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Usable STEM: Student Outcomes in Science and Engineering Associated with the Iterative Science and Engineering Instructional Model

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Abstract: While our world consistently presents complicated, interdisciplinary problems with STEM foundations, most pre-university curricula do not encourage drawing on multidisciplinary knowledge in the sciences and engineering to create solutions. We developed an instructional approach, Iterative Science and Engineering (ISE), that cycles through scientific investigation and engineering design and culminates in constructing a solution to a local environmental challenge. Next, we created, revised, and evaluated a six-week ISE curricular program, Invasive Insects, culminating in 6th–9th-grade students building traps to mitigate local invasive insect populations. Over three Design-Based Research (DBR) cycles, we gathered and analyzed identical pre and post-test data from 554 adolescents to address the research question: what three-dimensional (3D) science and engineering knowledge do adolescents demonstrate over three DBR cycles associated with a curricular program following the Iterative Science and Engineering instructional approach? Results document students' significant statistical improvements, with differential outcomes in different cycles. For example, most students demonstrated significant learning of 3D science and engineering argument construction in all cycles—still, students only significantly improved engineering design when they performed guided reflection on their designs and physically built a second trap. Our results suggest that the development, refinement, and empirical evaluation of an ISE curricular program led to students' design, building, evaluation, and sharing of their learning of mitigating local invasive insect populations. To address complex, interdisciplinary challenges, we must provide opportunities for fluid and iterative STEM learning through scientific investigation and engineering design cycles.

Keywords: science education; engineering education; interdisciplinary science

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1. Introduction

COP28, the Conference of the 197 nations following the United Nations Conventions on Climate Change, resulted in groundbreaking, multinational cooperative agreements that recognized and addressed climate-fueled disasters [1]. In particular, COP28 resulted in several multi-nation agreements to guide a transition away from fossil fuels. A second accomplishment was the creation of a set of criteria and an emergency fund that would provide emergency resources and financial support for under-resourced countries experiencing severe impacts from climate change.

Interestingly, the conversations occurring at COP28 involved individuals from a wide range of expertise areas. Individuals needed to review, summarize, and interpret a variety of complex data types and information. Problem solving and communication was needed so that individuals from very different situations and areas of expertise could communicate and deliberate effectively. Experts were needed who were fluent in problem solving across overlapping areas of science, technology, engineering, and mathematics (STEM) to discuss, interpret, design, and adopt interdisciplinary solutions.

Across many contexts, our world continues to present challenges that rely on complex, interdisciplinary problem solving and solution generation. Whether individuals or governments need to create a water filtration system to increase potable water availability or a vaccine modification to challenge a virus variant, we need individuals who are practiced and comfortable with interdisciplinary STEM problem solving and solution creation. To prepare for our future, we need STEM education programs in pre-college, formal, and informal settings that emphasize the natural integration of science and engineering as they guide learners toward creating solutions.

Several organizations have expressed a need for pre-university instructional materials emphasizing the integration of science and engineering to promote real-world problem solving [2]. The vision document behind the United States' Next Generation Science Standards [3] explains, "the line between applied science and engineering is fuzzy. It is impossible to do engineering today without applying science in the process" [3]; (p. 32). "In reality, scientists and engineers move, fluidly and iteratively, back and forth among spheres of activity, and they conduct activities that might involve several modes" [3]; (p. 46). Other national policy documents recognize this need, including those by the National Academies of Sciences, Engineering, and Medicine (NASEM). As outlined in one NASEM recent policy document, "Science is an essential tool for solving the greatest problems of our time and understanding the world around us. [it] enables people to address complex challenges in local communities and at a global scale, more readily access economic opportunity and rein in life-threatening problems such as those wrought by a global pandemic." [4]. To further emphasize this need, a recent National Academy of Sciences President stated, "Today, unless we can spread both scientific thinking and these critical scientific values much more broadly throughout society, I fear for humanity's survival" [5].

This urgency is not reflected in the priority placed on science education in formal educational settings. A recent report on classroom elementary science instruction [6] concluded that elementary schools do not prioritize science and engineering instruction despite children's natural interest in investigations and explorations. One study found that the average time devoted to teaching science in US elementary schools is 20 min per day, a few days a week [6]. When science instruction exists, it seldom provides opportunities for learners to practice epistemic agency, i.e., the ability of students to shape the knowledge and practices of their learning within their classroom community [7].

In the United States, a shift in thinking [3] resulted in the creation of the Next Generation Science Standards [8] and similar state standards and provided two notable changes in our expectations of teaching science. First, the new vision emphasized a shift from students learning science as disconnected ideas toward three-dimensional (3D) science performance expectations that emphasize learning disciplinary core ideas and crosscutting concepts through science and engineering practices [3]. Second, the vision included engineering as a critical component of science. Research studies also suggest benefits of introducing science and engineering at early ages to increase later engagement [9] and the importance of using engineering contexts to increase the relevance of abstract science concepts [10]. In addition, many students have narrow understandings of what engineers do. For example, in a recent activity where we asked young children to draw a picture of one or more engineers, a majority of elementary and middle school children drew pictures of people who work on robots or on computers as compared to people who solve problems within and across many areas, including medicine and environmental science [11].

We propose that classroom activities that support students in harnessing their intellectual and creative resources towards iterative cycles of science and engineering might start with asking questions and engaging in scientific investigations, but they do not end there. Three-dimensional science learning is fostered through additional activities that guide students towards cooperative problem generation, the design of solutions, and the implementation and testing of solutions in local, real-world contexts.

To evaluate this hypothesis, we designed the Iterative Science and Engineering (ISE) instructional model that guides youth in deepening their learning of science content through the practices of both science and engineering. Using our instructional model as a template, we then created a six-week curricular program that manifested the learning approach and provided opportunities for students to draw from their interdisciplinary knowledge development in the life sciences toward the design of solutions. Finally, we conducted three cycles of design-based research (DBR) studies to address the research question: what three-dimensional (3D) science and engineering knowledge do adolescents demonstrate over three DBR cycles associated with a curricular program following the Iterative Science and Engineering instructional approach?

A New Instructional Model

Many existing programs guide the learning of STEM topics through either science or engineering practices, but not both. For example, the 5-E instructional model [12] provides a five-step approach to science investigation (Engage, Explore, Explain, Elaborate, Evaluate). The 5-E instructional model is based on the research-based learning cycles of Atkin and Karplus [13] and Piaget [14] and it is currently associated with more than 235,000 lesson plans. Other programs emphasize science learning through the practices of engineering [15,16]. While many of these programs are outstanding, they also reveal a gap in the literature. We address this gap by designing and evaluating an instructional model and a curricular program that fosters learning science content through science and engineering practices in a creative, mutually beneficial process.

We designed our instructional model, Iterative Science and Engineering (ISE) to expand on the 5-E learning cycle [12] so that the instructional activities systematically provide science investigation and engineering design iterations, each of which inform the next. This design was created to mirror how professionals apply scientific and engineering knowledge seamlessly. As shown in Table 1 and Figure 1, activities in ISE are grounded in an interdisciplinary phenomenon introduced in the Engage phase, such as an invitation from the Department of Agriculture to study local invasive insects. This phase is followed by two or three cycles of Explore that include multiple rounds of data collection including, for example, data collected on the number and kinds of invasive insects in their region and data collected to evaluate the effectiveness of a trap designed to mitigate local invasive insect populations. The Explore phases are followed by Explain, which focuses on the analysis of student-generated data from the previous round and the construction of arguments that utilize their own data as evidence. In Engineer, students draw from their data and analysis in a multi-step engineering design process emphasizing the engineering practices [8] and leading to multiple designs, and, in some cases, the actual building of insect traps to mitigate local invasive insect populations. Overall, in any enactment of the full ISE model, students cycle between phases emphasizing science investigation (e.g., Explore and Explain) and engineering design (Engineer) up to three times. In the final phase, Educate, student teams are provided with a formal opportunity to share what they have learned with others. In presentations that include short videos or infographic posters created by the student teams, students share their solutions, decisions, justifications, and data to peers and stakeholders, including local scientists, peers, family members, and community members.

Table 1. Phases of the iterative science and engineering instructional model. Red indicates iteration.

Complete Phases of the ISE Instructional Model	**Cycle 1**	**Cycle 2**	**Cycle 3**
Engage: Students ask questions about a phenomenon that engages their curiosity and provides a purpose for why they study this problem.	**Engage** Focused on science only	**Engage** focused on solutions to local problems	**Engage** focused on solutions to local problems
Explore: Students collect data to use as evidence to understand their problem.	**Explore**	**Explore**	**Explore**

Table 1. *Cont.*

Complete Phases of the ISE Instructional Model	Cycle 1	Cycle 2	Cycle 3
Explain: Students analyze their data and use it as evidence to construct arguments that address their questions and consider a solution.	**Explain**	**Explain**	**Explain**
Engineer: Students define their problem and design and build a solution that meets specific design criteria and constraints.	**Engineer** design only	**Engineer** design and one build	**Engineer** design and first build
Explore: Students collect data to use as evidence to evaluate their first build (solution).			**Explore** peer critique first build
Explain: Students analyze and use their data as evidence to construct arguments to address questions and revise their solutions.			**Explain** critique designs on multiple criteria
Engineer: Students revisit their design and build a second improved or efficient design.			**Engineer** design and second build
Explore (optional): Students place their solution and collect data on the effectiveness of their solutions.			
Explain (optional): Students analyze and use their data as evidence to construct arguments and determine solution effectiveness.			
Educate: Students synthesize key ideas from their designs and data to educate local stakeholders about their solution for their area.	**Educate**	**Educate**	**Educate**

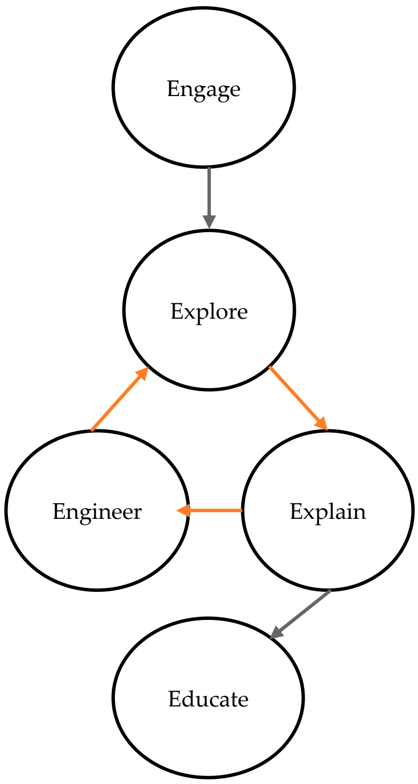


Figure 1. Phases of the iterative science and engineering instructional model.

Once our ISE instructional model was developed, we created a six-week interdisciplinary biology curricular unit, Invasive Insects, which was our first manifestation of the ISE instructional model. We designed our unit to not only create examples of activities to realize each phase but to gather classroom-based empirical data associated with student outcomes when guided by the Invasive Insects ISE curricular unit and the ISE instructional model.

2. Materials and Methods

We implemented three research cycles of Design-Based Research [17] to gather empirical information on outcomes associated with three implementations of the Invasive Insects ISE program. The DBR approach is a learning science research methodology designed to provide empirical information about "novel conditions for learning that theory suggests might be productive but are not common or well understood" [18] (p. 22). The DBR approach was an excellent methodological fit for our research studies, as this approach is specifically designed to cycle through steps of design, enactment, analysis, and revision to guide improvements of an early innovation. As our innovation, the ISE-designed Invasive Insects instructional program, was still in an early phase of development, it was not suitable for another more formal research methodology, such as a quasi-experimental or experimental design with control and experimental sub-groups.

DBR studies are conducted in research cycles, with each research cycle consisting of four steps: design, enact, analyze, and reflect (see Figure 2). Each research cycle results in the collection of data on features of the innovative learning environment and student and teacher evidence of how such environments work in the settings for which they are designed [18]. As the test responses and work products generated by students are only a proxy for the learning process itself, the final step of each cycle is a reflection on the goals, the salient features of the learning environment, population, and learning outcomes in order to develop design principles to support changes for the next cycle and to help explain learning outcomes.

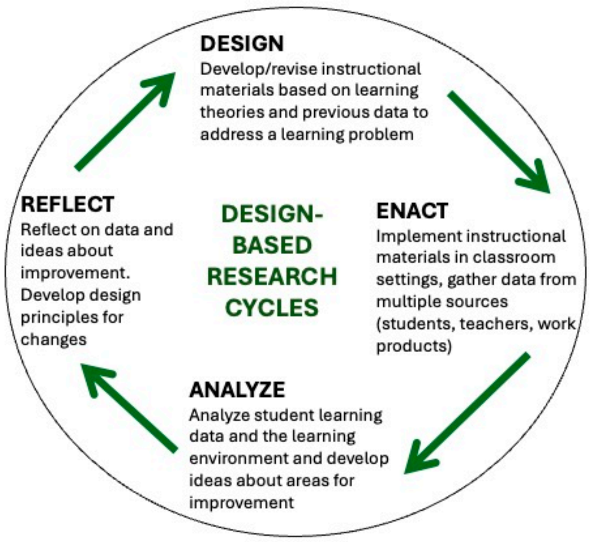


Figure 2. The four steps of design-based research cycles.

Data Sources

We designed and validated our assessment instruments following recommendations on developing assessments that validly measure student proficiency in science [19] and that are aligned with the vision outlined in the recent framework for K–12 science education [3]. More specifically, we built on our previous work in the design and validity evaluation of science assessments [20] to create tasks that mirrored many of the activities conducted in class but with scaffolds or hints diminished or removed to provide the evidence of students' abilities to construct scientific arguments without assistance. After the task design, we conducted cognitive interviews with ten students to provide validity information that provided evidence that the items elicited information about the intended construct [20].

Prior to instruction, all students completed the eleven-item pretest. Upon completion of the curriculum, all ISE and comparison students took a post-test identical to the pre-test. In all cycles, the pre/post-test was worth 21 points. Constructing scientific arguments accounted for nine points, and the remaining short answer items accounted for 12 points. In the three constructing scientific argument questions, students were required to complete scientific arguments with varying levels of scaffolds, such as sentence stems. The remaining questions included a variety of constructed response items, including items asking students to construct food webs and provide improvements to a proposed solution for addressing an invasive species not studied in the curriculum (see Supplementary Materials for test).

Prior to each research cycle, we recruited 6–9th grade teachers who demonstrated interest in the study of an innovative ISE curricular program that was aligned to the state and national science standards in their region. Prior to implementation, all teachers participated in a six-hour professional learning workshop on the ISE instructional model, the Invasive Insects curricular program, and relevant scientific information, including the species and known impact of local invasive insects on ecosystem stability. In Cycle 1 only, we had two sixth grade teachers from the same school who were interested in six weeks of instruction on the same science content (ecology and biodiversity) aligned to their state standards, while only one teacher was interested in using our ISE-Invasive Insects materials. Therefore, for Cycle 1 only, we gathered data on both an ISE cohort and a Comparison cohort. In other words, we implemented our ISE program with five classes taught by one teacher (ISE), while the second teacher used the district-approved textbook for the same standard-aligned topics (Comparison).

Following the university and school district ethics and research committee requirements, all teachers and students provided written approval and consent to participate in the research studies. Data from the identical pre-test and post-test assessments were collected from 554 students in four schools (Table 2) Two researchers scored each of the tests. Codes were compared to compute interrater reliability (k = 96.2%). To examine accuracy, 80 spot checks were completed, indicating 100% accuracy in data entry. We conducted a Kolmogorov–Smirnov test for normality before evaluating any pre-test/post-test or between-group differences. In all cases, results indicated that the data were not normally distributed ($p < 0.05$). Therefore, to calculate changes between the pre-test and post-test for the ISE group, we used a Wilcoxon Sign Rank test. To compare the ISE and comparison groups' ability to construct a scientific argument after the completion of the respective curriculums, we conducted a Mann–Whitney U test. Finally, to examine the magnitude of the effects of both pre-test/post-test changes for the ISE group as well as the argument comparison between groups, we calculated r^2 by dividing the square of the Z statistic by the sample size.

Table 2. Population for cycles 1, 2, and 3 schools.

	Cycle 1	Cycle 2		Cycle 3	
	1A	**2A**	**2B**	**3A**	**3B**
N	208	169	16	78	83
Grade	6	6	8	7	9
White	80.90%	81.23%	50.43%	52.92%	55.75%
African American/Black	0.96%	0.77%	3.42%	2.97%	6.15%
Hispanic	13.94%	13.67%	33.33%	4.29%	30.21%
Asian	0.10%	0.19%	4.27%	9.02%	1.87%
Am. Indian/Alaska Native	0.10%	0.19%	2.56%	0.22%	0.67%
Two or More Races	3.15%	3.18%	5.13%	30.58%	3.88%
Free/Reduced Meals	19.48%	25.31%	41.88%	charter	49.73%

3. Results and Discussion

3.1. Cycle 1

Student populations for Cycle 1 consisted of seven sixth grade classes (1A) in one urban middle school, with five classes following the ISE curricula and two classes following a biology unit addressing the same state standards (Comparison).

Cycle 1 activities consisted of the development of the six weeks of student activities organized into an 83-page student notebook and a corresponding teacher notebook that included background information on the five parts of the ISE instructional approach (Engage, Explore, Explain, Engineer, Educate), scientific content, and expected student responses. In the Cycle 1 version of Invasive Insects, the five phases each appeared only one time (see Table 1). The Engage activity consisted of student teams collecting field-based observations on the number and kinds of organisms found in their local school yard (see Table 1). Students' field-based observations were collected into a database on the number and kinds of animals observed in their local area, including the local invasive insects. Class data were organized into one class-wide spreadsheet that was analyzed and used as evidence in students' construction of arguments. Students then conducted research on the local invasive insect that was their responsibility. Student teams investigated if their invasive insect was disruptive to local ecosystem stability, health, or agriculture. The unit culminated in an activity to create a plan for building a trap to mitigate local invasive insects, but students generated only one drawing and did not build any physical traps. The unit concluded with the creation of short videos or slideshow presentations to educate peers, local scientists, community members, and others.

As mentioned earlier, for Cycle 1, we had two different conditions of enactment within the same school: ISE classes that followed the Invasive Insects curriculum and Comparison classes the spent the same six weeks on the same ecology and biology content using the district-approved textbook. The ISE classes had four opportunities to practice the development of scientific arguments, while the second group, Comparison, generated conclusions to their study but did not engage in argument construction. In addition, the ISE classes spent two class sessions in engineering design activities, resulting in a plan and a drawing for building a proposed insect trap. Both ISE and Comparison groups completed their unit by creating an infographic or video that described what they had learned.

Cycle 1 results are represented in Table 3. This table shows the means and standard deviations by group for the overall pre-test and post-test scores as well as the total scores for the two subparts (i.e., argument and other). Overall, the ISE group scored statistically significantly higher on the post-test than on the pre-test ($p < 0.001$, $r^2 = 0.57$). This finding was true for both of the subparts as well, i.e., the argument ($p < 0.001$, $r^2 = 0.44$) and other items ($p < 0.001$, $r^2 = 0.48$). In a review of ISE and Comparison students, one result of interest is in the area of constructing a scientific argument. While both groups experienced instructional resources emphasizing the same 3D biology concepts, the ISE group had practice with arguments and using their own data as evidence to construct a scientific argument. When comparing the argument results for the ISE and Comparison groups, there were no statistically significant differences by group on the pre-test ($p = 0.114$). However, on the posttest, the ISE group scored statistically significantly higher on argument items than the Comparison students ($p < 0.001$, $r = -0.28$). As might be expected, however, as neither the ISE nor Comparison group had activities that emphasized engineering design, neither group demonstrated significant pre to posttest improvement on the engineering design tasks.

Table 3. Cycle 1 descriptive statistics for pre-test and post-test scores.

		Pre-Test Scores		**Post-Test Scores**	
	n	**Mean**	**SD**	**Mean**	**SD**
ISE Total	129	6.26	3.57	9.99 *	4.03
ISE "Other"	129	3.91	2.05	5.85 *	2.26
ISE Argument	129	2.36	2.05	4.12 *	2.31
Comparison Argument	79	1.87	1.80	2.77 *	2.26

Note. * Indicates $p < 0.01$.

3.2. Cycle 2

Between Cycle 1 and Cycle 2, we gathered information from Cycle 1 teachers and students that we used to make improvements to the Cycle 2 Invasive Insects unit. However, as outlined in Table 1, we still only implemented each phase (Engage, Explore, Explain, Engineer, Educate) one time. Drawing from student and teacher interviews and our research results, we made two major changes to the Cycle 2 version of Invasive Insects. First, we introduced an invitation from the Department of Agriculture to study local invasive insects (Figure 3) as the first Engage activity in the beginning of lesson 1. This placement provided an opportunity to provide a clear interdisciplinary phenomenon to introduce epistemic agency [7] for students' study of local invasive insects throughout the unit. Building from this charge for studying local invasive insects, students conducted many of the same activities as in Cycle 1, including gathering data on local organisms and creating a class-wide database on the number and kinds of animals observed in their local area. Student teams conducted research on one local invasive insect to determine if their invasive insect was disruptive to local ecosystem stability, health, or agriculture.

A second change to Cycle 2 was more time on the engineering design activities. We articulated the steps of the Engineering Design Process and expanded the associated student activities into a seven-step process (Define, Research, Design, Build, Place, Reflect, Educate). Working in teams, students looked to the Department of Agriculture to define their problem, researched their invasive insect, and created several designs for different kinds of traps. In Build, they created one physical version of their insect traps, on which they then reflected in terms of how effective they believed it to be. The unit concluded with the Educate phase, including the creation and delivery of presentations to educate peers, local scientists, and community members.

Student populations for Cycle 2 consisted of six sixth grade classes (2A) and one eighth grade class (2B). Results for Cycle 2 are presented in Table 4. In Cycle 2, the combined group of all students as well as School 2A experienced statistically significant differences ($p < 0.001$) from the pre-test to the post-test in all categories except engineering design ($p = 0.100$). School 2B did not experience any statistically significant improvements from pre-test to post-test. Our analysis does not fully explain this outcome, except that we observed that the classroom teacher did not follow our curricular program closely. The largest percent increase in any one category was School 2A's scientific argument score, which increased 131.3% from 1.6 to 3.7 out of nine total possible points. The largest percent increase in any category for School 2B was in the science non-argument category, increasing 28.7% from 3.77 to 4.85 points.

Department of Agriculture
350 North Redwood Road, PO Box 146500

Dear Field Biologists,

Over the past several years, people in Utah have had a big problem with the insects shown here:

Balsam Wooly Adelgid

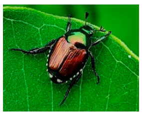
Boxelder Bug

Brown Marmorated Stink Bug

Common Silverfish

Elm Seed Bug

Japanese Beetle



Small Hive Beetle

Velvet Long horned Beetle

These insects are very annoying and may eat or destroy many of the plants and animals in Utah. Because of this, we need your help in studying these animals and in finding out how to remove or reduce them so that the plants and animals that live here, including us, can do well. Over the next few weeks, your task is to create a solution to decrease the number of these insects in your community.

What is a solution? Good question!

A **solution** is *a plan to solve a problem***.** In this case, your solution will be designing and building a trap to reduce the number of one of these insects in your area.

Your teacher will be giving you more information to help you learn about your insect and other animals that live in your area so you can create your solution to share with others.

Thank you,

The Department of Agriculture

Figure 3. Invitation letter from the Department of Agriculture.

Table 4. Cycle 2 pre-test and post-test results.

		Pre-Test		Post-Test	
	n	**Mean**	**SD**	**Mean**	**SD**
Combined Total	105	5.65	3.74	9.52 *	4.20
Combined Sci Argument		1.90	1.85	3.78 *	2.18
Combined Sci (no argument)		2.74	1.91	4.59 *	1.95
Combined Eng (max 2)		1.00	0.87	1.15	0.85
2A Scientific Argument	93	1.60	1.59	3.70 *	2.15
2A Total	93	5.03	3.42	9.35 *	4.15
2B Scientific Argument	12	3.77	2.24	4.46	2.40
2B Total	12	8.92	3.64	11.00	3.92

Note. * Indicates $p < 0.01$.

3.3. Cycle 3

As occurred between previous cycles, we drew on teacher interviews and the consistent lack of improvement on our pre-post engineering design assessment tasks to make more pronounced changes to the Invasive Insects unit for Cycle 3. In particular, we gathered essential information from our teachers who indicated that the two groups of Cycle 2 students who physically built their insect traps seemed more engaged in the unit and had stronger final presentations. Building from student outcomes and feedback, we initiated a significant change to the Cycle 3 version of Invasive Insects: we introduced iterations between the Explore–Explain–Engineer phases, and we asked teachers to implement each of these phases two times. This action resulted in two important changes. First, we required that all student teams needed to physically construct at least two builds of their insect trap. Second, we added four reflection questions after student teams constructed their first build of their insect traps to specifically guide the creation of a more successful second trap build. Sample student trap designs and these reflection prompts are presented in Figure 4. The reflection questions included asking student teams for information on their selected lure, trap entrance, and trapping mechanism that would more likely attract their chosen invasive insect but no other animals or insects in the area. Some of the changes that students made to their builds included the trap components that were suggested by the questions, but students also cited improvements they needed to make in terms of trap structure and stability, cost of materials (students were given a USD 10 constraint with which to "purchase" supplies), and trap maintenance. After completing their two trap builds, students researched and chose an optimal location for their traps. While some students were able to place their traps in the locations they had selected and collect a brief amount of data about trap effectiveness, most teams did not have time for these activities in the allocated six weeks. As shown in Table 1, the final phase progression of activities in Cycle 3 was: Engage, Explore, Explain, Engineer, Explore, Explain, Engineer, and Educate.

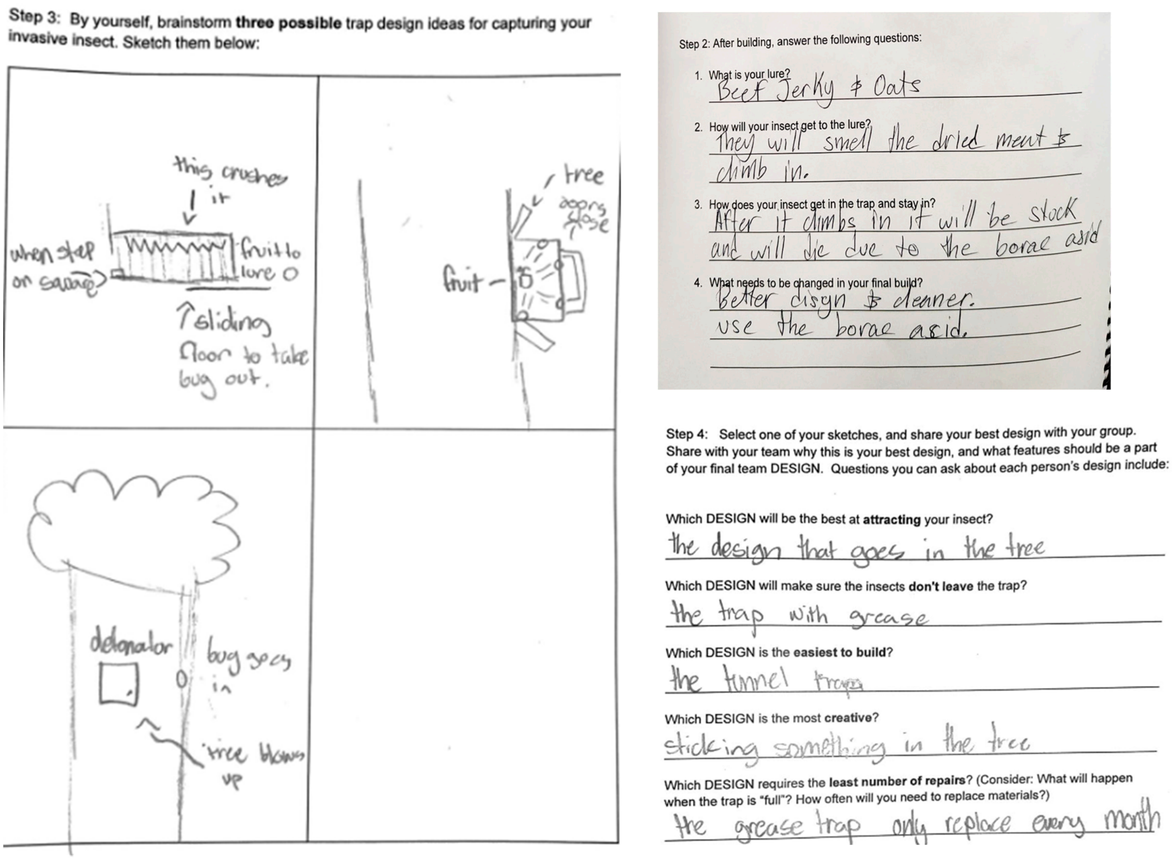


Figure 4. Sample student trap drawings and reflections between Builds 1 and 2.

Student populations for Cycle 3 consisted of four seventh grade classes (3A) and four ninth grade classes (3B). Table 5 shows the descriptive statistics for the pre-tests and post-tests in Cycle 3. Results demonstrated statistically significant improvements ($p < 0.01$) by all groups from pre-test to post-test in all categories. Furthermore, Cycle 3 was the first time any group showed statistically significant differences on the engineering design assessment tasks. The largest change in any category was School 3A's engineering design score, which improved 0.56 points out of a total of 3 possible, indicating 90.3% improvement. Similarly, the largest improvement for School 3B was also the engineering design score, which improved an average of 0.59 points for 68.6% improvement in this category.

Table 5. Cycle 3 statistics for pre-test and post-test scores.

		Pre-Test		Post-Test	
	n	**Mean**	**SD**	**Mean**	**SD**
Combined Total	139	9.57	3.78	12.76 *	3.10
Combined Scientific Argument		4.63	2.45	6.43 *	2.03
Combined Science Other		4.19	1.38	5.02 *	1.15
Combined Eng (max 3)		0.73	0.84	1.31 *	0.91
School 3A Total	73	8.40	3.81	12.66 *	2.97
School 3A Scientific Argument		3.89	2.47	6.60 *	1.98
School 3A Science Other		3.89	1.40	4.88 *	1.08
School 3A Eng (max 3)		0.62	0.79	1.18 *	0.84
School 3B Total	66	10.86	3.32	12.86 *	3.27
School 3B Scientific Argument		5.44	2.18	6.24 *	2.08
School 3B Science Other		4.53	1.29	5.18 *	1.20
School 3B Eng (max 3)		0.86	0.88	1.45 *	0.96

Note. * Indicates $p < 0.01$.

4. Conclusions

Over three Design-Based Research (DBR) cycles, student learning outcomes demonstrated significant pre-post improvements in each cycle, even as the results varied by cycle and population. Between each cycle, we gathered data from students and teachers and analyzed our learning outcomes to guide the development of design principles and changes to the instructional program.

The most significant changes to the curricular program were implemented for Cycle 3. As outlined in Table 1, in Cycle 3, we implemented iterations of three of the phases, Explore, Explain, and Engineer, to more demonstrably guide students in the fluid and interactive work that includes multiple physical builds and multiple rounds of reflection and that combines science and engineering as is commonly performed by professionals. Cycle 3 student outcomes demonstrated statistically significant differences in the engineering design portion of the pre- and post-test for the first time. We believe this outcome can be associated with specific, teacher-influenced DBR improvements to the curricular materials drawn from teachers' and students' feedback, including adding a second build of insect traps, reflection questions to guide students towards informed improvements, and two rounds of data collection and analysis.

Our Design-Based Research suggests that, over three DBR cycles, a curricular program developed to foster iteration between the aspects of science investigation (Explore, Explain) and engineering design (Engineer) is associated with improvements in developing three-dimensional science and engineering solutions and 3D knowledge that integrates science and engineering. Our outcomes also suggest that, with improvements generated by the Design-Based Research (DBR) research approach, we can provide information to inform and improve our Iterative Science and Engineering instructional model.

Our paper began with an example of a real-world context, COP28, in which experts were needed who were fluent in problem solving across overlapping areas of science, technology, engineering, and mathematics (STEM) in order to collectively discuss, interpret, design, and adopt interdisciplinary solutions. Recognizing that these global challenges are not simple, it is essential that we foster engineering design, collaboration, creativity, and solution generation as a part of formal STEM learning. Therefore, our work leads to a recommendation:

Pre-university instructional programs need to provide multiple opportunities for students to practice iterations of science investigation and engineering design towards solutions to local, interdisciplinary problems.

While we recognize that more research is needed, we welcome dialogue and research studies that extend this conversation and investigate instructional approaches, such as ISE, that connect science learning to applications and solutions so that, collectively, we can provide students with opportunities to practice complex, interdisciplinary problem solving and solution generation needed for the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci14111255/s1, Assessment to Measure Next Generation Science Knowledge of Life Sciences through Science and Engineering Practices. The University of Utah.

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