

# The state of introductory biology following 16 years of pedagogical reform since *Vision and Change for Biology Undergraduate Education*

Maia V. Palka,<sup>1</sup> Bridgette Clarkston,<sup>1</sup> Blaire Steinwand<sup>2</sup>

**AUTHOR AFFILIATIONS** See affiliation list on p. 8.

**ABSTRACT** Nearly two decades ago, over 500 biology educators from across North America contributed to the creation of the *Vision and Change for Undergraduate Biology Education: A Call to Action* report, with recommendations for the development of a deep understanding of core biological ideas and practices in undergraduate students and the integration of evidence-based practices into biology classrooms. Introductory biology courses provide a conceptual foundation in biology while also developing skills essential to both the transition from high school to university and general scientific literacy. Thus, alignment of introductory biology classrooms to *Vision and Change* is important for fostering biological and scientific literacy in all students, even those whose only exposure to biology is introductory courses. Following the dissemination of *Vision and Change* were numerous frameworks, resources, and instruments that support the implementation of these recommendations in undergraduate biology programs. Here, we synthesize the tools, evidence-based practices, and structural transformations that have been used to align introductory biology courses to *Vision and Change* with the aim of providing both an overview of the current landscape of introductory biology education and a starting point for institutions, who, like us, are evaluating their progress toward alignment with *Vision and Change*.

**KEYWORDS** introductory biology, *Vision and Change*, curricular reform, evidence-based pedagogy, scientific literacy

In response to a desire to promote biological literacy and support the diversity of learners in biology, over 500 biology educators from across North America collaboratively identified essential core concepts, competencies, and student-centered pedagogical practices nearly two decades ago, aimed at supporting a broader and more diverse population of learners (1–3). This effort culminated in the *Vision and Change for Undergraduate Biology Education: A Call to Action* report, which has motivated the development of numerous frameworks and resources that continue to guide transformative change in biology education (4–6). Coinciding with the dissemination of *Vision and Change* were other influential frameworks that followed similar guiding principles and paralleled one another in the fundamental skills and concepts that students should master by graduation. For example, “The *Framework for K-12 Science Education*” was developed to guide science instruction at the K-12 level and aligns closely with the principles outlined in *Vision and Change*, reflecting agreement across different levels of science education and consensus among science educators regarding effective teaching and learning practices (7). Both *Vision and Change* and the *Framework* emphasize the importance of developing scientific practices (i.e., competencies) in students to facilitate inquiry, create connections across disciplines and core concepts, and develop a strong understanding of core ideas fundamental to a particular discipline (1). Since 2010, several

**Editor** Sumali Pandey, Minnesota State University Moorhead, Moorhead, Minnesota, USA

Address correspondence to Blaire Steinwand, blaire.steinwand@ubc.ca, Bridgette Clarkston, bridgette.clarkston@botany.ubc.ca, or Maia V. Palka, maia.palka@gmail.com.

The authors declare no conflict of interest.

**Received** 9 July 2025

**Accepted** 7 September 2025

**Published** 25 September 2025

Copyright © 2025 Palka et al. This is an open-access article distributed under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International license](https://creativecommons.org/licenses/by-nc-nd/4.0/).

institutions across North America have implemented course-level or programmatic changes to their biology programs in response to the call to transform biology undergraduate education (8). These range from small-scale initiatives that promote active learning in the classroom to programmatic transformations aligned with the recommendations outlined in *Vision and Change*. Large-scale transformations to programs and curriculum require both time and ideological change (9). As a result, many institutions have yet to fully align their biology curricula with *Vision and Change* and implement at scale the evidence-based instructional practices that support higher-level biological literacy for a greater number and diversity of undergraduate students (8, 10, 11).

Introductory biology courses serve a broad and interdisciplinary audience, including biology majors, non-biology STEM majors, and students outside of science altogether (1). Alignment with *Vision and Change* in introductory biology curricula is particularly important since, for many non-biology students, these courses may be their only formal exposure to biological literacy, scientific inquiry, and core concepts fundamental to understanding the natural world. This perspective synthesizes the peer-reviewed literature on introductory biology reforms that have arisen in response to *Vision and Change*, with the aim of providing both a brief overview of the current state of introductory biology education and a resource for other institutions who, like us, are still working to align their introductory biology programs with *Vision and Change*.

## CONSENSUS-BASED FRAMEWORK FOR INCREASED STRUCTURE IN INTRODUCTORY BIOLOGY CURRICULA

One of the most critical ideas presented by *Vision and Change* was identifying five core concepts and six core competencies that are fundamental for students to develop a comprehensive understanding of biology within the context of a degree program (1, 2, 4, 5). These fundamental guiding principles were broad, overarching goals meant to serve as a resource for faculty, but their utility required further delineation and articulation to effectively guide instruction. This inspired the development of detailed frameworks to support the implementation and integration of core concepts and competencies into biology curricula, thus increasing consistency and structure across biology programs (4–6). These resources are arguably the most powerful tools for guiding alignment in biology education and are currently guiding a biology program review underway at our institution.

### Core principles, outcomes, and learning objectives to guide alignment

The BioCore Guide (4) is a nationally validated framework that supports the interpretation of the core concepts outlined by *Vision and Change* to ensure they are integrated into learning goals and course outcomes. By outlining the overarching principles that define individual core concepts, the BioCore guide connects biological principles to different sub-disciplines at different biological scales, illuminating how they can be taught across the curriculum. The BioCore Guide is a useful resource for transforming biology curricula using backward design or for mapping existing programs to *Vision and Change* to identify misalignments within a curriculum. Following the BioCore Guide, a set of 163 lesson-level learning objectives for introductory biology was developed to support the integration of the core concepts into day-to-day lesson planning (6). Although there is no functionally equivalent framework to the BioCore Guide for interpreting the *Vision and Change* core competencies (i.e., a set of overarching principles and statements that broadly connect core competencies to biological disciplines), the BioSkills Guide (5) provides a comprehensive set of 77 learning outcomes aimed at incorporating core competencies into lesson plans, assessments, and classroom activities.

## Validated instruments for the evaluation and assessment of introductory biology programs

The development of a suite of validated instruments for curricular and programmatic assessment is driving transformation and measuring progress toward pedagogical change in introductory biology. Instruments such as the BioMAPS (i.e., GenBio-MAPS and EcoEvo-MAPS), Biology Core Concept Inventory (BCCI), BioSkills Curriculum Survey and Test of Scientific Literacy Skills (TOSLS), and the Partnership for Undergraduate Life Sciences Education (PULSE) Vision & Change Rubrics, among others, can be used to elucidate how well introductory biology curricula at the course or program level align with *Vision and Change* (12–17). Each tool can be used to assess a different aspect of coherence with *Vision and Change*, and thus, each can play a fundamental role in identifying gaps in introductory biology programs that need to be addressed. For instance, the BioSkills Curriculum Survey, which evaluates how BioSkills learning outcomes are taught and assessed, can be used by instructors to shed light on which core competencies may get left out of the classroom at the level of lesson plans and assessments and thus need to be better integrated during course planning (12). On the other hand, GenBio-MAPS is a nationally validated instrument that directly evaluates student understanding of the *Vision and Change* core concepts at multiple points throughout an undergraduate degree, including after the completion of introductory coursework (14). Assessing students multiple times throughout their undergraduate degree allows institutions to evaluate what knowledge students have prior to university coursework and how they are progressing through a degree program. While these tools evaluate students' understanding of core concepts and competencies, additional instruments have been developed to address other *Vision and Change* outcomes. For example, TOSLS evaluates students' ability to apply scientific literacy skills (18–20), while BCCI assesses how students make interdisciplinary connections across the *Vision and Change* core concepts (15).

Finally, the PULSE is a collaborative community of life science educators developed to support institutions working to align with national initiatives that aim to improve STEM education (like *Vision and Change*) (13, 21). Among the many resources that PULSE offers to support curricular or programmatic change in undergraduate biology education, the PULSE Vision & Change Rubric is a self-assessment tool that includes five rubrics that directly assess programmatic alignment with different aspects of *Vision and Change*, from curriculum alignment to an institution's receptivity to change (13, 17, 22). These rubrics can be used in tandem with other instruments to identify gaps and lend evidence to support curricular reform.

Together, these instruments have facilitated the identification of gaps in biology curricula, in students' understanding of core concepts and competencies within individual programs, and act as valuable tools for examining the efficacy of various interventions and pedagogical innovations on student learning. For example, they have been used to explore how student understanding of specific *Vision and Change* outcomes differs across institution types (i.e., community colleges) (23) and to test hypotheses about the effects of evidence-based practices on student learning (for instance, how the length of time allocated for individual active learning exercises within a classroom influences student performance) (24). Branchaw et al. (13) provide a comprehensive summary of these resources allowing educators and institutions to identify which tools are most appropriate for their specific goals (13).

## EVIDENCE-BASED PRACTICE AND PEDAGOGY

Beyond promoting biological literacy using core concepts and competencies, *Vision and Change* recommended that undergraduate biology classrooms adopt student-centered pedagogical practices for the benefit of all students and to overcome inequitable outcomes experienced by equity-deserving groups (i.e., women and gender-diverse students, first-generation students, and persons excluded because of their ethnicity or race [PEERs]) (1, 5). These practices include (i) active learning in the classroom, (ii) using

diverse assessments that not only evaluate student understanding but also facilitate learning, provide frequent feedback, and can be used by instructors to guide and inform teaching practices, (iii) providing students with greater opportunities to participate in authentic research experiences, and (iv) engaging students in real-world biological challenges and problems that teach core ideas through a contextual lens (1).

The positive outcomes of incorporating student-centered pedagogical practices into introductory biology programs extend across the cognitive and affective domains of learning and support the development of metacognitive skills (25). In the cognitive domain, certain student-centered practices (i.e., high-structured classrooms and teaching concepts within relative contexts) can cultivate higher-order thinking—such as applying conceptual knowledge to novel problems, rather than relying on lower-order tasks like factual recall, thereby promoting deeper learning and even longitudinal transfer of knowledge (26–29). In fact, students entering undergraduate biology programs retain very little content from their high school or pre-university coursework, particularly because pre-university coursework often emphasizes memorization and lower-order thinking (30). While no study has directly attempted to quantify how students retain content knowledge from introductory biology courses, multiple studies across different levels of education consistently demonstrate that knowledge is not consistently retained from one course to the next (30, 31) but increased opportunities for students to engage in higher-order thinking, inquiry, and problem-based learning in introductory biology courses and promote content retention (26, 28, 32).

The affective domain of learning, which refers to the attitudes, motivation, and emotions that influence how students learn, underpins the cognitive outcomes that define success in most introductory biology courses. The same practices that support the cognitive domain of learning have a positive impact on students' attitudes, confidence, and motivation to learn (25, 33, 34). At the same time, some student-centered pedagogical practices (i.e., formative assessments and reflections) emphasized in biology classrooms foster the metacognitive skills that students need to monitor and evaluate their own understanding, recognize gaps in their understanding, and modify their study habits to support their own learning (35, 36). Combining pedagogical practices that consider both affective and cognitive domains of learning is particularly powerful for reducing or eliminating achievement gaps among diverse groups of students (37).

### Active learning

Classrooms that promote learning by actively engaging students in the learning process support higher-order thinking, facilitate the development of scientific literacy skills, and improve student performance, retention, and self-efficacy while reducing inequitable outcomes (20, 25, 27, 34, 37–41). By engaging students in dialogic and/or interactive classroom discourse using polling systems, “think-pair-share,” and collaborative group work, instructors invite their students to actively participate in the learning process (20, 39, 42–44). The development of various instruments has facilitated the assessment of instructors' use of active learning practices such as Classroom Observation Protocol for Undergraduate STEM (COPUS), Classroom Discourse Observation Protocol, Follow-Up Discourse Observation Protocol, Practical Observation Rubric to Assess Active Learning (PORTAAL), and Decibel Analysis for Research in Teaching (DART) (45–48). These instruments can be used to characterize active learning behaviors and evaluate and quantify the patterns and frequency of discourse moves in the classroom or, in the case of DART, the level of student engagement as measured by noise in the classroom. A detailed comparison of COPUS, PORTAAL, and DART was provided by Asgari et al. (48) that educators can use to identify which tool is best suited for a particular use (48).

### Structural redesign of introductory biology programs to facilitate student engagement and deeper learning

High-structure biology courses go beyond just interweaving active learning exercises throughout lectures: they invert traditional, often high-enrollment classrooms by having

students learn content before class and, instead, use class time for collaborative problem-solving, discussions, and applied practice (39, 49, 50). These environments, when applied in introductory biology settings, have numerous positive benefits for student learning including increased learning gains, reduced failure rates, and even positive outcomes in the affective domain of learning (e.g., self-efficacy) while disproportionately benefiting students identifying from groups historically disadvantaged in traditional classrooms (i.e., PEERs and first-generation university students) by reducing achievement gaps (40, 51, 52). They improve student preparedness for upper-year courses and boost 3-year graduation rates (49). Platforms like “Codon Learning,” which was developed and is directly supported by the authors of the BioCore and BioSkills Guide, are making adoption of high structure and alignment with consensus-based framework seamless for instructors.

### Structural redesign of introductory biology “lectures” to support scientific literacy

Introductory biology programs have also undergone structural transformations aimed at supporting the early development of scientific literacy skills that align with the *Vision and Change* core competencies (e.g., 19, 20, 53–56). These often take the form of tutorials or discussions and often focus on interpreting primary literature or practicing quantitative thinking skills. Disciplinary first-year seminars—high-structure, low-enrollment introductory courses that teach fundamental biology concepts through inquiry-based activities and interdisciplinary topics—are becoming increasingly common in introductory STEM programs (e.g., *Exploring Biology*, University of Wisconsin–Madison) (57, 58). These seminars increase the likelihood that students will continue in higher-level biology coursework, support scientific literacy skills, promote student engagement through discussions and group work, and foster strong student-instructor relationships that support the transition from pre-university to higher education (57, 58). Another innovative practice designed to promote scientific literacy skills in introductory biology curriculum is Consider, Read, Elucidate hypotheses, Analyze and interpret data, Think of the next Experiment (CREATE) (59). From interpreting background information to proposing future experiments, CREATE courses guide students through the process of science with a highly scaffolded approach to interpreting primary literature, thus providing practice in scientific literacy skills while also supporting the affective domain of learning (59–62). The CREATE approach has been shown to have positive outcomes in promoting inquiry skills and student self-efficacy, in some cases even when delivered in an online format (59, 61), and has been adopted at a number of institutions (e.g., *Introduction to Scientific Thinking* at City College of New York; *Thinking Like a Life Scientist* at the University of British Columbia)

### A shift toward the use of formative assessments

Despite these *Vision and Change* recommendations, many lower-level undergraduate biology courses continue to use summative assessments that evaluate lower-order thinking, often failing to evaluate students’ understanding of scientific practices as they assess students’ factual content knowledge instead of their conceptual understanding of biology (63). The shift toward more student-centered pedagogical practices has prompted a reevaluation of how student learning should be assessed (1). Although summative assessments such as midterms and final exams still dominate the approach to evaluation in introductory biology, an increasing number of instructors are adopting formative and alternative assessment to improve student learning (53, 64, 65). Unlike traditional high-stakes, summative assessments, low-stakes formative assessments, quizzing, and project-based assessments facilitate learning. Implementing multiple low-stakes formative assessments within an introductory biology classroom in the form of tests/quizzes that provide immediate feedback to students increases student learning gains and longitudinal knowledge transfer (65, 66). Alternative assessment strategies that incorporate student reflections are gaining popularity, as they not only

support improvements in student performance and learning outcomes but also promote the development of metacognitive awareness (67).

### Course-based undergraduate research experiences

*Vision and Change* strongly emphasized the importance of providing biology students with authentic research experiences throughout an undergraduate degree (1, 2). Unfortunately, engaging students in research can be challenging, especially in high-enrollment settings. Research experiences have historically been largely inaccessible to students early in their undergraduate career and particularly difficult for PEERs and those with less social capital such as first-generation students to acquire (68–71). Course-based undergraduate research experiences (CUREs) provide a solution to this problem (68, 70, 72–74). CUREs engage students in genuine, open-ended scientific inquiry as part of a regular course by immersing students in iteration, collaboration, and relevance of scientific discovery (70, 71, 75), promoting self-efficacy, critical thinking skills, and the use of higher-order cognitive skills (69, 76–79).

Students who participate in CUREs early in their undergraduate STEM programs are significantly more likely to persist and graduate with degrees among numerous other positive outcomes, highlighting the importance of offering CUREs at the introductory level within biology (69, 70, 80). This is reflected in the growing emphasis on CUREs in introductory biology programs at institutions across North America. These range from CUREs that utilize place-based learning by asking ecologically relevant questions about organisms on campus (i.e., quantifying invertebrate biodiversity) to those that use model systems to investigate questions in cell biology (i.e., using yeasts to explore chemotherapy resistance) and even CUREs that support the development of bioinformatics skills (i.e., Genomics Education Partnership), among many others (73, 81–83). While the unpredictable nature of answering novel research questions can make CUREs challenging for students, these difficulties can be constructive because students learn to become proficient at problem solving and develop better strategies for coping with failure in academic contexts (84, 85). In fact, students who engage in CUREs often find future research opportunities more accessible, and CUREs that promote place-based learning or community integration also foster civic engagement (68, 69, 79, 86).

### Learning in context

Learning environments that situate fundamental concepts in the context of real-life problems, topics, and case studies promote the use of higher-order cognitive skills by helping students make connections across concepts, increase student civic engagement, and support the longitudinal retention of content (1, 29–31, 87–91). Introductory biology courses are a particularly excellent setting for teaching biological concepts within the context of different relevant scenarios to promote a deeper understanding of core disciplinary ideas. The positive outcomes of contextual learning across all levels of education led to the development of Science Education for New Civic Engagements and Responsibilities (SENCER), a widespread initiative launched by the National Center for Science and Civic Engagement in 2001 that advocates for the instruction of scientific concepts through the lens of relevant societal problems (i.e., climate change and public health concerns) to provide students with a meaningful understanding of scientific core concepts while engaging them in real-life challenges (1, 87, 88). Since its deployment, over 500 different institutions have participated in SENCER programming either at the scale of entire courses or as learning activities within a course. Introductory biology programs at several institutions have been transformed according to SENCER ideals through the development of entire courses (i.e., *Biological Inquiry* at Wofford College; *Environmental Biology: Ecosystems of Southwest Florida* at Florida Gulf Coast University; *Living Systems: Global Concepts, Local Connections* at Calvin College) or through the development of specific learning activities (i.e., *Cells as City* from Northern Virginia Community College; *Painting and Printing with Bacterial Pigments* at Eugene Lang College for Liberal Arts) (53, 88). Leight et al. (92) suggest that

introductory biology students may struggle more with retaining content compared to more advanced undergraduate students because more experienced students are better equipped to apply new knowledge to concepts they have previously learned. Since contextual learning promotes the development of higher-order thinking, which in turn supports students' ability to apply knowledge to new contexts (93), perhaps providing introductory biology students with a more cohesive learning experience, where they can learn fundamental biological concepts through real and relevant examples, may improve content retention into second year by enabling them to more meaningfully apply and connect new knowledge to what they have previously learned.

## BARRIERS TO CHANGE

Despite numerous resources, tools, and communities available to support curricular or programmatic alignment with *Vision and Change*, barriers at various levels continue to impede programmatic transformation. For many faculty, pedagogical change conflicts with their professional identity as scientists (94). The professional identity of many faculty is often research-oriented: graduate programs often emphasize research skills over pedagogical practices, and teaching-focused positions are frequently considered less desirable than those that predominantly focus on research, which can discourage early-career scientists from investing time in developing pedagogical expertise (94–96). In fact, faculty who are highly productive in their research field reportedly use fewer active learning strategies in their classrooms, likely because these faculty have limited time to invest in developing new lesson plans that incorporate student-centered pedagogy into their classrooms (95). Lesson planning for active learning can require more preparation time than traditional lecturing; thus, highly research-active faculty would benefit from additional support to help them balance lesson development with their research responsibilities (94, 95). Furthermore, because graduate students are not often exposed to formal training in teaching, lesson planning, and curriculum development, those who become faculty tend to teach the way they were taught, which, even when interactive, is often authoritative in nature (46, 47, 94, 95). Lastly, more experienced teaching faculty may be resistant to changing teaching strategies they have used for many years, thus limiting the successful adoption of student-centered teaching practices within a classroom (94, 97). This resistance may stem from skepticism about the evidence supporting these approaches or from concerns that students are not always receptive to change, leading to worse evaluations of teaching (94, 95). These barriers are further compounded by the lack of incentives for faculty to develop their teaching skills and invest in curriculum change. Unlike publications, teaching awards, or evaluations, pedagogical innovation is rarely recognized or rewarded by institutions (94–96). Consequently, transformation often comes at a high cost to faculty, with little institutional reward and the perceived risk of poorer student evaluations due to resistance to change. Pedagogical ideology, lack of time and resources and incentives, and large class sizes are perceived by instructors as significant barriers to creating more active, student-centered classrooms and providing students with authentic research experiences in introductory biology programs (9, 97, 98).

While some initiatives, like PULSE and SENCER, explicitly promote *Vision and Change* (13, 17, 22, 87, 99), many professional development programs within institutions are broader in scope, focusing on general pedagogy and curriculum design rather than discipline-specific reform (94). For example, at our institution, the Center for Teaching and Learning offers professional development on student-centered pedagogical practices, like active learning, but these opportunities are often offered outside of a disciplinary context. Tools like the BioCore Guide and BioSkills Guides, for instance, are not part of development programs. When instructors are introduced to these tools, it is often out of the context of their own classrooms, leaving them with little support throughout their implementation. Thus, a significant barrier toward curricular alignment with *Vision and Change* at a departmental and instructor level may be a lack of exposure and familiarity with the *Vision and Change* principles as well as the numerous resources

and tools available (97, 100). In other words, instructors at many institutions may simply be unaware of the resources and evidence-based pedagogical practices available, and even those who are aware often lack the institutional support needed to implement them effectively. At the departmental level, effective programmatic curricular alignment is large-scale and longitudinal. This type of transformation requires a significant amount of buy-in from many faculty members. Building communities and fostering collaboration among faculty teams are critical for increasing exposure to resources, supporting a sense of ownership, and ultimately strengthening faculty commitment to change (96, 98, 99, 101, 102).

## CONCLUSION

Transforming undergraduate biology education to align with *Vision and Change* requires a shift in teaching practices toward student-centered lesson plans, assessments, and providing students with authentic research experiences (1). Thus far, these transformations have required a slow and incremental process with significant faculty involvement and buy-in, both at the departmental and instructor levels, to help provide instructors with support to overcome perceived barriers (i.e., large class sizes and lack of time to develop new course materials) (6), and opportunities to develop a sense of ownership through a shared vision among faculty (98, 103, 104). This shared vision can be supported through the development of faculty learning communities and professional development opportunities, where instructors meet regularly to discuss teaching strategies, course design, and participate in workshops to enhance their skills in creating active learning environments (95, 98, 99, 101–104). Faculty and departments can take advantage of the suite of resources, frameworks, and instruments discussed here to facilitate the alignment of programs with the goals of *Vision and Change* by identifying gaps in existing programs and providing tools for backward curricular design. Ultimately, biology programs aligned with *Vision and Change* will support the development of a deep understanding of core biological ideas and practices in all undergraduate students while reducing inequitable outcomes and enhancing student self-efficacy through the adoption of evidence-based, student-centered teaching practices.

## ACKNOWLEDGMENTS

We thank Jeffery Richards, Shawn Mansfield, and Pamela Kalas of the Botany and Zoology Departments at University of British Columbia for their support through the process of writing this perspective. The literature search and writing of this perspective was conducted on the traditional, ancestral, and unceded territory of the x<sup>w</sup>məθk<sup>w</sup>əy'əm (Musqueam) people.

This work was funded by the Departments of Zoology and the Department of Botany at the University of British Columbia.

## AUTHOR AFFILIATIONS

<sup>1</sup>Department of Botany, Beaty Biodiversity Research Centre and Museum, The University of British Columbia, Vancouver, British Columbia, Canada

<sup>2</sup>Department of Zoology, The University of British Columbia, Vancouver, British Columbia, Canada

## AUTHOR ORCIDS

Maia V. Palka  <http://orcid.org/0009-0005-8743-4438>

Bridgette Clarkston  <http://orcid.org/0000-0003-3859-8098>

Blaire Steinwand  <http://orcid.org/0009-0002-7210-3204>

## AUTHOR CONTRIBUTIONS

Maia V. Palka, Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing | Bridgette Clarkston, Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review and editing | Blaire Steinwand, Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review and editing

## REFERENCES

- American Association for the Advancement of Science. 2011. Vision and change in undergraduate biology education: a call to action: a summary of recommendations made at a national conference organized by the American Association for the Advancement of Science.
- Woodin T, Carter VC, Fletcher L. 2010. Vision and change in biology undergraduate education, a call for action—initial responses. *LSE* 9:71–73. <https://doi.org/10.1187/cbe.10-03-0044>
- Woodin T, Smith D, Allen D. 2009. Transforming undergraduate biology education for all students: an action plan for the twenty-first century. *LSE* 8:271–273. <https://doi.org/10.1187/cbe.09-09-0063>
- Brownell SE, Freeman S, Wenderoth MP, Crowe AJ. 2014. BioCore guide: a tool for interpreting the core concepts of vision and change for biology majors. *LSE* 13:200–211. <https://doi.org/10.1187/cbe.13-12-0233>
- Clemmons AW, Timbrook J, Herron JC, Crowe AJ. 2020. BioSkills guide: development and national validation of a tool for interpreting the *vision and change* core competencies. *LSE* 19:ar53. <https://doi.org/10.1187/cbe.19-11-0259>
- Hennessey KM, Freeman S. 2024. Nationally endorsed learning objectives to improve course design in introductory biology. *PLoS One* 19:e0308545. <https://doi.org/10.1371/journal.pone.0308545>
- Quinn H, Schweingruber H, Keller T, eds. 2011. A framework for K–12 science education: practices, crosscutting concepts, and core ideas. National Academies Press, Washington, DC.
- Hsu JL, Misra A, Wolyniak MJ, Goller CC, Mathews S, Swamy U, Newman DL, Moore ME. 2025. Charting a new vision: lessons on *vision & change* from a network of biology educators. *J Microbiol Biol Educ* 26:e0017224. <https://doi.org/10.1128/jmbe.00172-24>
- Spell RM, Guinan JA, Miller KR, Beck CW. 2014. Redefining authentic research experiences in introductory biology laboratories and barriers to their implementation. *CBE Life Sci Educ* 13:102–110. <https://doi.org/10.1187/cbe.13-08-0169>
- Heil A, Olaniran J, Gormally C, Brickman MP. 2024. It's in the syllabus: what syllabi tell us about introductory biology courses. *CBE Life Sci Educ* 23:ar37. <https://doi.org/10.1187/cbe.23-05-0081>
- Clark N, Hsu JL. 2023. Insight from biology program learning outcomes: implications for teaching, learning, and assessment. *LSE* 22:ar5. <https://doi.org/10.1187/cbe.22-09-0177>
- Clemmons AW, Donovan DA, Theobald EJ, Crowe AJ. 2022. Using the intended-enacted-experienced curriculum model to Map the *Vision and change* core competencies in undergraduate biology programs and courses. *CBE Life Sci Educ* 21:ar6. <https://doi.org/10.1187/cbe.21-02-0054>
- Branchaw JL, Pape-Lindstrom PA, Tanner KD, Bissonnette SA, Cary TL, Couch BA, Crowe AJ, Knight JK, Semsar K, Smith JL, Smith MK, Summers MM, Wienhold CJ, Wright CD, Brownell SE. 2020. Resources for teaching and assessing the *vision and change* biology core concepts. *LSE* 19:es1. <https://doi.org/10.1187/cbe.19-11-0243>
- Couch BA, Wright CD, Freeman S, Knight JK, Semsar K, Smith MK, Summers MM, Zheng Y, Crowe AJ, Brownell SE. 2019. GenBio-MAPS: a programmatic assessment to measure student understanding of *vision and change* core concepts across general biology programs. *LSE* 18:ar1. <https://doi.org/10.1187/cbe.18-07-0117>
- Cary TL, Wienhold CJ, Branchaw J. 2019. A biology core concept instrument (BCCI) to Teach and Assess Student Conceptual Understanding. *CBE Life Sci Educ* 18:ar46. <https://doi.org/10.1187/cbe.18-09-0192>
- Summers MM, Couch BA, Knight JK, Brownell SE, Crowe AJ, Semsar K, Wright CD, Smith MK. 2018. EcoEvo-MAPS: an ecology and evolution assessment for introductory through advanced undergraduates. *CBE Life Sci Educ* 17:ar18. <https://doi.org/10.1187/cbe.17-02-0037>
- Aguirre KM, Balser TC, Jack T, Marley KE, Miller KG, Osgood MP, Pape-Lindstrom PA, Romano SL. 2013. PULSE vision & change rubrics. *CBE Life Sci Educ* 12:579–581. <https://doi.org/10.1187/cbe.13-09-0183>
- Killpack TL, Popolizio TR. 2023. An equity-focused redesign of an introductory organismal biology lab course to develop foundational scientific practices. *J Microbiol Biol Educ* 24:e00213–22. <https://doi.org/10.1128/jmbe.00213-22>
- Borchardt R, Salcedo T, Bentley M. 2019. Little intervention, big results: intentional integration of information literacy into an introductory-level biology lab course. *J Biol Educ* 53:450–462. <https://doi.org/10.1080/00219266.2018.1494029>
- Auerbach AJ, Schussler EE. 2017. Curriculum alignment with *vision and change* improves student scientific literacy. *CBE Life Sci Educ* 16:ar29. <https://doi.org/10.1187/cbe.16-04-0160>
- Dou R. 2018. Review: partnership for undergraduate life sciences education (PULSE). *Am Biol Teach* 80:64–64. <https://doi.org/10.1525/abt.2018.80.1.64>
- Brancaccio-Taras L, Pape-Lindstrom P, Peteroy-Kelly M, Aguirre K, Awong-Taylor J, Balser T, Cahill MJ, Frey RF, Jack T, Kelrick M, Marley K, Miller KG, Osgood M, Romano S, Uzman JA, Zhao J. 2016. The PULSE vision & change rubrics, version 1.0: a valid and equitable tool to measure transformation of life sciences departments at all institution types. *CBE Life Sci Educ* 15:ar60. <https://doi.org/10.1187/cbe.15-12-0260>
- Courtney NA, Smith MK, Esparza D. 2025. Community college biology students' understanding of *vision and change* core concepts. *J Microbiol Biol Educ* 26:e0021124. <https://doi.org/10.1128/jmbe.00211-24>
- Cen X, Lee RJ, Contreras C, Owens MT, Maloy J. 2024. Time spent on active learning activities does not necessarily correlate with student exam performance: a controlled case study. *J Microbiol Biol Educ* 25:e0007324. <https://doi.org/10.1128/jmbe.00073-24>
- Auerbach AJ, Andrews TC. 2018. Pedagogical knowledge for active-learning instruction in large undergraduate biology courses: a large-scale qualitative investigation of instructor thinking. *Int J STEM Educ* 5:19. <https://doi.org/10.1186/s40594-018-0112-9>
- Tal T, Tsaushu M. 2018. Student-centered introductory biology course: evidence for deep learning. *J Biol Educ* 52:376–390. <https://doi.org/10.1080/00219266.2017.1385508>
- 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 USA* 111:8410–8415. <https://doi.org/10.1073/pnas.1319030111>
- Jensen JL, McDaniel MA, Woodard SM, Kummer TA. 2014. Teaching to the test...or testing to teach: exams requiring higher order thinking skills encourage greater conceptual understanding. *Educ Psychol Rev* 26:307–329. <https://doi.org/10.1007/s10648-013-9248-9>
- Dresner M, de Rivera C, Fuccillo KK, Chang H. 2014. Improving higher-order thinking and knowledge retention in environmental science teaching. *Bioscience* 64:40–48. <https://doi.org/10.1093/biosci/bit005>
- Jones H, Black B, Green J, Langton P, Rutherford S, Scott J, Brown S. 2015. Indications of knowledge retention in the transition to higher education. *J Biol Educ* 49:261–273. <https://doi.org/10.1080/00219266.2014.926960>
- Custers EJFM. 2010. Long-term retention of basic science knowledge: a review study. *Adv Health Sci Educ Theory Pract* 15:109–128. <https://doi.org/10.1007/s10459-008-9101-y>
- Luckie DB, Aubry JR, Marengo BJ, Rivkin AM, Foos LA, Maleszewski JJ. 2012. Less teaching, more learning: 10-yr study supports increasing student learning through less coverage and more inquiry. *Adv Physiol Educ* 36:325–335. <https://doi.org/10.1152/advan.00017.2012>

33. Ainscough L, Foulis E, Colthorpe K, Zimbardi K, Robertson-Dean M, Chunduri P, Lluca L. 2016. Changes in biology self-efficacy during a first-year university course. *CBE Life Sci Educ* 15:ar19. <https://doi.org/10.1187/cbe.15-04-0092>
34. Ballen CJ, Wieman C, Salehi S, Searle JB, Zamudio KR. 2017. Enhancing diversity in undergraduate science: self-efficacy drives performance gains with active learning. *LSE* 16:ar56. <https://doi.org/10.1187/cbe.16-12-0344>
35. Stanton JD, Halmo SM, Carter RJ, Yamini KA, Ososanya D. 2024. Opportunities for guiding development: insights from first-year life science majors' use of metacognition. *J Microbiol Biol Educ* 25:e0005324. <https://doi.org/10.1128/jmbe.00053-24>
36. Sebesta AJ, Bray Speth E. 2017. How should i study for the exam? Self-regulated learning strategies and achievement in introductory biology. *CBE Life Sci Educ* 16:ar30. <https://doi.org/10.1187/cbe.16-09-0269>
37. Bauer AC, Coffield VM, Crater D, Lyda T, Segarra VA, Suh K, Vigueira CC, Vigueira PA. 2020. Fostering equitable outcomes in introductory biology courses through use of a dual domain pedagogy. *CBE Life Sci Educ* 19:ar4. <https://doi.org/10.1187/cbe.19-07-0134>
38. Freeman S, O'Connor PA, Parks JW, Cunningham MA, Hurley D, Haak D, Dirks C, Wenderoth MP. 2007. Prescribed active learning increases performance in introductory biology. *CBE Life Sci Educ* 6:132–139. <https://doi.org/10.1187/cbe.06-09-0194>
39. Styers ML, Van Zandt PA, Hayden KL. 2018. Active learning in flipped life science courses promotes development of critical thinking skills. *CBE Life Sci Educ* 17:ar39. <https://doi.org/10.1187/cbe.16-11-0332>
40. Theobald EJ, Hill MJ, Tran E, Agrawal S, Arroyo EN, Behling S, Chambwe N, Cintrón DL, Cooper JD, Dunster G, et al. 2020. Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math. *Proc Natl Acad Sci USA* 117:6476–6483. <https://doi.org/10.1073/pnas.1916903117>
41. Sathy V, Hogan KA. 2022. Inclusive teaching: strategies for promoting equity in the college classroom. West Virginia University Press.
42. Pahl K. 2017. Best practices for the think-pair-share active-learning technique. *Am Biol Teach* 79:3–8. <https://doi.org/10.1525/abt.2017.79.1.3>
43. Tanner KD. 2013. Structure matters: twenty-one teaching strategies to promote student engagement and cultivate classroom equity. *CBE Life Sci Educ* 12:322–331. <https://doi.org/10.1187/cbe.13-06-0115>
44. Cooper KM, Schinske JN, Tanner KD. 2021. Reconsidering the Share of a think-pair-share: emerging limitations, alternatives, and opportunities for research. *CBE Life Sci Educ* 20:fe1. <https://doi.org/10.1187/cbe.20-08-0200>
45. Smith MK, Jones FHM, Gilbert SL, Wieman CE. 2013. The classroom observation protocol for undergraduate STEM (COPUS): a new instrument to characterize university STEM classroom practices. *CBE Life Sci Educ* 12:618–627. <https://doi.org/10.1187/cbe.13-08-0154>
46. Kranzfelder P, Bankers-Fulbright JL, García-Ojeda ME, Melloy M, Mohammed S, Warfa A-R. 2019. The classroom discourse observation protocol (CDOP): a quantitative method for characterizing teacher discourse moves in undergraduate STEM learning environments. *PLoS One* 14:e0219019. <https://doi.org/10.1371/journal.pone.0219019>
47. Cen X, Kight M, Lee R, Kranzfelder P, Lo SM, Maloy J, Owens MT. 2025. Development of the follow-up discourse observation protocol (FUDOP) for characterizing instructor active learning follow-up behaviors. *LSE* 24. <https://doi.org/10.1187/cbe.24-08-0207>
48. Asgari M, Miles AM, Lisboa MS, Sarvary MA. 2021. COPUS, PORTAAL, or DART? Classroom observation tool comparison from the instructor user's perspective. *Front Educ* 6:740344. <https://doi.org/10.3389/educ.2021.740344>
49. Riedl A, Yeung F, Burke T. 2021. Implementation of a flipped active-learning approach in a community college general biology course improves student performance in subsequent biology courses and increases graduation rate. *CBE Life Sci Educ* 20:ar30. <https://doi.org/10.1187/cbe.20-07-0156>
50. Shaffer J. 2025. High structure course design: an evidence-based guide for designing, implementing and assessing STEM courses. Macmillan Learning.
51. Freeman S, Haak D, Wenderoth MP. 2011. Increased course structure improves performance in introductory biology. *LSE* 10:175–186. <https://doi.org/10.1187/cbe.10-08-0105>
52. Eddy SL, Hogan KA. 2014. Getting under the hood: how and for whom does increasing course structure work? *LSE* 13:453–468. <https://doi.org/10.1187/cbe.14-03-0050>
53. Goldey ES, Abercrombie CL, Ivy TM, Kusher DI, Moeller JF, Rayner DA, Smith CF, Spivey NW. 2012. Biological inquiry: a new course and assessment plan in response to the call to transform undergraduate biology. *CBE Life Sci Educ* 11:353–363. <https://doi.org/10.1187/cbe.11-02-0017>
54. Speth EB, Momsen JL, Moyerbrailean GA, Ebert-May D, Long TM, Wyse S, Linton D. 2010. 1, 2, 3, 4: infusing quantitative literacy into introductory biology. *CBE Life Sci Educ* 9:323–332. <https://doi.org/10.1187/cbe.10-03-0033>
55. Tsunekage T, Bishop CR, Long CM, Levin II. 2020. Integrating information literacy training into an inquiry-based introductory biology laboratory. *J Biol Educ* 54:396–403. <https://doi.org/10.1080/00219266.2019.1600569>
56. Krontiris-Litowitz J. 2013. Using primary literature to teach science literacy to introductory biology students. *J Microbiol Biol Educ* 14:66–77. <https://doi.org/10.1128/jmbe.v14i1.538>
57. Wienhold CJ, Branchaw J. 2018. Exploring biology: a vision and change disciplinary first-year seminar improves academic performance in introductory biology. *CBE Life Sci Educ* 17:ar22. <https://doi.org/10.1187/cbe.17-08-0158>
58. Minchella DJ, Yazvac CW, Fodrea RA, Ball G. 2002. Biology resource seminar: first aid for the first year. *Am Biol Teach* 64:352–357. <https://doi.org/10.2307/4451310>
59. Gottesman AJ, Hoskins SG. 2013. CREATE cornerstone: introduction to scientific thinking, a new course for STEM-interested freshmen, demystifies scientific thinking through analysis of scientific literature. *CBE Life Sci Educ* 12:59–72. <https://doi.org/10.1187/cbe.12-11-0201>
60. Pugh-Bernard A, Kenyon KL. 2021. Mini-review: CREATE-ive use of primary literature in the science classroom. *Neurosci Lett* 742:135532. <https://doi.org/10.1016/j.neulet.2020.135532>
61. Garzke J, Steinwand BJ. 2024. CREATE'ing improvements in first-year students' science efficacy via an online introductory course experience. *J Microbiol Biol Educ* 25:e0007923. <https://doi.org/10.1128/jmbe.00079-23>
62. Stevens LM, Hoskins SG. 2014. The CREATE strategy for intensive analysis of primary literature can be used effectively by newly trained faculty to produce multiple gains in diverse students. *CBE Life Sci Educ* 13:224–242. <https://doi.org/10.1187/cbe.13-12-0239>
63. Uminski C, Burbach SM, Couch BA. 2024. Undergraduate biology lecture courses predominantly test facts about science rather than scientific practices. *CBE Life Sci Educ* 23:ar19. <https://doi.org/10.1187/cbe.23-12-0244>
64. Brazeal KR, Brown TL, Couch BA. 2016. Characterizing student perceptions of and buy-in toward common formative assessment techniques. *CBE Life Sci Educ* 15:ar73. <https://doi.org/10.1187/cbe.16-03-0133>
65. Bailey EG, Jensen J, Nelson J, Wiberg HK, Bell JD. 2017. Weekly formative exams and creative grading enhance student learning in an introductory biology course. *CBE Life Sci Educ* 16:ar2. <https://doi.org/10.1187/cbe.16-02-0104>
66. Walck-Shannon EM, Cahill MJ, McDaniel MA, Frey RF. 2019. Participation in voluntary re-quizzing is predictive of increased performance on cumulative assessments in introductory biology. *LSE* 18:ar15. <https://doi.org/10.1187/cbe.18-08-0163>
67. Osterhage JL, Usher EL, Douin TA, Bailey WM. 2019. Opportunities for self-evaluation increase student calibration in an introductory biology course. *LSE* 18:ar16. <https://doi.org/10.1187/cbe.18-10-0202>
68. Smith KPW, Waddell EA, Dean AN, Anandan S, Gurney S, Kabnick K, Little J, McDonald M, Mohan J, Marena DR, Stanford JS. 2023. Course-based undergraduate research experiences are a viable approach to increase access to research experiences in biology. *J Biol Educ* 57:618–632. <https://doi.org/10.1080/00219266.2021.1933135>
69. Dunbar-Wallis AK, Katcher J, Moore W, Corwin LA. 2024. Bee the CURE: increasing student science self-efficacy, science identity, and predictors of scientific civic engagement in a community college CURE. *LSE* 23:ar46. <https://doi.org/10.1187/cbe.24-01-0015>
70. Brownell SE, Kloser MJ. 2015. Toward a conceptual framework for measuring the effectiveness of course-based undergraduate research experiences in undergraduate biology. *Studies in Higher Education* 40:525–544. <https://doi.org/10.1080/03075079.2015.1004234>

71. Cooper KM, Soneral PAG, Brownell SE. 2017. Define your goals before you design a CURE: a call to use backward design in planning course-based undergraduate research experiences. *J Microbiol Biol Educ* 18:10. <https://doi.org/10.1128/jmbe.v18i2.1287>
72. Dolan EL, Lally DJ, Brooks E, Tax FE. 2008. Prepping students for authentic science. *Sci Teach* 75:38–43.
73. Lopatto D, Alvarez C, Barnard D, Chandrasekaran C, Chung H-M, Du C, Eckdahl T, Goodman AL, Hauser C, Jones CJ, et al. 2008. Genomics education partnership. *Science* 322:684–685. <https://doi.org/10.1126/science.1165351>
74. Wei CA, Woodin T. 2011. Undergraduate research experiences in biology: alternatives to the apprenticeship model. *CBE Life Sci Educ* 10:123–131. <https://doi.org/10.1187/cbe.11-03-0028>
75. Buchanan AJ, Fisher GR. 2022. Current status and implementation of science practices in course-based undergraduate research experiences (CUREs): a systematic literature review. *LSE* 21:ar83. <https://doi.org/10.1187/cbe.22-04-0069>
76. Nyutu EN, Carmona-Galindo V, Polanco M. 2024. Assessment of community-engaged research experiences in introductory general biology laboratories. *Am Biol Teach* 86:426–431. <https://doi.org/10.1525/abt.2024.86.7.426>
77. Shortlidge EE, Bangera G, Brownell SE. 2016. Faculty perspectives on developing and teaching course-based undergraduate research experiences. *Bioscience* 66:54–62. <https://doi.org/10.1093/biosci/biv167>
78. Cooper KM, Knope ML, Munstermann MJ, Brownell SE. 2020. Students who analyze their own data in a course-based undergraduate research experience (CURE) show gains in scientific identity and emotional ownership of research.. *J Microbiol Biol Educ* 21:10. <https://doi.org/10.1128/jmbe.v21i3.2157>
79. Cooper KM, Blattman JN, Hendrix T, Brownell SE. 2019. The impact of broadly relevant novel discoveries on student project ownership in a traditional lab course turned CURE. *CBE Life Sci Educ* 18:ar57. <https://doi.org/10.1187/cbe.19-06-0113>
80. Rodenbusch SE, Hernandez PR, Simmons SL, Dolan EL. 2016. Early Engagement in Course-Based Research Increases Graduation Rates and Completion of Science, Engineering, and Mathematics Degrees. *CBE Life Sci Educ* 15:ar20. <https://doi.org/10.1187/cbe.16-03-0117>
81. Pavlova IV, Remington DL, Horton M, Tomlin E, Hens MD, Chen D, Willse J, Schug MD. 2021. An introductory biology research-rich laboratory course shows improvements in students' research skills, confidence, and attitudes. *PLoS One* 16:e0261278. <https://doi.org/10.1371/journal.pone.0261278>
82. Guenther MF, Raimondi SL, Marsh TL. 2019. A one-year introductory biology majors' lab sequence incorporating vision & change. *J Microbiol Biol Educ* 20:10. <https://doi.org/10.1128/jmbe.v20i1.1636>
83. Yang MA, Korsnack K. 2024. Pairing a bioinformatics-focused course-based undergraduate research experience with specifications grading in an introductory biology classroom. *Biol Methods Protoc* 9:bpae013. <https://doi.org/10.1093/biometmethods/bpae013>
84. Corwin LA, Ramsey ME, Vance EA, Woolner E, Maiden S, Gustafson N, Harsh JA. 2022. Students' emotions, perceived coping, and outcomes in response to research-based challenges and failures in two sequential CUREs. *CBE Life Sci Educ* 21:ar23. <https://doi.org/10.1187/cbe.21-05-0131>
85. Gin LE, Rowland AA, Steinwand B, Bruno J, Corwin LA. 2018. Students who fail to achieve predefined research goals may still experience many positive outcomes as a result of CURE participation. *CBE Life Sci Educ* 17:ar57. <https://doi.org/10.1187/cbe.18-03-0036>
86. Bangera G, Brownell SE. 2014. Course-based undergraduate research experiences can make scientific research more inclusive. *CBE Life Sci Educ* 13:602–606. <https://doi.org/10.1187/cbe.14-06-0099>
87. Ballou J. 2012. Reshaping how educators view student STEM learning. *Sci Edu Civic Engag: Int J Winter* 2012:27–36.
88. 2016. National center for science and civic engagement. Available from: <https://sencer.net/>
89. Adams JA, Dewsbury BM, Tanzer JR. 2024. Learning in context: undergraduate students' knowledge and the content retention of anatomy between discipline-specific and integrated course approaches. *Anat Sci Educ* 17:1308–1322. <https://doi.org/10.1002/ase.2469>
90. Norman G. 2007. How basic is basic science? *Adv in Health Sci Educ* 12:401–403. <https://doi.org/10.1007/s10459-007-9077-z>
91. Doornik DE, van Goor H, Kooloos JGM, Ten Broek RP. 2017. Longitudinal retention of anatomical knowledge in second-year medical students. *Anat Sci Educ* 10:242–248. <https://doi.org/10.1002/as.e.1656>
92. Leight H, Saunders C, Calkins R, Withers M. 2012. Collaborative testing improves performance but not content retention in a large-enrollment introductory biology class. *CBE Life Sci Educ* 11:392–401. <https://doi.org/10.1187/cbe.12-04-0048>
93. Cleveland LM, Olimpo JT, DeChenne-Peters SE. 2017. Investigating the relationship between instructors' use of active-learning strategies and students' conceptual understanding and affective changes in introductory biology: a comparison of two active-learning environments. *CBE Life Sci Educ* 16:ar19. <https://doi.org/10.1187/cbe.16-06-0181>
94. Brownell SE, Tanner KD. 2012. Barriers to faculty pedagogical change: lack of training, time, incentives, and...tensions with professional identity? *LSE* 11:339–346. <https://doi.org/10.1187/cbe.12-09-0163>
95. Apkarian N, Henderson C, Stains M, Raker J, Johnson E, Dancy M. 2021. What really impacts the use of active learning in undergraduate STEM education? Results from a national survey of chemistry, mathematics, and physics instructors. *PLoS One* 16:e0247544. <https://doi.org/10.1371/journal.pone.0247544>
96. Anderson WA, Banerjee U, Drennan CL, Elgin SCR, Epstein IR, Handelsman J, Hatfull GF, Losick R, O'Dowd DK, Olivera BM, Strobel SA, Walker GC, Warner IM. 2011. Science education. changing the culture of science education at research universities. *Science* 331:152–153. <https://doi.org/10.1126/science.1198280>
97. Shadle SE, Marker A, Earl B. 2017. Faculty drivers and barriers: laying the groundwork for undergraduate STEM education reform in academic departments. *Int J STEM Educ* 4:8. <https://doi.org/10.1186/s40594-017-0062-7>
98. Auerbach AJ, Schussler E. 2017. A vision and change reform of introductory biology shifts faculty perceptions and use of active learning. *CBE Life Sci Educ* 16:ar57. <https://doi.org/10.1187/cbe.16-08-0258>
99. Allen T, Arriola PE, Breitenberger C, Klyczek K, Marrs KA, Matzner S, Miller KG, Powell-Coffman JA, Thatcher M. 2025. Building communities of practice among undergraduate STEM departments to foster emergent transformation: a report on the impact of multiple-year engagement within the PULSE midwest and great plains regional network. *CBE Life Sci Educ* 24:ar5. <https://doi.org/10.1187/cbe.24-02-0042>
100. Kiser S, Kayes KJ, Baumgartner E, Kruchten A, Stavrianeas S. 2022. Statewide curricular alignment & learning outcomes for introductory biology: using vision & change as a vehicle for collaboration. *Am Biol Teach* 84:130–136. <https://doi.org/10.1525/abt.2022.84.3.130>
101. Sachmpazidi D, Olmstead A, Thompson AN, Henderson C, Beach A. 2021. Team-based instructional change in undergraduate STEM: characterizing effective faculty collaboration. *Int J STEM Educ* 8:15. <https://doi.org/10.1186/s40594-021-00273-4>
102. Olmstead A, Beach A, Henderson C. 2019. Supporting improvements to undergraduate STEM instruction: an emerging model for understanding instructional change teams. *Int J STEM Educ* 6:20. <https://doi.org/10.1186/s40594-019-0173-4>
103. Matz RL, Fata-Hartley CL, Posey LA, Laverty JT, Underwood SM, Carmel JH, Herrington DG, Stowe RL, Caballero MD, Ebert-May D, Cooper MM. 2018. Evaluating the extent of a large-scale transformation in gateway science courses. *Sci Adv* 4:eaau0554. <https://doi.org/10.1126/sciadv.aau0554>
104. Matz RL, Jardeleza SE. 2016. Examining the role of leadership in an undergraduate biology institutional reform initiative. *CBE Life Sci Educ* 15:ar57. <https://doi.org/10.1187/cbe.15-10-0222>