integration where we require students to use knowledge, methods, and concepts from two or more different disciplines? Are we using a real synthesis of approaches to solve problems beyond the scope of a single discipline (e.g., bioinformatics integrates biology, mathematics, and computer science) (National Academy of Sciences et al. 2005)? There has been this push to make science and, in some cases, biology specifically more interdisciplinary, where are those pushes coming from and are we succeeding?

Our purpose here is to provide to other biologists the perspective of biologists, who may be more research-focused, and nonhigher education researchers that are interested in making biology education more interdisciplinary, but often find themselves looking from outside in at these pushes and initiatives. We hope that our perspective will increase participation and will lead to an increased dialog with the research faculty that may not be so teaching-focused and the researchers of science education in the K-12 setting that are preparing our future students. We believe that this will help in making these initiatives successful in higher education. To that end, we first will provide a brief overview of some of these pushes, some of the outcomes reported, and the barriers to success that we recognized. We will then discuss our view on one challenge reported and our belief that it is becoming less of an issue due to changes in K-12 curricula. Finally, we will review a biology degree in the California State University system and examine how it only minimally appears to offer an interdisciplinary experience. We will conclude with our ideas on how biologists, who for one reason or the other have not been part of these conversations in the past, can make small steps toward and become active participant in making interdisciplinary education a reality for future undergraduate students.

Studies and reports

There have been many initiatives over the years that have been put forth to enhance undergraduate science education. Here, we provide a brief overview of a few of these "calls to action," that come up in conversations with other biologists and have emphasized interdisciplinary science education. Here, we discuss four: *Transforming Undergraduate Education in Science Mathematics Engineering and Technology* (National Research Council 1999); *BIO2010: Transforming Undergraduate Education for Future Research Biologists* (National Research Council 2003); *A New Biology for the 21st Century* (National Research Council 2009); and *Vision and Change in Undergraduate Education, A Call to Action* (American Association for the Advancement of Science 2011). These four have garnered more than 4,000 references, reviews, and follow-up reports (e.g., Google Scholar, PubMed, and Scopus) and, thus, our discussion here is not intended to be exhaustive or all-inclusive, but rather to provide a brief overview of each.

In 1999, the report *Transforming Undergraduate Education in Science Mathematics Engineering and Technology* (SME&T) was released and noted that undergraduate students were not being prepared for the future. Specifically, this report emphasized that the curriculum of students in the sciences is overly focused on their singular discipline and little attention is given to providing students with an understanding of how disciplines interconnect (National Research Council 1999). This call to action provided an extensive framework to change undergraduate SME&T(i.e., Science, Technology, Engineering and Mathematics [STEM]) education, including suggestions to have all students (i.e., part of general education) take introductory interdisciplinary courses in STEM and for the science majors to continue their interdisciplinary education throughout their degree program. Importantly, it was suggested that these STEM courses should explore fundamental and unifying concepts across the sciences (a theme we will return to later when examining Next-Generation Science Standards [NGSS]). This movement was important in getting all of us familiar with the term STEM (originally SMET) and began our ongoing conversation about STEM (Catterall 2017). In the first several years after this report was published, it appeared as little advancement had been made, there was no consensus about how this should be implemented, how to serve diverse students, what the learning outcomes for an interdisciplinary course should be, or how to overcome institutional and professional obstacles (Labov 2004). Additionally, insight into how to best implement pedagogy in these types of courses was just emerging (National Research Council 2000; Wood and Gentile 2003; Etkina et al. 2005). While this report did not drive a revolution in interdisciplinary education, it did result in several innovations in undergraduate education (National Research Council 2011).

The *BIO2010 Transforming Undergraduate Education for Future Research Biologist* study was initiated in 2000 by the National Academies of Science, National Institutes of Health (NIH), and Howard Hughes Medical Institute (HHMI). The NIH and HHMI noted that biomedical researchers needed increasing amounts of knowledge and skill in mathematics, physical, and computer sciences to be successful in their careers. This study aimed to identify ways to make undergraduate biology education more interdisciplinary through strengthening the connections between it and chemistry, physics, engineering, mathematics, and computer science (National Research Council 2003). While this study was initiated in part to train future biomedical researchers, it emphasized that the reforms should be broad and include all types of biology and other sciences. One of the biggest impacts on undergraduate biology education that has been credited to *Bio2010* is its role in jumpstarting curricular changes that resulted in the integration of mathematics and biology more explicitly (Gross 2004; Baker 2010). The push for this integration was offered through the support of the National Science Foundation (NSF) Undergraduate Biology and Mathematics grants program as well as Project Kaleidoscope which launched a 3-year Facilitating Interdisciplinary Learning project, funded by W. M. Keck Foundation, to improve learning environments in science and mathematics (Kezar and Elrod 2012). There are also examples of widespread institutional change, for example, at St Olaf College. Starting in 2001, there was a concerted effort to explicitly build future STEM education around interdisciplinarity, where faculty was brought in with joint appointments, specific interdisciplinary space was created, and leadership was committed to the change (Van Wylen et al. 2013). Even with the positive impact *Bio2010* has had, problems and challenges were recognized including poor support and the entrenchment of the long-standing disciplinary silos (Gross 2004; Baker 2010). Ultimately, it was suggested that there is a need for a well-funded NSF initiative for undergraduate biology, similar to the large funding initiatives done for chemistry, physics, and calculus, which goes beyond just mathematics and biology (Baker 2010). There were also negative unintended consequences of the push to implement the suggestions of *Bio2010*, some college and universities downsized or outright eliminated nonbiomedical subdisciplines in the undergraduate life sciences (Alberts 2003) and as a consequence, there was a noted decrease in the biological knowledge of researchers and physicians (Hoagland 2004).

Following the *Bio2010* study was the *A New Biology for the 21st Century* study. This study emphasized a *New Biology* that focused on not only integration within biology, to bring back the more integrated intradisciplinary biology, but also increased integration with other STEM disciplines. *New Biology* emphasized not only the importance and continuation of the changes brought on by *Bio2010* but also broadening it by focusing on the importance of four real-world problems and needs: food production, ecosystem restoration, biofuels, and human health (National Research Council 2009; Labov et al. 2010). It was noted that this initiative had the benefit of capturing the attention of students that were interested in solving real-world problems. It serves these students by making connections between what they learn in the classroom and the impacts that the issues can have on their family and their community; this was viewed as a powerful motivator for students to pursue science (Hulleman and Harackiewicz 2009). Following hot on the heels of the *New Biology*, sharing many common elements and being very synergistic with it (Woodin et al. 2010), was the *Vision and Change in Undergraduate Biology Education A Call to Action* study (American Association for the Advancement of Science 2011). Because they occurred so close to one another in time, they have a strong linkage in their calls for change. The *Vision and Change* report resulted from many discussions including a conference held in 2009 with support of the National Academies of Sciences, NSF, NIH, HHMI, and AAAS. The report lays out specific overarching core concepts that students should understand upon completion of a degree in biology including evolution; transformation of energy and matter; information flow; exchange and storage; and structure and function (concepts we will see again when discussing NGSS). Importantly, V*ision and Change* also emphasized multiple competencies that students should master several of which are interdisciplinary. The competencies laid out have significant overlap with the other initiatives (i.e., *New Biology*, *Bio2010*) and emphasized science integration with society; the interdisciplinary nature of biology; quantitative skills; communication and collaboration; modeling, simulation, and computational skills (Woodin et al. 2010; American Association for the Advancement of Science 2011). Several years after the release of the *Vision and Change* report, the implementation of the proposed changes was mixed. There was also inconsistent dissemination and acknowledgment of *Vision and Change* across the subdisciplines of biology (Vasaly et al. 2014). It has only been in the last 5 years that we have started to see the framework developed to assess the core concepts laid out by

Vision and Change (Brownell et al. 2014; Cary and Branchaw 2017; Branchaw et al. 2020). What about the competencies and specifically the interdisciplinary nature of biology? In the last *Vision and Change* report from 2018, “Unpacking a Movement and Sharing Lessons Learned,” the term interdisciplinary only appears twice in 42 pages of the report (American Association for the Advancement of Science 2018). Tripp and Shortlidge (2019) recognized that the competencies related to the interdisciplinary nature of biology laid out in *Vision and Change* lacked the framework and definitions necessary for success. It took almost 10 years, but we have a foundation from which learning outcomes, activities, and measurements of success toward students becoming more interdisciplinary can be measured and a major competency envisioned by *Vision and Change* can be met.

Each of these four studies made calls for an increase in interdisciplinary undergraduate education, but they had their key differences in their target audiences and how much of their focus was on the interdisciplinary nature of biology, specifically. The *SME&T* study was broadly interested in the development of an interdisciplinary curriculum for all undergraduate students, science and nonscience alike. The overall goal was to improve the technical competency in STEM in the US population. The long-term vision was to create a continuous interdisciplinary experience for all students, starting at the K-12 level and extending through undergraduate education (National Research Council 1999). The *Bio2010* study was primarily focused on identifying fundamental concepts within each discipline that would allow students in the life sciences to make interdisciplinary connections. Specifically, this study focused on training future interdisciplinary biomedical researchers. In the end, this study had a somewhat narrow focus and the concepts identified did not necessarily reflect modern, advancing biology across the various subdisciplines. It was even recognized that the results of the study would not be applicable to all biology students (National Research Council 2003). *New Biology* was also interested in the development of an interdisciplinary curriculum in the life sciences. This study targeted the training of future researchers that were needed to tackle real world and applied problems. Again, creating a narrower vision that would not necessarily be applicable to all students in life sciences (National Research Council 2009). *Vision and Change* study was focused on a revolution in undergraduate biology education. The interdisciplinary nature of biology was only one component of a much larger call for educational change impacting all students across all biology subdisciplines. Within *Vision and Change* only one of the six core competencies focused on the interdisciplinary nature of science at the conceptual level and one other emphasized the need to be able to communicate with other disciplines (American Association for the Advancement of Science 2011). These four studies, while sharing a call for interdisciplinarity in the life sciences, were quite different in their overall objectives.

Barriers to success

There are many possible reasons that a lot of the changes meant to be initiated by these studies and initiatives fail to catch hold. These include institutional challenges, issues with communication and dissemination, the long development time of the framework necessary for success, and faculty and student preparedness.

There are often issues surrounding the departments that are identified as the key players necessary for success, specifically, departmental silos remain a major barrier to creating interdisciplinary study (Baker 2010). Not only do the interdepartmental silos create barriers, so do the intradepartmental silos created by subdisciplines (Jacobs 2014). These entrenchment barriers often feel insurmountable at times. Often it is the view of disciplines that we lose too much by developing these courses and that the concerns about loss of depth in the interdisciplinary curriculum are justifiable. This is because such curricula creates knowledge that is lesser than discipline-based knowledge (Millar 2016). Other institutional challenges arise from administration, these studies have been used as an impetus to reorganize and refocus entire departments or colleges, often eliminating breadth and hindering the development of interdisciplinary curricula and research (Alberts 2003; Hoagland 2004). Additionally, when there are successes within a group of motivated individuals, there are further challenges of establishing and continuing the programs due to issues from budgeting to new campus leadership that may turnover institutional plans (Kezar and Elrod 2012). Many of the courses and changes that first come out of these initiatives often fail to catch on and often after just a few years no longer exist (Gross 2004). We could go on and on examining institutional challenges, but it takes time to make changes to manifest and stick at the institutional level.

Communication between those with the vision, those that teach the courses, and administration that supports the initiatives appears to be a key component to successful implementation. To incorporate interdisciplinary learning in STEM, it is necessary to create a collective review process for creating interdisciplinary coursework and programs (Kezar and Elrod 2012). However, there is often a lack of communication between departments. For example, it has been reported that frequently during the development of curricula around common concepts of mathematics and biology, the best practices of connecting mathematical concepts in biology settings or vice versa have failed to materialize because those involved in each department do not work together to develop a common framework (Labov et al. 2010). There are also issues with communication and larger collaboration because funding of these initiatives is often through individual grants (Baker 2010). Additionally, when something does catch hold and lead to institutional change (Van Wylen et al. 2013), these things rarely spread outside the home institutions (Gross 2004). We have also seen that when studies are first published, they are slow to spread (Vasaly et al. 2014). Anecdotally, at Fresno State probably half of the Department of Biology remained unaware of *Vision and Change* until at least 2014, and finding a textbook that was framed around it was a challenge for a good number of years. Again, it takes time to spread the word on initiatives and time to reach critical mass for change.

Vision and Change and the growth of the movement it started have demonstrated that it takes time to develop the necessary framework and tools to ensure success. It took nearly 10 years for dedicated individuals to develop ways to assess the students in the areas of core concepts (Brownell et al. 2014; Cary and Branchaw 2017; Branchaw et al. 2020) and competencies (Tripp and Shortlidge 2019). We did not have the necessary validated tools to measure the impact of the curricular changes suggested. It is problematic and, for some, discouraging when there is a new study or a new initiative every 5–10 years that suggest new changes because it often takes more time than that to establish the necessary framework for the previously suggested initiative. It is no wonder that a lot of those that were most involved could not maintain their enthusiasm and a movement gets visionary burnout (Gross 2004). Again, it takes time and if we keep jumping from one idea to the next without giving time for these things to mature, we are going to continue questioning why things fail to materialize.

Paraphrasing a colleague, professors in biology are required to teach courses that can make up a majority of their job duties, but they often have no formal training in even basic pedagogy. Despite the information being available for >20 years, covering best pedagogical practices, many faculty members in the natural sciences have no idea that there exists an extensive literature on how people learn (National Research Council 2000; Wood and Gentile 2003; Moats 2014; Owens et al. 2018). This sentiment is reflected in the literature and it is suggested that the ability of faculty to create and implement interdisciplinary curricula is too demanding and assumes a level of intellectual competency that may not exist for all teachers at all universities (Gross 2004; Hoy 2004; Cvijovic et al. 2016). This can be attributed in part to discouragement and devaluing of efforts by faculty to improve teaching effectiveness, especially at research universities (Wood and Gentile 2003).

Finally, one of the common sentiments expressed throughout much of the literature is that students are either unprepared for or do not have the intellectual capability to handle these types of interdisciplinary courses (Gross 2004). There are often misunderstandings at the level of preparation students may have for one area or another that often get conflated to complete lack of preparation of students (Labov et al. 2010). This could be due to students having difficulty seeing the purpose of studying mathematics, physics, and, to a lesser extent, chemistry, as a necessary and integral part of their biology curriculum (Taly et al. 2019). Unfortunately, it is often decided that the solution often to this problem is to limit the interdisciplinary experience to the best students and those biology students interested in research (Bialek and Botstein 2004) but limiting course access and development has a significant impact on diversity (Gross 2004). We believe that we are underestimating the intellectual capabilities and preparedness of our students. Through conversations with our K-12 education researchers and specialists in the university setting it has become clear that they are getting the K-12 students ready for an interdisciplinary future right now.

Engaging with K-12 education

The National Research Council (NRC) (2012) released *A Framework for K-12 Science Education* which outlined a new vision for science education in the United States and serves as the foundation for the NGSS that are designed to guide science instruction, curriculum, and assessment within K-12 schools. While previous science education reform documents (e.g., National Research Council 1996) depicted science as a series of disconnected facts that were often presented to students devoid of context, the NGSS calls for students to actively engage in science and engineering practices. Now, science teachers are asked to engage their students in eight science and engineering practices (https://www.nextgenscience.org/) to make sense of disciplinary core ideas and integrate concepts across four domains: (1) Physical sciences; (2) Life sciences; (3) Earth and space sciences; and (4) Engineering, technology, and applications of science (National Research Council 2012).

A key element in the framework used to develop NGSS is the incorporation of *crosscutting concepts*. These concepts are explicitly integrated into the curriculum and provide students with a foundation that allows them to connect various disciplines, such as chemistry, mathematics, biology, engineering, into a coherent and scientifically based worldview. These *crosscutting concepts* include patterns; cause and effect; scale, proportion, and quantity; systems and system models; energy and matter; structure and function; and stability and change. *Crosscutting concepts* introduce students to an interdisciplinary education very early in their educational career and use real-world examples for them to make the connections. There is evidence to suggest that teaching the STEM disciplines in an interdisciplinary manner, especially when embedded in real-world contexts, increases the relevance for both students and teachers which, in turn, increases motivation for learning and improves student interest, achievement, and persistence (National Research Council 2014). These outcomes can also help address calls for college and workplace readiness and increase the number of students who choose to pursue a STEM-related career. Importantly, this is building the students' foundation for future interdisciplinary education. The students are learning how concepts from two or more disciplines are connected and how they can be used together to solve problems and this experience hits on an important part of being interdisciplinary as defined by the NSF (National Academy of Sciences et al. 2005).

To date, 44 states across the country have formally adopted the NGSS as written or slightly modified versions. More than 70% of US students are now learning science that is based on the NGSS (https://ngss.nsta.org/about.aspx). The argument that students just are not ready for interdisciplinary courses at the college level is quickly evaporating.

Review of a biology degree in the California State University system

The California State University (CSU) system has a teaching mission and, ideally, should be an agent of change. Given the initiatives to enhance interdisciplinary undergraduate science and biology education and given that California has been preparing students using NGSS since 2013, is there any real appearance of an interdisciplinary science experience in the biology programs in the CSU system? To understand this better, we examined how integrated the core degree in biology (i.e., the required courses and not those that students elect to take) was with the other science courses that are frequently required. We reviewed the publicly available degree roadmaps of the 22 campuses that offer a degree in biology (institutional websites accessed between September and November 2020). From the roadmaps, we looked for the number of STEM courses explicitly required in disciplines outside of biology. We counted the number of courses students are required to take in chemistry, physics, calculus, statistics, and computer science. These courses were chosen because they are frequently referenced in the initiatives to make undergraduate education more interdisciplinary. Many of the campuses offered multiple degree options in biology, for example, microbiology or molecular and cellular biology. When multiple options were available, we examined the roadmaps and identified the required science courses outside the program that were shared between the cores of each option. In the end, we reviewed 22 departments and more than 230 non-biology STEM courses. Students taken are between two and four courses in chemistry, with four being average; one and two courses in physics, with two being average; zero and one course in calculus, with one being average; and zero and one course in statistics, with one being average. Only one campus requires a single course in computer science. The roadmaps recommend that these courses should be taken at different stages throughout a student's 4-year academic career, with 82% listed as lower-division and 18% listed as upper-division. However, the roadmaps themselves may offer multiple pathways to navigate these courses and there are instances where even the lower-division courses are recommended 23% of the time to be taken in the third or fourth year of the students' careers.

The interdisciplinary science components of the biology degree are what we would all probably expect to see and in fact, it looks a lot like the degree many of us may have earned as an undergraduate ourselves. What we wanted to have a better understanding of is how interdisciplinary is this biology degree, students take a variety of STEM classes, but how integrated are they into their other biology courses? The roadmaps only tell us what courses

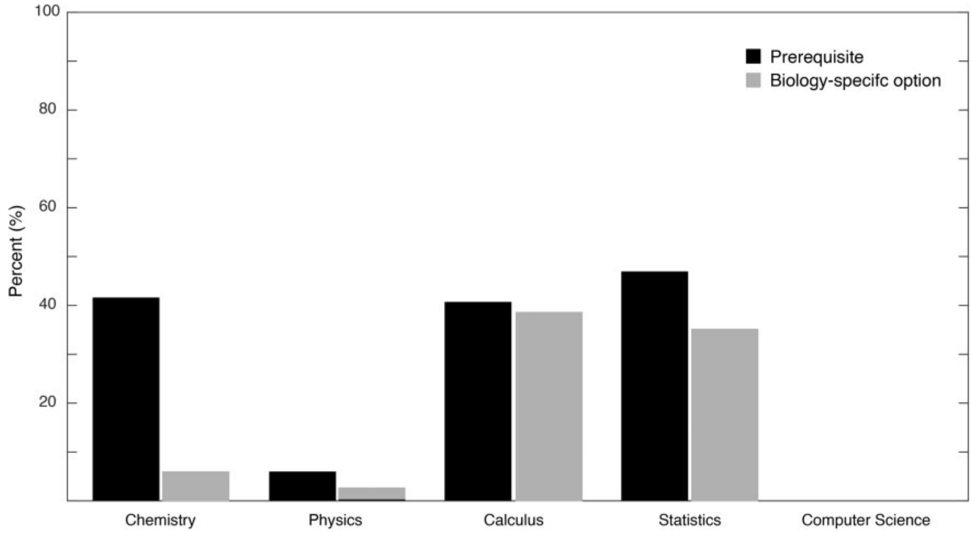

Fig. 1. Percentage of STEM courses required outside of biology that is required for at least one biology course and those that have biology-specific options. On average, these courses make up 30 units (range: 17–43) of the 77 units (range: 63–87) for a degree in biology in the CSU system. The CSU system requires 120 units total for a degree.

they take, but do they need to apply what they learn in these science courses to solve problems in biology? To approach this question, we identified the courses that were offered as biology/life science-specific, and we also looked at the required courses and determined if these were marked as prerequisites (i.e., must have been completed) for other required/core biology classes in the degree program (Fig. 1). Surely, if a student is required to integrate information, data, techniques, tools, perspectives, concepts, or theories from one of these other disciplines to solve biology problems from an interdisciplinary perspective, these science courses could come in a biology-specific flavor at best or at least be required before or required concurrently with the appropriate biology course.

The courses that most often had biology-specific options were mathematics courses like calculus and statistics (Fig. 1). We could not determine why mathematics was often offered with biology-specific options by looking at the roadmaps. However, we came up with two possibilities based on the literature. First, they could be the result of initiatives like *Bio2010*, which had a strong focus on integrating mathematics and biology (Kezar and Elrod 2012). Alternatively, the existence of these specific classes may be due to the perception that biology students are disinterested or bad at mathematics and were created to offer an alternative to general calculus and statistics and keep students in the major (Aikens and Dolan 2014, Wachsmuth et al. 2017). This deserves additional analysis but is beyond the scope of this article. The remaining courses rarely offered biology-specific options. We did not conclude much from this other than that explicit interdisciplinary core courses appear to rarely be offered as part of the science breadth training biology majors receive.

Next, we looked at whether these discipline-specific courses were required before enrolling in biology classes later in the major. Again, the thought behind this examination was that the completion of or concurrent enrollment in one of these other science classes may be indicative of a more interdisciplinary biology degree. These other courses are integral because the knowledge gained in them is necessary to solve problems from an interdisciplinary perspective in one of the required biology courses that make up the degree. Combining all the data from the different degree programs, we find that these courses appear as a prerequisite up to 47% of the time and often are never prerequisites for anything. Statistics is the most required course, often for a class in ecology, and is frequently combined with biology-specific research methods. This is followed by chemistry and calculus. Physics is rarely a prerequisite for any core courses in biology. Computer science is part of the degree at one CSU campus, but not required for any courses (Fig. 1). As a note, this takes into account courses that might be chained prerequisites where, for example, to take Biology 3 you need Chemistry 4, but to complete Chemistry 4 you need to have completed Chemistry 1, 2, and 3. On the surface, this gives the impression that the completion of these courses in other science disciplines are either not needed or, more likely, are not being integrated into the biology curriculum in a way that requires students to solve problems using interdisciplinary practices. This matches quite well with the finding that only 45% of STEM faculty have interdisciplinary learning outcomes in their college courses (Tripp and Shortlidge 2019). Again, we believe this deserves a more rigorous analysis that is beyond the scope of this paper.

Many would agree that this science breadth make-up of a degree in Biology is important, but why are these courses so poorly integrated into our core curriculum when we are requiring our students to take them? With all the emphasis on making biology more interdisciplinary, the obvious route would be to make these interdisciplinary connections more explicit and the pathway through the other sciences as related to a biology degree more defined for students. While it is suggested by the roadmaps that students take these courses throughout their career, a specific sequence of courses across the sciences is not often explicit or required and, again, they often rarely serve as prerequisites for biology courses. These roadmaps often described these courses as support courses or cognates and very rarely as interdisciplinary. With the way the different CSU campuses set up their roadmaps they have created an image that the core of their biology degrees is only minimally or superficially interdisciplinary. This may not reflect the true nature of their programs and there are courses offered on the campus that are truly interdisciplinary (e.g., Computational Biology, Biophysics, and Bioinformatics) but these are taken as electives.

Conclusion

From the outside looking in perspective, we can summarize what we have learned about interdisciplinary education in a higher education setting in this way: several issues are recognized in society that could be addressed by changes in undergraduate education. There are enthusiastic, engaged individuals that get together for a study and create a shared vision to address these problems. Frequently, it is identified that there needs to be more interdisciplinary education. A report is written, and initiatives are launched and funded by government and private agencies. The original visionaries champion these initiatives and work on developing new curricula and programs to address the issues. The word spreads but not evenly across all circles of academics that have individuals that seemingly should be or want to be involved. Institutional support is uneven, from administration changing priorities or following the money, to research institutions devaluating or actively discouraging pedagogical training. When the money ends or the visionaries burn out, there is often no support to maintain the momentum of change. This cycle seems to repeat every 5–10 years, and the result is a degree in biology on the surface looks a lot like it did 30 years ago.

The studies and the initiatives that they inspire are indeed ambitious. As biologists, we should want to be on the inside and not the outside looking in if we want to see change and if we want to see biology education become more interdisciplinary. It is important that the necessary and ongoing institutional support and professional development opportunities for faculty that want to be involved should not only be provided but encouraged and valued as well. It also seems that these processes move slowly, and it takes time for the best practices to emerge and mature. During this development, there needs to be more communication and we should not remain siloed in our disciplines of biology or chemistry or university science education or K-12 science education. There is a lot we can learn from each other. We think many things are within the control of faculty and departments that can make an impact immediately and support the incredible efforts of those that envisioned and are working hard toward making interdisciplinary education integral to biology education.

We can all take part in making biology education more interdisciplinary, even if we just consider ourselves a research biologist that also teaches. We think we can better support and contribute to these initiatives in a few ways.

- Establish faculty learning communities, ideally with institutional support and recognition, and involving those with the expertise to make interdisciplinary biology a reality. This includes faculty from a broad range of science departments and degree programs, faculty researching science education in a university environment, faculty preparing K-12 science teachers, or researching K-12 science pedagogy. These types of faculty learning communities can go a long way in fostering change (Cox 2004). By bringing together these groups and discussing similarities and differences in goals and learning outcomes as well as the challenges that are encountered along the way, can ultimately result in enhancing interdisciplinary curricula across K-12 and higher education (e.g., You et al. 2021).
- Do not underestimate the intellectual capabilities and preparedness of our students to take on the

interdisciplinary course. More than 70% of the country has implemented NGSS or similar standards. Those involved in implementation have invested an incredible amount of time, continue to take part in multi-layered professional development opportunities and work extensively with the administration to drive system-wide policy changes (Tyler et al. 2020). These take time but the students enrolling in our undergraduate biology courses tomorrow are already benefiting from this work today. Have a conversation with our colleagues in K-12 education and you will recognize they are working with educators to prepare our future students (https://www.nextgenscience.org/). The core ideas, practices, and crosscutting concepts that NGSS has spent many years developing and implementing are building the foundation for our students to act as interdisciplinary thinkers and problem solvers.

- This would seem to go without saying, but we need to directly integrate and make explicit to the students the connections between biology and those science breadth courses essential to the degree (physics, math, etc.). Too often these prerequisites and other science courses ultimately act as gatekeeping mechanisms rather than a meaningful interdisciplinary integration into the degree (Ayalon 1995; Gasiewski et al. 2012). Additionally, explicitly reinforce the concepts and their connections to other disciplines throughout the students' biology coursework. If your department or degree program already has made a lot of these steps, make the degree roadmaps and curricular plans reflect that change and easier to navigate for students and faculty outside your institution looking to drive change at their own.
- We can encourage faculty, or even institutionalize this practice by making it a requirement for tenure, to develop courses to provide authentic interdisciplinary experiences in the core programmatic courses using best practices like course-based undergraduate research (Auchincloss 2014) or problem-based learning (Allen and Tanner 2003; Zukmadini and Susilo 2015). Even if a truly interdisciplinary course is out of reach for faculty or departments, the development and offering of team-taught multidisciplinary courses leveraging the expertise of several faculty to better integrate the content would go a long way (Hoy 2004).

Funding

This work was supported by the National Science Foundation (CAREER 1551526; to D.D.L.) and the National Science Foundation and Louis Stokes Alliances for Minority Participation (CSU-LSAMP Bridge to the Doctorate HRD-1905148; to K.M.E.). CSU-LSAMP Bridge to the Doctorate program is provided by the National Science Foundation under Grant #HRD-1905148.

Conflict of interest

The authors declare no conflicts of interest.

Data availability

The data underlying this article are publicly available on each California State University campus website.

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