Strategies to empower students through open pedagogy and citizen science

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ABSTRACT

Open pedagogy and citizen science both aim to elevate individual contributions to science and education to the greater global community: the first through a collective enterprise to communicate knowledge, and the second through collective participation in science. Here we present strategies for utilizing the overlap between open pedagogy and citizen science approaches to empower students and improve learning, inclusion, and accessibility. Student-driven education and research can increase engagement with learning. Similarly, student creation of materials promotes engagement with content and ownership. Class products can be used beyond the classroom—for example, in future job or graduate school applications. Contributions to the greater public also motivate civic-minded students to produce materials to enhance future learners' understanding by fostering connections to diverse communities. Teaching models that synergize open education and citizen science approaches involve two prongs: (1) student participation in a citizen science project that contributes data, and (2) communicating the data, results, and implications to stakeholder communities. These implementations can range from simple (e.g., pairing one project with social media posts) to complex (e.g., multiple, often interconnected, citizen science projects where students produce instructions, best practices, and other communications). We must overcome many challenges to achieve broader acceptance of this pedagogy, including the re-creation of curricular standards in higher education and Retention, Promotion, and Tenure criteria. Nonetheless, we can leverage a combination of open pedagogy and citizen science to help students develop skills to assess and communicate scientific information effectively, and thus advance the next generation of global leaders.

Keywords: open pedagogy, citizen science, participatory science, democratization of science, open-enabled practices, collaborative frameworks, higher education, interdisciplinary

Estrategias para empoderar a los estudiantes a través de la pedagogía abierta y la ciencia ciudadana

Resumen

Tanto la pedagogía abierta como la ciencia ciudadana apuntan a elevar las contribuciones individuales a la ciencia y la educación a la comunidad global en general: la primera a través de una empresa colectiva para comunicar conocimiento, y la segunda a través de la participación colectiva en la ciencia. Aquí presentamos estrategias para utilizar la superposición entre la pedagogía abierta y los enfoques de ciencia ciudadana para empoderar a los estudiantes y mejorar el aprendizaje, la inclusión y la accesibilidad. La educación y la investigación impulsadas por los estudiantes pueden aumentar el compromiso con el aprendizaje. De manera similar, la creación de materiales por parte de los estudiantes promueve el compromiso con el contenido y la propiedad. Los productos de clase se pueden utilizar más allá del aula, por ejemplo, en futuras solicitudes de empleo o de estudios de posgrado. Las contribuciones al público en general también motivan a los estudiantes con mentalidad cívica a producir materiales para mejorar la comprensión de los futuros estudiantes al fomentar conexiones con comunidades diversas. Los modelos de enseñanza que combinan los enfoques de educación abierta y ciencia ciudadana implican dos vertientes: (1) la participación de los estudiantes en un proyecto de ciencia ciudadana que aporta datos y (2) comunicar los datos, los resultados y las implicaciones a las comunidades de partes interesadas. Estas implementaciones pueden variar desde simples (por ejemplo, combinar un proyecto con publicaciones en redes sociales) hasta complejas (por ejemplo, múltiples proyectos de ciencia ciudadana, a menudo interconectados, donde los estudiantes producen instrucciones, mejores prácticas y otras comunicaciones). Debemos superar muchos desafíos para lograr una aceptación más amplia de esta pedagogía, incluida la recreación de estándares curriculares en la educación superior y criterios de retención, promoción y titularidad. No obstante, podemos aprovechar una combinación de pedagogía abierta y ciencia ciudadana para ayudar a los estudiantes a desarrollar habilidades para evaluar y comunicar información científica de manera efectiva y así hacer avanzar a la próxima generación de líderes globales.

Palabras clave: pedagogía abierta, ciencia ciudadana, ciencia participativa, democratización de la ciencia, prácticas abiertas, marcos colaborativos, educación superior, interdisciplinario.

基于开放教学法和公民科学的学生赋权策略

摘要

开放教学法和公民科学都旨在将个人对科学和教育的贡献提升到更大的全球社区：前者通过一项集体事业传播知识，后者则通过集体性的科学参与。本文中，我们提出了一系列策略，利用开放教学法和公民科学方法之间的重叠来为学生赋权，并改善学习、包容性和可及性。以学生为主导的教育和研究能提高学习的参与度。同样，学生的创作材料能促进内容参与和（学生对内容的）所有权。课堂产品能用于课堂之外，例如，用于未来的工作或研究生资格申请。对广大公众的贡献也激励有公民意识的学生制作材料，通过培养与不同

社区的联系来增进未来学习者对此的理解。将开放教育和公民科学方法相结合的教学模式涉及两个方面：(1)学生参与为数据作贡献的公民科学项目，(2)向利益攸关方社区传播数据、结果和启示。这些实施的范围可以从简单（例如，将一个项目与社交媒体帖子配对）到复杂（例如，学生在通常相互关联的多个公民科学项目中提供说明、最佳实践和其他信息）。我们必须克服许多挑战，以使这种教学法得到更广泛的接受，包括重新制定高等教育的课程标准以及“保留、晋升和终身教职”标准。尽管如此，我们能利用开放教学法和公民科学的结合来帮助学生培养有效评估和传播科学信息的技能，从而促进下一代全球领导者的发展。

关键词：开放教学法，公民科学，参与式科学，科学民主化，开放实践，协作框架，高等教育，跨学科

Introduction

Since the mid-20th century, the United States public education system has become more *practically* equitable through federal laws and Supreme Court cases that bring more diverse audiences into classrooms while leaving *foundational* equitability evolving at a slower pace. By foundational equitability, we refer to the deep role that emotion, culture, and life experiences play in successful education (McConnell & Eva, 2012; Oatley & Nundy, 1998; Rager, 2009; Tyng et al., 2017), wherein students can connect curricular content with their personal experiences and knowledge. Among a plethora of observed issues with United States public schools (e.g., Spring, 2019), we address two broad student-centered foundational problems: the disenfranchisement of students from the system of knowledge creation; and the disenfranchisement of students from the system of knowledge distribution. In other words, students are provided curricular materials written by other people, about math, science, history, and literature made by even more contributors/creators (with whom they may not identify). In STEM fields, this dual disenfranchisement underpins both the “leaky pipeline” and “missing scaffolding” explanations for the underrepresentation of marginalized groups (Witteveen & Attewell, 2020). To foster deep emotional connections between students and curriculum, instructors must strive to make curriculum relevant to students’ lives. To do so, we propose that instructors and institutions can employ a thoughtful combination of citizen science (CS) and open pedagogy (OP) to make STEM accessible and inclusive, ultimately increasing student persistence, retention, and success.

CS is defined as engaging non-professional researchers to make scientific contributions through observations, data collection, and data analysis (Bonney et al., 2009). These often motivating and transformative experiences provide a unique way for students to participate in research projects worldwide. CS is also referred to as participatory science or community science, with the latter being preferred in order to promote inclusivity (refer to (Cooper et al., 2021) for a broader discussion). In this article, we refer to CS as a variety of participatory projects that guide decentralized data collection where participants share the goal of advancing scientific research and share their data outside of the classroom (*sensu* (Vance-Chalcraft et al., 2022)).

OP, defined by Jhangiani and DeRosa (2017) as both "an access-oriented commitment to learner-driven education AND as a process of designing architectures and using tools for learning that enable students to shape the public knowledge commons of which they are a part," is one of the most exciting and impactful areas for curricular redesign in open education. Whereas Schade et al. (2021) previously identified the intersections between CS and OP, we posit that OP and CS provide complementary mechanisms for democratizing education (Figure 1). Specifically—by engaging participants in the use of accessible methods and tools to co-create knowledge that will itself be made publicly available, CS and OP synergistically empower students to increase their sense of belonging and self-efficacy, which, ultimately, we hope will increase persistence and retention in STEM. Given the importance of diverse collaborations for producing high-impact research (Ding et al., 2021; Freeman & Huang, 2014; Kaplan Mintz et al., 2023; McCarty et al., 2013; Yang et al., 2022), these approaches have long-term implications for research innovation across STEM disciplines. In order to support our position that CS and OP have the potential to increase the persistence of diverse students via sense of belonging and self-efficacy in STEM we first discuss the ways that CS and OP support student learning grounded in educational theory, then share our own innovative approaches and experiences at North Carolina State University (NCSU) as a resource for expansion / improvement at other institutions.

Theoretical Foundation

Believing that one can enter a STEM career is the first step towards moving in that career direction. Bandura and others (Bandura, 1977; Bandura & Locke, 2003; Bandura & Wessels, 1994; Britner & Pajares, 2006; Hiller & Kitsantas, 2015; Zimmerman, 2000) have illustrated the importance of self-efficacy in education, which is one of the many barriers preventing some students from entering STEM, even though the door is open to them. Another important consideration is that no student starts their academic journey from the same starting line, nor do they experience identical barriers to success. Nonuniformity in the amount of effort required to achieve a particular goal (such as reaching a particular

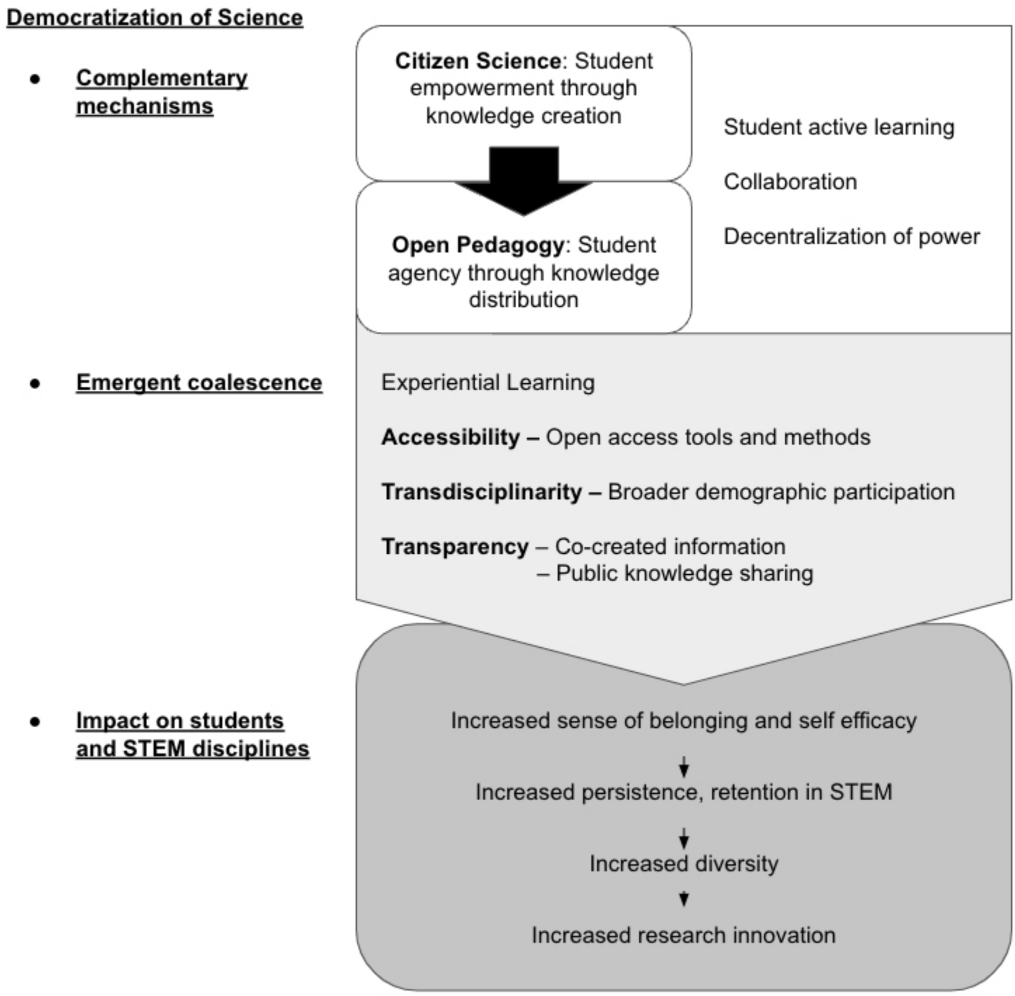

Figure 1. *Citizen science and open pedagogy provide complementary mechanisms to support and enhance student learning, belonging, and retention.*

score on curricular tests), we posit, can further diminish a student's belief in themselves, especially when students are treated as independent repositories of knowledge instead of a class-wide collective body of knowledge in which each student contributes what they can towards a common goal.

One avenue to increase student self-efficacy is CS (Hiller & Kitsantas, 2015; Schuttler et al., 2018), because students perform aspects of authentic science research as opposed to pre-scripted labs in an effort to address a scientific research question. We also advocate for OP as a critical piece of self-efficacy because each student contributes as they can towards a holistic product. CS and OP both allow each student to tailor learning experiences and assessments to their individual interests, abilities, and developmental stages. Additionally, CS and OP bring students into the fold of science practice by making them stakeholders in the knowledge, not just bystanders of knowledge.

Employing CS and OP within formal education settings (e.g., classrooms, laboratories) can accentuate the learning process through the cognitivist and constructivist philosophies. The cognitivist philosophy underpinning the use of CS in classrooms is Discovery Learning (Bruner, 1960, 1961), distinguished by the notions that: 1) a student can learn anything if it is presented in an appropriate way; and 2) students choose their own knowledge to adopt based on their chosen hypotheses and experiences (Ozdem-Yilmaz & Bilican, 2020). In this, Bruner (1960; 1961) emphasized the importance of discovery in the learning process so that students have the opportunity to develop new thought processes leading from observation to prediction. Experiential Theory of Learning (Boyatzis et al., 2001) within the constructivist philosophy is also relevant because students are directly interacting with subjects in some CS projects (Bonney et al., 2009; Brossard et al., 2005). As Lehane (2020) further points out, experiential learning mimics the process through which scientists often engage. This learning theory has four prongs: Concrete Experience, Abstract Conceptualization, Reflective Observation, and Active Experimentation (Kolb, 1984; Lehane, 2020). OP dovetails with CS in this educational framework by allowing for personalized Reflective Observation that is also public / open and can contribute to Abstract Conceptualization when students are allowed to dissect then rebuild complicated ideas on their own terms and in coordination with peers.

Role of Citizen Science and Open Pedagogy in Formal Education Settings

Despite the alignment with established educational learning theory, CS and OP are only rarely used in formal educational settings, i.e., K-12 or higher education (Bedell & Gates, 2021; Jenkins, 2011; Schuttler et al., 2019; Shah & Martinez, 2016; Vance-Chalcraft et al., 2022; Vitone et al., 2016), yet they lend themselves naturally to discovery and experiential learning. The recently established USECitSci Network (https://qubeshub.org/community/groups/usecitsci) is a National Science Foundation-funded Research Coordination Network (RCN) that is promoting the use of CS in higher education and coalescing instructors to develop new pedagogical interventions and educational research into the effects and best-practices of using CS with undergraduate students. By bringing together experts across several disciplines and areas including discipline-based education research, participatory science, community engagement, curriculum design, and assessment, USECitSci is catalyzing the development of frameworks and generating research to better implement CS across campuses. The activities of USECitSCi Network not only help center CS in existing theoretical frameworks, but also formalize the impact of CS as a high-impact pedagogical practice.

An essential theoretical consideration is that CS is a definitive tool for affecting the Concrete Experience aspect of experiential learning, and it has the potential to facilitate Abstract Conceptualization. Nonetheless, it is imperative to remember that CS is a tool to be used by the instructor, not as a standalone practice that automatically yields student growth. A CS project can independently facilitate discovery, but an instructor must provide structured opportunities for guided exploration and reflection so that Bruner's (1961) and Boyatzis et al.'s (2001) theories can be realized—for example, via OP. Importantly, CS not only improves learning gains (Vance-Chalcraft et al., 2022); it can also increase students' sense of belonging, participation in, and access to science (Johns et al., 2021; Vance-Chacraft et al., 2021) *if* the students are given the opportunity to personalize the experience or reflect on their scientific contribution (see (Bedell & Gates, 2021)). This pedagogical intervention therefore has a high potential impact on diversity in STEM.

Practitioners of OP embrace collaboration, student agency, and authentic audiences while recognizing the differences in privilege and progress that impact how students balance the benefits of sharing and a need for privacy. This open educational practice challenges traditional teaching roles and has the power to transform the educational experience for both instructors and students. For example, instructors might redesign or re-format assignments so that students create products that can be shared with audiences beyond the classroom. By setting an intention to share student work, the instructor makes the work more meaningful, increasing student motivation, pride, and ownership of the work. OP in practice can appear in multiple forms. Some popular examples include students using social annotation tools such as Hypothes.is (https://web.hypothes.is/) to understand and construct shared knowledge around scholarly content (D'Agostino, 2022), or working with Wiki Education to address knowledge and representation gaps in Wikipedia content (Davis, 2021). Similar to CS, OP increases students' sense of contribution, ultimately cultivating an identity of expertise and belonging in STEM that may increase persistence and retention.

There is considerable overlap and complementarity between CS and OP (Schade et al., 2021); Figure 1). Both aim at the same target: making an individual's contribution available to the greater global community. And, like Universal Design for Learning, the methods for implementing CS and OP ultimately improve inclusivity through accessibility and first-hand participation in knowledge creation—and thus align with broader initiatives to address systemic issues impeding progress and innovation (Tananbaum, 2020; Teo, 2020). Open and collaborative practices also invite and empower diverse voices in data collection and distribution as consistent with the ethics of care framework. The ethics of care framework centers experiential knowledge and social justice, aiming to maximize the diversity of participants engaged while maintaining a relationship of reciprocity (Brannelly, 2018). When barriers to student participation and engagement are dissolved, students may feel more welcomed to and invested in the learning process. The combined CS-OP approach embodies the ethics of care by enabling any individual to participate in the scientific process and by making the research results available to the public via open databases and report-backs. By shifting focus from formal academic experience to lived experience as valuable place-based expertise, CS empowers diverse individuals as important contributors to science. Indeed, open accessibility ensures the creation of larger and more diverse data sets than could be collected by a single individual or research team.

Similarly, CS protocols are often designed and revised to maximize participation by minimizing the need for prior knowledge, funding, or access to specialized equipment. Instead, CS research relies on participants' observations and anecdotes to compile a holistic dataset. OP engages students in the co-creation of course materials. Both approaches place emphasis on the intellectual contributions of individual participants as scholars generating new information. CS methods often must be readily adaptable and accessible to different audiences. This goal aligns closely with the FAIR principles of Open Science (Wilkinson et al., 2016) and cornerstones of OP.

Most CS projects, by definition, include open education resources (OER): materials for learning, teaching, research, and data visualization, provided in any format or medium, which are available in the public domain or under an open license copyright that permits access, re-use, re-purpose, adaptation, and redistribution at no cost (*Open Educational Resources | UNESCO*). Data are collected via open online tools and portals (e.g., Google Forms / Qualtrics, SciStarter, iNaturalist); and dashboards are often provided to visualize the growing dataset (e.g., map location of each datapoint or participant). Together, these online tools provide powerful resources for online/remote learning. For this reason, many citizen science projects were adopted and adapted for science education during the COVID-19 pandemic (Farrell et al., 2021; Schirmel, 2021; Van Haeften et al., 2021). However, it's important to note that CS and OP were incorporated successfully, and with great effect, long before the COVID-19 pandemic. Indeed, the impact of CS-OP approaches on student learning and engagement transcend the pandemic and learning modalities.

Table 1. *Citizen Science projects that have been adapted for K-12+ education. Here we highlight projects that the authors have used or developed directly; but see Supplemental Table 1 for a more extensive list.*

Name of project	Research topic	Education level	Model level	Field / discipline	Individual or group work	Type of data collected	Additional classroom component(s)	Link to platform
Sourdough for Science	microbial ecology and succession	developed for 6-8; adapted for K-5 and higher ed	intermediate	microbial ecology	both / either	measurements	graph data, bread tasting	https://studentsdiscover.org/lesson/sourdough-for-science/ https://scistarter.org/sourdough-for-science
NASA GLOBE Observer Clouds	climate	lower-level higher ed	simple	environmental science	individual	observations	hypothesis development	https://observer.globe.gov/do-globe-observer/clouds https://scistarter.org/NASA-GLOBE/globe-observer-clouds
NASA GLOBE Observer Trees	benefits of trees	lower-level higher ed	simple	environmental science	individual	observations	tree benefit calculator, hypothesis development	https://observer.globe.gov/do-globe-observer/trees https://scistarter.org/national-tree-benefit-calculator
Great North American Fungi Quest	mycology	lower-level higher ed	intermediate	environmental science	group	observations, identification	graph data	https://scistarter.org/great-north-american-fungiquest
Bumble Bee Watch	pollinators	lower-level higher ed	intermediate	environmental science	group	observations, identification	graph data	https://scistarter.org/bumble-bee-watch
SquirrelMapper	evolution	lower-level higher ed	intermediate	environmental science	group	observations, identification	graph data	https://squirrelmapper.org/
Silent Earth	noise pollution	lower-level higher ed	intermediate	environmental science	group	measurements	graph data	https://scistarter.org/silent-earth

Debris Tracker	plastic pollution	lower-level higher ed	intermediate	environmental science	group	observations	graph data	https://debristracker.org/
Candid Critters	wildlife behavior	lower-level higher ed	simple to intermediate	biology, ecology	both / either	identification	graph data, hypothesis development	https://emammal.si.edu/north-carolinas-candid-critters
Ant Picnic	entomology; foraging behavior	developed for K-8; adapted for higher ed	simple to intermediate	biology, ecology	group	observations, identification	graph data	http://studentsdiscover.org/lesson/ant-picnic/
A Diversity of Guts	anatomy	9-12, higher ed	simple to intermediate		both / either	measurements	graph data, hypothesis development	http://studentsdiscover.org/lesson/a-diversity-of-guts/
Mosquito Byte	vector ecology	K-12+	simple	ecology	individual	observations	graph data, hypothesis development	https://vectorecology.org/outreach/mosquito-bite-app/
Where's *Delftia*?	microbial ecology	lower-level higher ed	intermediate	environmental science; microbial ecology	group	swab and soil samples	DNA extraction tools	go.ncsu.edu/delftia
Globe at Night	light pollution	K-12+	simple	environmental science; astronomy	individual	observations	graph data	https://globeatnight.org/
C-BARQ/Fe-BARQ	pet behavior	K-12+	simple	animal science	individual	observations	survey	https://scistarter.org/c-barq-and-fe-barq
Project Squirrel	wildlife behavior	K-12+	simple	ecology	both / either	observations	survey	https://scistarter.org/project-squirrel
Stall Catchers	Alzheimer's	K-12+	simple	biology, neuroscience	individual	observations		https://stallcatchers.com/main
ISeeChange	climate change	K-12+	simple	environmental science	both / either	observations		https://www.iseechange.com/
Phylo	evolution	lower-level higher ed	simple to intermediate	biology	individual	DNA alignment data	survey	https://phylo.cs.mcgill.ca/

eBird	ornithology	K-12+	simple	biology	both / either	observations		https://ebird.org/home
Adrift	microbiology	lower-level higher ed	intermediate	environmental science; microbiology	individual	mapping	graph data	https://adrift-project.com/
FoldIt	microbiology	lower-level higher ed	intermediate	biology, microbiology	individual	protein folding schemes	survey	https://scistarter.org/foldit
Caterpillars Count!	biodiversity; phenology	lower-level higher ed	intermediate	biology, ecology	group	observations, measurements	graph data	https://scistarter.org/caterpillars-count
Shark Tooth Forensics	paleontology	K-12, lower-level higher ed	simple	ecology	both	observations, measurements	graph data	http://studentsdiscover.org/teaching-modules/shark-teeth-forensics/

Instructors can incorporate CS and OP into course curricula to help students build skills and achieve learning outcomes (Table 2). Combining CS-OP approaches has the potential to connect students to public resources by contributing work that is useful, relevant, and impactful. However, clear communication and scaffolding are needed to ensure that the work can be used and understood across diverse contexts and audiences. For example, a course might be deliberately structured to include several in-class discussions and activities to learn and practice scientific methods and communication, aligned with "milestone" assignments and reflection that build toward a final product to be shared beyond the class (see NCSU examples below). The ideal version of CS-OP contribution is a "two-way street" where openness is an invitation, not just to receive information but to collaboratively build. The work is more meaningful when users (e.g., the public, future students, etc.) can both engage with the science and understand and contribute novel content. Similarly, there is a need to understand the various participating communities so the work can be personally meaningful for diverse audiences, rather than extractive or disconnected—disenfranchised. The deliberate consideration of relevant "stakeholder" groups ensures that the resulting knowledge can be shared and disseminated effectively (refer to Next Steps).

Table 2. *Skills built and learning outcomes achieved by incorporating citizen science (CS) and open pedagogy (OP) in the classroom.*

Approach	Activity or Assignment	Skills built	Learning outcome achieved	Class	Instructor(s)
OP	social annotation of published research articles	critical reading and synthesis	Explain and critique published ecological research; Interpret and synthesize published research to summarize what is known and identify gaps in current knowledge	AEC 400, AEC 437/537, AEC 460, BSC 592	McKenney; Gates
OP	case studies	data collection, graphing, analysis, and interpretation	Apply problem solving and critical thinking skills to case studies and other assignments	AEC 400; ENV 101	McKenney; Lupek
OP	Ecology IRL, Featured Ecologist, term research project; figure design, collaborative writing assignments	critical reading and synthesis of published and popular media, figure design, scientific writing	Identify specific examples linking ecological concepts to real-world environmental challenges, including JEDI (justice, equity, diversity, and inclusion) issues; Communicate ecological concepts via original figures, scientific writing, and other creative formats	AEC 400	McKenney
CS-OP	field labs	species identification and data mining using open online tools (e.g., iNaturalist)	Collect data using appropriate equipment, methods, and techniques	AEC 460; ES 100; ENV 101	McKenney; Leggett; Lupek
OP	data analysis	data management, formatting, analysis, and interpretation using open software	Curate and analyze data using Excel / Google Sheets and R; Collaborate productively, both in person and online	AEC 460	McKenney
OP	experimental write-up	professional development, team building, communication	Analyze microbiome sequencing data in the R environment to address a scientific question; Assess the critical roles that gut microbial communities play across host systems and life processes	AEC 437/537	McKenney

Approach	Activity or Assignment	Skills built	Learning outcome achieved	Class	Instructor(s)
OP	peer reviews	effective communication, science writing	Critique constructively, and respond to constructive feedback, via peer reviews	AEC 460	McKenney
OP	lab write-ups, presentations	effective communication, science writing, figure design	Communicate scientific goals, results, and importance effectively via writing, figures, and oral presentations	AEC 460	McKenney
OP	graphing data with Climate Tool-Box	data graphing, interpretation	Identify, list and in some cases apply basic conservation science tools to explore the causes and consequences of global conservation challenges	AEC 245	McKenney
OP	figure design, collaborative in-class activities in Google Slides	formal and informal research; critical discussion, reading and synthesis, collaborative teamwork, poster design, effective visual and written science communication	List, describe, explain, and create visualizations to convey your understanding of the intricate relationships among fundamental concepts in the discipline and tenable approaches for achieving measurable conservation outcomes	AEC 245	McKenney
CS	participate in CS project of choice via SciStarter; write a popular science article or personal reflection about the CS project and relevant research topic	effective communication, research analysis, critical reading, rhetorical strategies	Communicate scientific outcomes and experiential learning to popular audiences	ENG 101, HON 202; ES 100; ENV 101	Krieg; Leggett; Lupek
OP	podcasts explaining key metagenomic concepts and processes	script writing, interviewing, multimedia,	Summarize salient information about the studies or techniques you learn	BIT 477/577	Goller
OP	video tutorial creation	explain complex processes in accessible ways	Create a script and record a short tutorial on the subject you researched.	BIT 477/577	Goller

OP	accessible genome announcements on WordPress site	explain bioinformatics tools and findings	Discuss research findings with peers, the public & other scholars	BIT 295; ENV 101	Goller; Lupek
OP	public information about electronic waste recycling efforts in your city	create multimedia resources to explain the results	Discuss research findings with peers, the public & other scholars	BIT 295	Goller
CS-OP	analysis of community samples and community engagement of results	create multimedia public resources to explain methods and results	Discuss research findings with peers, the public & other scholars	BIT 477/577; BIT 479/579	Goller
CS-OP	participate in CS project of choice in small groups and create infographic of data collected	data collection, analysis, effective communication	Communicate scientific outcomes and experiential learning to popular audiences	ENV 101	Lupek
OP	create educational products to teach a targeted audience about climate change	communicate effectively, think critically	interpret credible references on climate change; explain climate change and its impacts to a selected audience	ES 100	Lupek

[1] AEC 400: Applied Ecology

[2] AEC 437/537: Gut Microbial Ecology

[3] AEC 460: Field Ecology

[4] BSC 592: Paleoecology, Phylogenetic Comparative Methods

[5] ENV 101: Exploring the Environment

[6] ES 100: Intro to Environmental Science

[7] AEC 245: Global Conservation Ecology

[8] ENG 101: Academic Writing and Research

[9] HON 202: American Ecopoetics

[10] BIT 477/577: Metagenomics

[11] BIT 295: Biotechnology & Sustainability

[12] BIT 479/579: High-throughput Discovery

CS-OP engagement can take many forms, with the common goal to engage and empower our students. Both active and informal learning can guide students beyond the curriculum, whether by practicing professional skills or applying course concepts to everyday life. For example, OP provides the opportunity to discuss open practices including privacy and data sharing with students—all important professional skills that require transparent conversations of ethics, empowerment, and data management as integral to collaboration. In this way, CS-OP educates the whole person and reinforces the relevance of STEM concepts and scientific practices to every aspect of life. When incorporated as part of a class and effectively aligned with curricula, CS-OP can be structured as course-based research experiences CRE, in which students and participants become drivers of education and authentic research. Students who participate in CS-OP assignments demonstrate increased buy-in, motivation, sense of belonging and self-efficacy in STEM (Bandura, 1977; Hiller & Kitsantas, 2015; Johns et al., 2021; Schuttler et al., 2019; Vance-Chalcraft et al., 2021, 2022) when they can self-identify as practicing scientists making novel contributions to research, and when they produce personally and professionally relevant materials. By making participation in science more accessible, instructors can help to address issues of historic, systematic exclusion from STEM (Johns et al., 2021; Paleco et al., 2021).

Below we discuss the potential for CS and OP to synergistically increase student empowerment and accessibility. In particular, we focus on two prongs of student engagement: (1) student participation in a CS project that contributes data, and (2) students participating in OP methods such as communicating project data, results, and implications to stakeholder communities.

Methods of Incorporation

NCSU as an Institutional Model

Both CS and OP align with and help to fulfill our land grant mission at NC State by contributing to "excellent teaching, the creation and application of knowledge, and engagement with public and private partners" (*About Us < North Carolina State University*, 2023). CS-OP frameworks build student connections to local and global communities, and also heighten students' place-based sense of belonging. In this section we highlight three institutional programs at NCSU that serve to enhance students' college experience: Citizen Science Campus, the Open Pedagogy Incubator, and the Alt-textbook Project.

Citizen Science Campus

NC State University provides a unique opportunity to examine CS projects because it has the nation's first Citizen Science Campus program (*Citizen Science Campus – NC State University*, 2019), an initiative organized by the Chancellor's Faculty Excellence Program in Leadership in Public Science in 2019. The program allows students from across campus to participate in CS projects through coursework, clubs, residential hall programs, library events, work-study experiences, or undergraduate research opportunities. CS projects are supported through a customized NCSU portal (*NCSU Home*, 2019) on the citizen science hub SciStarter and a citizen science project equipment lending program in the NCSU libraries lending programs (*Citizen Science Equipment*, 2016). The creation of the Citizen Science Campus program has resulted in a higher usage of CS projects in undergraduate classes at NCSU compared to other universities (Vance-Chalcraft et al., 2022). To date, the NCSU SciStarter portal has recorded 57,682 contributions from 1,361 students engaged at NC State. We have highlighted several projects that have been developed or adapted to enhance courses in higher education in Table 1 (though also see these resources for non-STEM K-12: https://docs.google.com/document/d/1i6D9zCM8LEMStjyAqBL2VDUOiFKBUfcSCTByD7TLQN0/edit?usp=sharing).

One of the flagship events of the Citizen Science Campus program is the Wolfpack Citizen Challenge. During this event, students contribute to ongoing CS research projects while learning about research primary investigators and the "big picture" behind their research. The Wolfpack Citizen Science Challenge focuses on a different citizen science project each year. Past projects include *Take a Walk on the Wild Side* (2016-2017), *Where's* Delftia*?* (2018; (Riley et al., 2020)), and *Never Home Alone* (2019). Throughout the four years of its facilitation, 3,877 people have contributed 31,153 observations to the projects (Table 3).

The Citizen Science Campus program includes other initiatives to further support its mission. For example, the SciStarter-NCSU portal hosts a featured project each month. In addition, the Citizen Science Campus has hosted a NC Citizen Science Symposium and a NC Participatory Science Networking event. The Citizen Science Campus program has had ripple effects across campus, resulting in CS projects being included in curricula across many disciplines, the creation of a citizen science minor for graduate students, and an active student-led Citizen Science Club. Collaborative efforts across campus courses and groups also supports NCSU's current interdisciplinary strategic plan initiative.

Open Pedagogy Incubator

The Open Pedagogy Incubator (Cross et al., 2020) is a NC State University Libraries-led, multi-semester-long program designed to support faculty in going beyond the first step in open education—adopting OER—to implement multiple open-enabled practices in their courses. Even though the Open Pedagogy Incubator began at NC State, it has since scaled into a statewide initiative with 30 faculty instructors from NCSU, University of North Carolina (UNC) in Chapel Hill, East Carolina University, UNC-Greensboro, UNC-Wilmington, UNC-Charlotte, North Carolina Central, UNC-Asheville, Western Carolina University, North Carolina Agriculture & Technology State University, and Appalachian State University have participated in annual cohorts to develop

Table 3. *Participation in citizen science projects hosted on NC State campus.*

Project	# Participants	# samples / observations	Populations Engaged	Source
Candid Critters	847	1,188,598	NCSU campus	(*NCSU Camera Trapping | EMammal*, n.d.)
Where's *Delftia*?	196	135	ES 100, LSC 170	(Riley et al., 2020)
Take a Walk on the Wild Side	24	380	NCSU campus	(*NCSU Wolfpack Citizen Science Challenge*, 2016)
Never Home Alone @ NCSU	298	782	NCSU campus	(*Never Home Alone @* (*NCSU*, 2019)
NCSU Wolfpack Citizen Science Challenge totals (2016-2020)	3,877	31,153	NCSU campus	(*NCSU Wolfpack Citizen Science Challenge*, 2016)

competencies in OP through a series of hands-on workshops, curated readings, and cohort discussions since 2020. The goal is for each participant to exit the program with one or more custom-designed interventions to engage students through responsive teaching practices that support learning outcomes and facilitate co-created deliverables. Importantly, practicing OP educators are invited to share ways they have enhanced their own courses with open materials after participating in OPI. For example, authors McKenney and Goller adopted Hypothes.is (https://web.hypothes.is/), a free online tool which facilitates social annotation, to enhance reading assignments, and gathered data to quantify the impacts of social annotation on students' sense of belonging and self-efficacy. Goller also made his course materials available to his students via podcasts; and McKenney formatted a case study activity so that student works could be curated as an exhibit for display at D.H Hill Jr. Library (go.ncsu.edu/aec400pokemon). These presentations help cohorts build community, explore interdisciplinary approaches, and reflect on personal philosophies and inclusive pedagogies through discussion of practice. In addition to providing a shared space to discuss OP materials and approaches, the Incubator connects faculty with OP discipline experts Tully and Cross, who help them navigate copyrights and licensing and identify conferences and outlets to disseminate OER. Participants have embraced opportunities to exchange traditional assignments for opportunities to work with Library digital media specialists to help students record multimedia and disseminate work publicly. The OPI has unlocked the potential for students to co-create with faculty and units across campus.

Alt-Textbook Project

The NC State University Libraries awards grants aimed at faculty instructors to adopt, adapt, or create free or low-cost alternatives to expensive textbooks. Over the past decade the Alt-Textbook Project (*Alt-Textbook Project*, 2013) has empowered educators to innovate pedagogically, enhance access for NC State students to high-quality, tailored educational materials, and reduce the financial burden of expensive textbooks and other course materials.

Instructors are invited to apply to the program every Fall and Spring semester. Grants are awarded between $1,000–$2,500 dependent upon the type of grant type. The Alt-Textbook committee reviews the respective merits of each proposal and decides whether to provide financial assistance or not. Generally speaking, those proposals with the greatest potential to impact a large number of students and classes and/or provide significant cost savings to students tend to be highly prioritized. As well as considering the financial impact to students, the program also prioritizes applications which are both feasible within a year-long timeframe, but also display a form of innovation which could be, for instance, new technologies, approaches, pedagogical strategies or a new OER for the field. A successful applicant is assigned a liaison from the libraries who helps shepherd the instructor through the process and is responsible for ensuring that the instructor has all necessary support and information available to them in order to successfully complete the project on time.

The Alt-Textbook Project has saved NCSU students, to date, $11.5 million across 84 unique projects. Ninety-nine faculty have been awarded Alt-Textbook grants representing 43 departments and impacting 104 classes. An analysis of the decade-long program, conducted in 2023, estimated that 78% of all instructors who received grant funding since 2013 still use either the original or updated OER originally adapted/created during the program. In terms of a wider impact, 57% of the instructors indicated that their openly created resource had been adopted by other NC State instructors and 28% had seen their materials reused at other institutions. The ease of disseminating OER has provided faculty with the opportunity to extend their impact beyond their home campus. In one particular project, dozens of other universities have reused the series of S.M.A.R.T. Lab videos (go.ncsu.edu/smartlabvideos), demonstrating various lab techniques and equipment, created by Dr. Maria Gallado-Williams in her organic chemistry class (Goodman, 2017).

Models for Open Education Approaches that Integrate Citizen Science

Several of us have incorporated a combined CS-OP approach in our courses at NCSU, which we describe here as models for other instructors. Each instance provides students the opportunity to participate in a CS project, and then to communicate the data, results, implications, and/or personal reflections with a broader audience. In Figure 2, we illustrate these opportunities as a spectrum of choices. A "simple" implementation, for example, might involve students participating in (i.e., collect data for and contribute to) a single CS project; or low-stakes communication of results via social media. An intermediate participation project would include data collection, contribution, analysis, and interpretation for a single CS project; and other forms of communication including an article for the school newspaper, a website or blog. A complex implementation could involve multiple intermediate instances across the semester (i.e., aligning several CS projects to different topics in a survey course), or a single intensive study integrated throughout the entire course (even including student development and launching novel CS projects, as a form of service learning effort and outreach to the broader community), followed by simple to intermediate communication, with potential for students to construct classroom implementation protocols, etc. Communication could also include dissemination of results to stakeholders and/or the organization leading the CS project.

Importantly, the CS and OP spectra are distinct, allowing an instructor to incorporate CS and OP at different levels. For example, Leggett's entry level Environmental Science course has students participate in a select CS project (simple CS) and provide reflection(s) on their experience. Krieg's ENG 101 students participate in a single CS project of their choice (simple CS), then research the topic and write an article about the project for the SciStarter blog (intermediate OP; see ("How Making a Picnic for Ants Can Help Us Understand This Crucial Species," 2021; "Sourdough for Science," 2022) as examples). Notably, the NC State University Libraries compiled resources to support Krieg's ENG 101 students as well as the broader campus (https://sites.google.com/ncsu.edu/eng-101-citizen-science/home?pli=1). Goller has included community participation through the use of sampling campaigns (simple CS) that are then analyzed by students enrolled in courses focusing on molecular biology techniques (intermediate CS; (Riley et al., 2020)). Goller's course centers OP through co-creation as students contribute results to a common project and share their methods and approaches. Lupek's first-year students participate in different citizen science projects in small groups throughout the semester (complex CS) and share their results and reflections on social media (simple OP) and with the organizers of their respective CS projects (intermediate OP). Gates's approach is similar to Lupek's. Students perform multiple CS projects in groups throughout the semester (complex CS) and develop a poster presentation (intermediate OP) in which groups use their data in conjunction with data from other groups to understand ecosystems around NCSU.

Interpretations and Recommendations—Reflections on Practice

Challenges to Overcome

CS-OP has the potential to address the dual disenfranchisement of students from the systems of knowledge creation and distribution. As instructors,

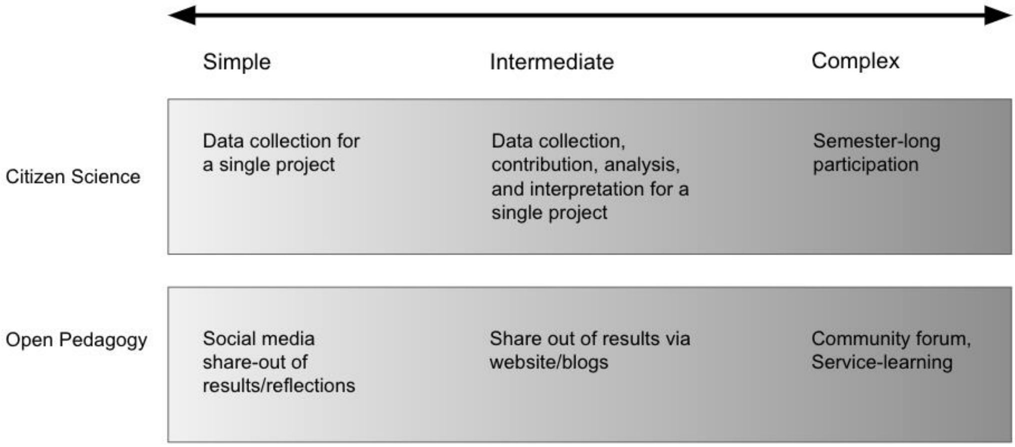

Figure 2. *Citizen Science and Open Pedagogy provide a spectrum of choices for curriculum implementation. Importantly, an instructor can "mix and match"—for example, incorporating intermediate Citizen Science participation with simple communication of results a la Open Pedagogy.*

we have, of course, grappled with challenges when attempting to implement meaningful CS-OP assignments in our classrooms. In this section, we discuss common pitfalls and possible solutions from the classroom to university level.

Student Privacy

To truly empower our students, we (instructors) must claim responsibility and strive for transparency in requesting permission to share student materials beyond our courses. Consent from students must be obtained in a way that is transparent, reduces the influence of inherent power dynamics, and avoids coercion. This might be achieved through consent waivers or the discussion of a "blanket protocol" for assignments on the first day of class. Coercion reduction can also be achieved when there is no grade consequence for students who do not feel comfortable sharing work beyond the course.

Equitability in Access to Technology

While many instructors turned to CS projects to provide remote experiential learning opportunities for their students during the COVID-19 pandemic (Farrell et al., 2021; Schirmel, 2021; Van Haeften et al., 2021), implementing CS-OP projects in a distance education environment is not without its challenges. The instructor must not only choose a CS project that aligns with the course's curriculum as it would in a traditional class; they also need to consider the students' physical locations and whether specific materials or technologies are required to complete the project.

Since most CS projects and OP methods rely on technology to disseminate data or share information, students who may not have access to that technology could be left behind both materially and psychologically. For example, many CS projects use mobile applications to collect and submit observations. If a student does not own a smartphone, they would be put at a disadvantage in completing the assignment. In addition, some countries do not support certain mobile applications—so even if a student has a smartphone, they may not be able to download the specific app needed to complete the assignment. In both cases, the lack of access to technology would prevent the positive impacts of participation in CS—and, indeed, might instead contribute to imposter syndrome or other senses of not belonging in STEM. NC State University Libraries attempt to address the accessibility gap with technology lending programs (*Technology Lending*, 1999); and some university classrooms are outfitted with laptops, in addition to computer labs located across campus that have software pre-installed (*Computer Labs in Colleges and Other Campus Units – Office of Information Technology*, 2023). If your institution of higher education does not have similar resources for students to borrow, there may be other options available, such as finding a CS project with different data collection or data submission procedures that better match technology conditions for your class. Alternatively, data from CS projects are often open access, providing instructors opportunities to download or visualize data for students, which can secondarily be used in OP practice. Finally, though not *sensu stricto* CS, it is possible to adapt the data collection protocol for a CS project that aligns with your course so that students can perform the project with minimal technology and without submitting data. OP methods can then be applied, regardless of which version of the CS project is implemented.

Large Enrollment Courses

Large enrollment courses (considered here to be student enrollment greater than 100; (Cash et al., 2017)) present a unique circumstance in higher education because many of the traditional interventions intended to increase student interaction are simply not feasible—or become less effective—when scaled for large class sizes. Even when students are assigned to work in groups and encouraged to ask each other for help, an instructor may struggle to facilitate conversations or answer all questions in a timely manner. When preparing students to do a new CS project, providing a pre-recorded tutorial or a live demonstration can help students navigate the project website or phone app, but some students may fall behind without one-on-one coaching. If too many students attempt to access a single website or other cloud-based resource during a synchronous class, they can crash or severely slow down the performance of the resource, further hampering accessibility, progress, and enthusiasm for the activity. After the data have been collected, submitted, and/or analyzed, it can be difficult to engage most of the students in large enrollment courses in meaningful discussion to ensure that everyone appreciates the relevance and impact of their work. Finally—however streamlined the assessment or straightforward the rubric, more students' submissions take more time to grade.

Over the years, authors of this paper have produced some solutions to the most pressing complications of incorporating CS-OP in large enrollment classes. For instance, a CS project might be deconstructed into a series of scaffolded activities. If time is limited, the instructor might incorporate peer reviews to help offset the grading labor. Interestingly, the growing *ungrading* movement (Kohn & Blum, 2020) simultaneously reduces grading time and can easily incorporate core fundamentals of OP, but even a “simple” implementation of ungrading with CS or OP activities requires thoughtful planning to run smoothly without engulfing more time and effort than is feasible. Another way to build community in your classroom is to extensively use collaborative data collection and analytical methods. Data-sharing epitomizes OP methods and affirms students’ sense of belonging and accomplishment. From traditional chalkboard data collection to web-based software such as the Google suite of collaborative tools, we have found that student satisfaction rises if they share data for a CS project with other members of their class. Even though large enrollment courses have many disadvantages compared to small enrollment courses with regards to instructor-student interactions and grading, large courses still provide opportunities for scaled CS data collection and OP interactions.

Institutional Resources and Support

CS and OP can enhance learning gains and improve student perceptions of themselves and of science (Collins, 2014). Yet many institutions lack the infrastructure to support instructors’ exploration, development, and implementation of these beneficial approaches. Even when instructors independently pursue professional development opportunities to increase their own awareness, creating CS-OP opportunities for students requires a large investment of time and intentionality in addition to trial and error. The long-term investment to implement and revise CS-OP effectively requires institutional support to ensure sustainable excellence. Unfortunately, the momentum of the established academic system and status quo practices may actually hinder innovation. For example, there may be pushback to changing the curriculum delivered to students (especially in large-enrollment introductory courses), for fear that reducing the number of curricular bullet points in a course may reduce educational rigor and not fulfill departmental educational goals.

Many institutions also lack a formal framework for instructors to receive credit for their investment in CS-OP innovation as they navigate reappointment, promotion, and tenure. That is, the existing format for evaluating instructors’ performances may not include metrics to capture instructors’ time investment into innovating techniques that augment student learning and sense of belonging. The co-creation of deliverables to disseminate research results and report back to participants has high impact on student learning and engagement (Collins, 2014), but those impacts may not be captured in students' course evaluations unless the instructor intentionally crafts questions designed to assess those specific activities. Furthermore, there is currently no model to include student products (e.g., PowerPoint slide decks shared in library exhibits, writing assignments published on blogs, presentations to peer classes and the broader community) as part of the instructor's professional dossier. It is particularly important for research and land grant institutions to center and value cooperative and collaborative pedagogical design within reappointment, promotion, and tenure structures, given their role in serving surrounding communities. The UNESCO Recommendation on Open Science, for example, calls for open science as a "foundational expertise of all researchers and incorporated into higher education research skills curricula" (p. 26) and taken into consideration for career promotion (*UNESCO Recommendation on Open Science – UNESCO Digital Library*, 2021); however, a framework for its effective dissemination and attribution of credit to students and instructors has not been universally established.

Next Steps

Having shared the ways we already incorporate CS and OP in our curricula and discussed models for (improving) institutional support, we now propose future directions to expand the use of CS-OP. For example, instructors can leverage CS-OP to create sustainable assignments and assessments that evolve over time. Students could design CS projects, create supporting OER (e.g., graphic protocols, spreadsheets for data curation and visualization), and launch their projects at local museums and/or public schools as part of service-learning projects. Given that CS builds shared data and OP promotes renewable assignments, iterative service learning can build toward greater engagement and shared understanding among students across several semesters. We believe the resulting body of student-created knowledge enhances students' sense of belonging in higher education and fosters a connection to a larger community that may aid in retention throughout undergraduate education as well as potentially fostering belief in a graduate career.

Beyond formal class assignments, campus-wide reports back to the public could couple with collaborative university extension to embody an institution of higher education's mission (e.g., NC State's mission as a land grant institution to reach all corners of the state). Citizen Science Club members or other participants across campuses could host informal research opportunities to collect, analyze, and interpret data in partnership with the general public. The results could then be disseminated via undergraduate magazines, digital bulletins, or informational signs around campus and in the broader community, and via talks hosted at local museums, schools, and public venues. Through these opportunities, students often explore research questions and diverse perspectives through a broader interdisciplinary lens. Together, CS-OP can bridge students' academic and real-world experiences and empower them to connect with internships and other professional opportunities.

Conclusions

CS and OP provide tools and a framework for students to collectively build towards a single objective, ultimately connecting students more effectively to their own research goals and to the broader scientific community. OP is a vehicle to increase students' sense of accomplishment; and CS is a concrete way to perform OP towards a common goal, without needing to create something new. When students see their work move beyond the classroom, they become more connected to and invested in research and research outcomes.

When used separately, CS and OP are powerful and innovative classroom tools, but together they have potential to engage and empower students to own their classroom experiences. Here we have outlined the multifaceted reach of CS-OP—how the model supports educational theory in practice and otherwise positively impact students' perceptions and engagement; and we provide several examples of our own innovation in the classroom, helpfully aligning CS and OP activities with skills and learning objectives as a model for others to follow. While NCSU provides an institutional model for large-scale implementation of CS-OP, there is still work to be done—both with regards to support and scaling our efforts to better engage the public as a valued partner.

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