Science investigation and engineering design for our complex world

8 essential features

THE UNIVERSITY OF UTAH

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Science investigation and engineering design for our complex world: 8 essential features

Here, we explore the critical need for STEM education to integrate science and engineering. Highlighting real-world projects, this eBook reveals eight essential features to empower students to tackle complex challenges and become innovative problem-solvers.

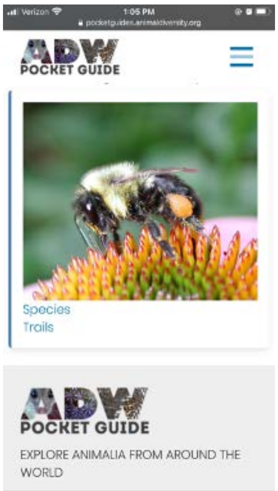
COP28, the Conference of the 197 nations following the United Nations Conventions on Climate Change, resulted in groundbreaking, multinational cooperative agreements recognizing and addressing climate-fueled disasters (COP28, 2023). In particular, COP28 resulted in several multi-nation agreements to guide a transition from fossil fuels. Interestingly, the conversations at COP28 required individuals to review and interpret various complex data types and information to generate solutions. Problem-solving and communication required individuals from very different situations and areas of expertise to bridge gaps and strategically simplify complex issues so those without deep expertise in a particular content area could communicate and deliberate effectively.

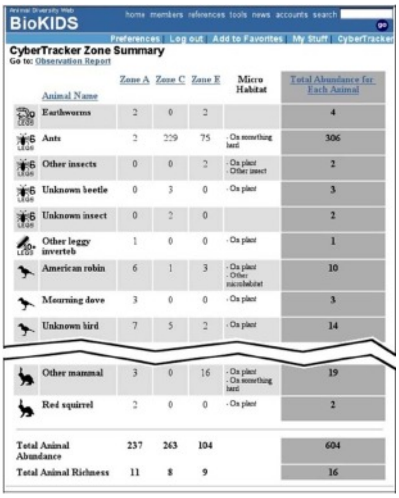
Similarly, we need science, technology, engineering, and mathematics (STEM) education programs in pre-college, formal, and informal settings that emphasize the natural integration of science and engineering to create solutions. Several organizations have expressed a need for pre-university instructional materials emphasizing integrating science and engineering to promote real-world problem-solving (e.g., United Nations, 2023). As outlined in one National Academies of Sciences, Engineering, and Medicine (NASEM) 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." (NRC, 2021). However, formal educational settings do not often emphasize problem-solving in science and engineering. One recent report found that the average time devoted to teaching science in US elementary schools is 20 minutes per day, a few days a week (NASEM, 2021), despite children's natural interest in investigations.

Three stories of science investigation and engineering design

We present three stories from over two decades of research and development in science investigation and engineering design. Each story represents 5-10 years of collaborative research and development in formal school settings. Following the stories, we present and discuss eight features in these programs that guide youth in science investigation and engineering design resulting in solutions to local environmental challenges.

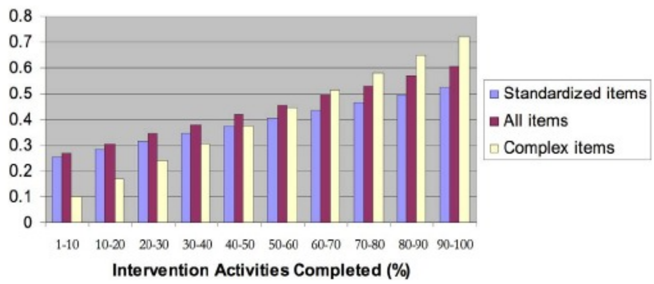
In **Detroit, Michigan, USA** with funding from the National Science Foundation, adolescents following the BioKIDS: Kids' Inquiry of Diverse Species



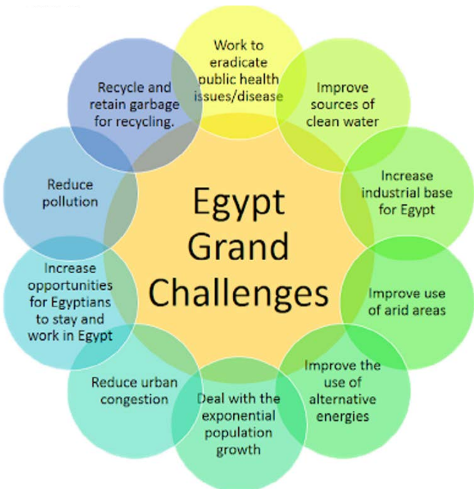


instructional program used a mobile app, the Animal Diversity Web Pocket Guide, to gather data on the amount and kinds of animals in their schoolyard. Student data were then used to answer questions such as, how biodiverse is my school yard?

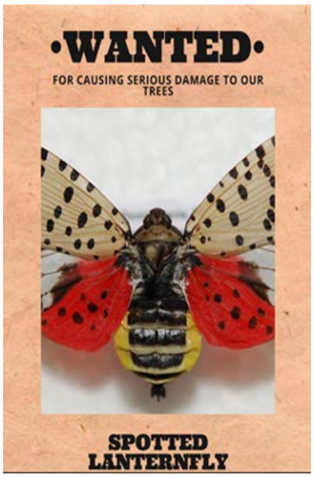
The results demonstrated significant learning gains for students who utilized our program compared to students who primarily studied the same ecology concepts using a textbook but could use as much of our Intervention program as they wished (X= amount of Intervention program utilized; N=1885).



In **Egypt,** with funding from USAID and in partnership with the Egyptian Ministry of Education, adolescents in select high schools followed a three-year curriculum that fostered the development of socially responsible leaders focused on STEM problem-solving for Egypt. Each semester culminated in an interdisciplinary capstone project using investigation and engineering design to solve one of Egypt's Grand Challenges. More than 96% of student graduates went on to study in high-ranking universities in Egypt, the United States, and other countries, and several students participated in international science competitions for the first time and often placed or won.



In **Philadelphia and Utah, USA,** with funding from the National Science Foundation, adolescents using the Invasive Insects curricular program were asked by the Department of Agriculture to study the potential harmful effects of one local invasive insect species and design a trap to mitigate the insect population. Students designed and built one or more versions of their insect traps, placed them in regional areas, and gathered data and information on trap effectiveness to share with local community members and environmentalists. Four different research studies conducted in diverse middle and high school settings demonstrated significant learning gains after involvement in the instructional programs (e.g., Songer & Ibarrola Recalde, 2021).



What do these three stories have in common?
After over two decades of design and study of instructional programs focused on adolescents' design of solutions to complex, interdisciplinary problems, we have realized eight essential components of these learning environments. We present the Eight Features (Ss) of Investigation and Design Success.

1. A spine, in other words, a particular investigation or design phenomenon with local relevance for context and meaning, is the focus of all instructional, assessment, and professional learning activities.

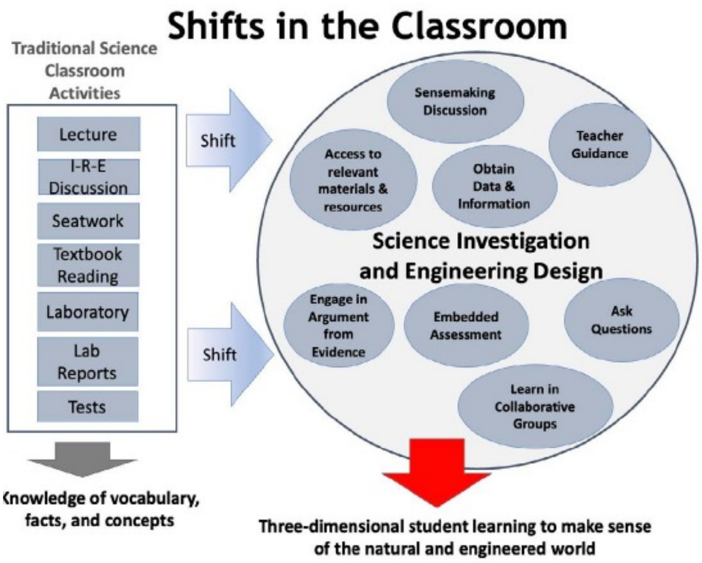
The spine focuses the problem-solving activities and provides motivation for students to make a difference in their community. In Egypt, the spine was the focus of one of Egypt's Grand Challenges each semester, which served as the cornerstone of students' semester-long capstone project. For example, to address the Grand Challenge of reducing pollution, students designed and built methane sensors on local garbage cans in Cairo and a mobile app to direct local garbage collectors to prioritize waste cans that generated the highest methane levels. In Invasive Insects, the spine was the challenge by the Department of Agriculture to study and design a trap to mitigate populations of one local invasive insect, such as the Spotted Lanternfly, which is pervasive across the east coast of the United States.

2. Products of learning need to be important, have a purpose or substance, and an audience of supporters.

Across our instructional programs, we design activities that empower adolescents to provide solutions to local challenges and share their insights and solutions with local stakeholders, including scientists, community members, and government organizations. This purpose for learning also motivates students to engage in the activities. Focusing activities around the local issue that is meaningful to students also shifts many aspects of classroom activities so that they differ from those commonly found in traditional science classrooms. For example, focusing on science investigation and engineering design leads to a different product. Instead of knowledge of vocabulary or facts, focusing on investigation and design leads to students' understandings that make sense of the natural and engineered world. In Egypt, students recognize that the products of their learning have value when they share their capstone projects and realize that "We are solving Egypt's problems." In Invasive Insects, students' traps are shared with local environmentalists to see how they compare or extend professionals' efforts.

3. Learning has to be reasonably challenging, with the ability to manage appropriate struggle with guidance as needed.

In our instructional programs, students ask questions, obtain data and information, and engage in sensemaking discussions. These activities are intentionally designed to lead to multiple answers and solutions. As a result, the role of teachers shifts to one who takes ideas like "what is evidence?" and leads students in sensemaking discussions. The concept of evidence might include discussing where the evidence comes from, how this evidence matches the scientific question, and how the concept of evidence differs from other similar ideas, such as data (evidence is data collected to address a particular scientific question). When needed, these sensemaking conversations facilitate appropriate struggle and guidance, such as hints or scaffolds. In BioKIDS and Invasive Insects, appropriate guidance took the form of scaffolds in student worksheets to guide students in developing a scientific explanation or argument that included three parts (claim, evidence, and reasoning). In Egypt, students sought out University STEM faculty for specialized equipment and guidance on capstones.



BioKIDS

Data Sheet 33

Scientific Question:
Which zone in the schoolyard has the highest biodiversity?

Make a CLAIM:
Write a complete sentence that answers the scientific question.
zone E and C have the highest Biodiversity in the school yard.

Hint: Look at Data Sheets 31 and 32 carefully.

Give your REASONING:
Write the scientific concept or definition that you thought about to make your claim.
Biodiversity is realated to abundance and richness because it shows the two amounts in one word.

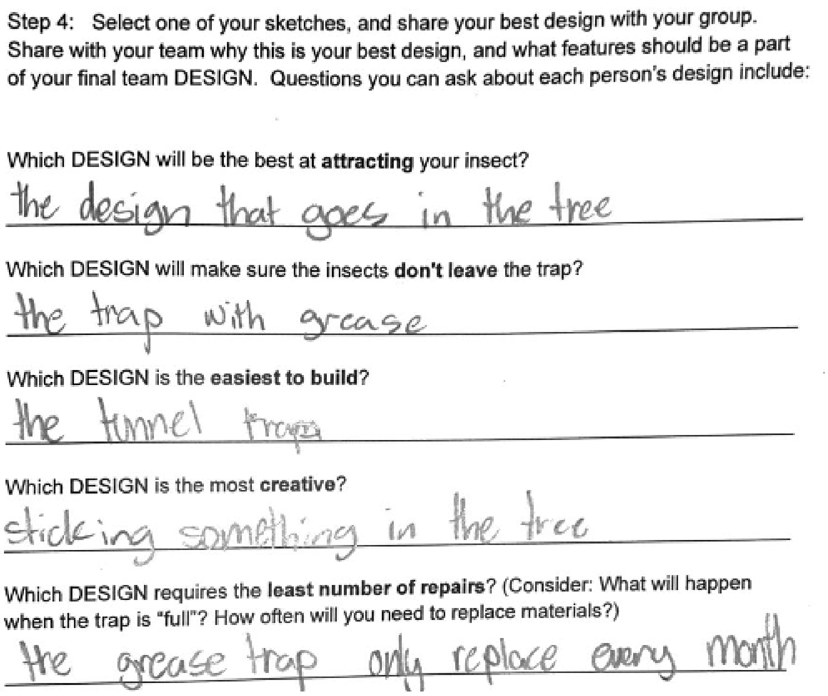
Hint: Think about how biodiversity is related to abundance and richness.

Give your EVIDENCE:
Look at your data and find two pieces of evidence that help answer the scientific question.
1. zone E has the most Abondonte.
2. zone C has the highest richness

Hint: Think about which zone has the highest abundance and richness.

Write your scientific EXPLANATION:
A scientific explanation is a paragraph that includes your claim, evidence, and reasoning. Remember to write in complete sentences!

Figure a: Select features of science investigation and engineering design and how they differ from activities in traditional science classrooms. From NASEM (2019), p.83. **Figure b:** sample student worksheet with scaffolds for developing a scientific explanation.


Step 4: Select one of your sketches, and share your best design with your group. Share with your team why this is your best design, and what features should be a part of your final team DESIGN. Questions you can ask about each person's design include:

Which DESIGN will be the best at **attracting** your insect?
the design that goes in the tree

Which DESIGN will make sure the insects **don't leave** the trap?
the trap with grease

Which DESIGN is the **easiest to build**?
the tunnel traps

Which DESIGN is the most **creative**?
sticking something in the tree

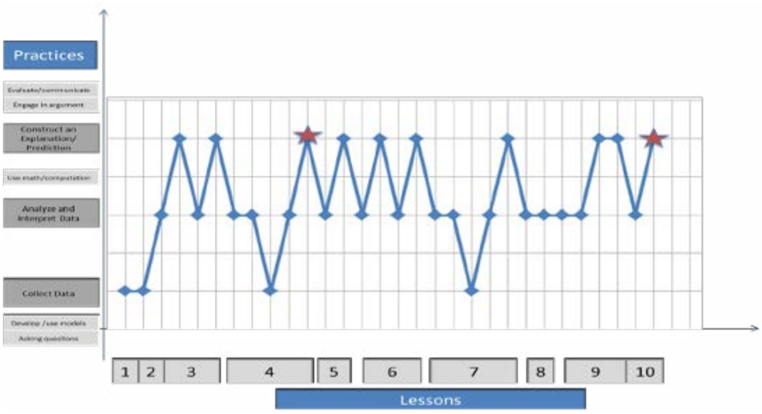
Which DESIGN requires the **least number of repairs**? (Consider: What will happen when the trap is "full"? How often will you need to replace materials?)
the grease trap only replace every month

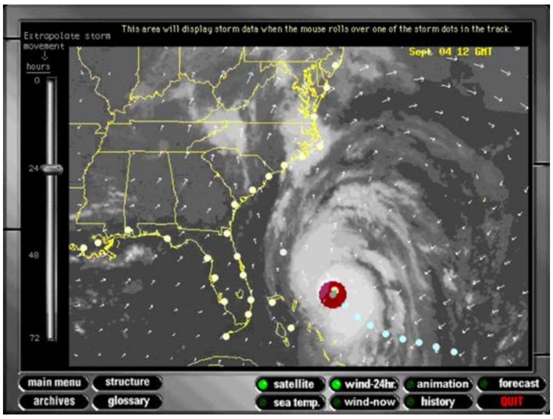
4. Students practice collaboration and synergy when they work as teams and draw from multiple expertise sources to address challenging questions and design solutions.

All of our instructional programs engage student teams in collaborative groups for problem-solving. For example, in Invasive Insects, students independently create at least three designs for their invasive insect trap. However, after independent sketches, the group uses a series of questions to evaluate the effectiveness, creativity, and ease of construction and repairs to determine which features to include in their build. In this way, students can model problem-solving and critique common with professional engineers and scientists.

5. Gather evidence of progress, e.g., Learning steps versus endpoints.

As illustrated in our student workbook examples, students have many opportunities to provide evidence on their progress and the places where their efforts fall short. In this way, students and teachers have multiple opportunities to check for understanding and to provide scaffolds or guidance. Our pre- and post-instruction assessments contain a majority of constructed response items designed to be very similar to the workbook activities, but often with scaffolds removed. In Egypt, student capstone projects demonstrate many kinds of evidence of learning throughout the semester, and the final capstone project counts for 60% of the semester grade.





6. Lessons are organized sequentially, building coherence and 3D learning over lessons, units, and years.

Our curricular programs consist of six-to-eight-week units that follow a sequence outlined in the vision document, A Framework for K-12 Science Education (NRC, 2012) and the Next Generation Science Standards (NGSS Lead States, 2013). For example, student activities start with generating a question or problem, followed by data collection, data analysis, and the construction of scientific arguments or explanations. In programs developed in more recent years (e.g., Invasive Insects), the lessons toggle between science investigation activities (e.g., data collection, analysis, and argument construction) and engineering design (e.g., multiple rounds of design and building of solutions). This sequencing supports adolescents' mirroring of the work of scientists and engineers in practicing fluid and iterative design and testing solutions to realize a well-designed solution.

7. Professional scientists, engineers, and educators must collaborate to strategically simplify tools that support adolescent problem-solving in complex interdisciplinary science and engineering.

The idea of strategic simplification recognizes the necessity of carefully selecting factors in the complex interdisciplinary problem context for simplification without introducing errors. The strategic simplification allows adolescents to not only grapple with the problem but realize possible fruitful solutions. This idea is captured well by Steve Jobs when he said, "Simple can be harder than complex; you have to work hard to get your thinking clean to make it simple. But it is worth it in the end because once you get there, you can move mountains." (Steve Jobs, Business Week, 1998). A strategic simplification example from BioKIDS includes the redesign of the ADW Pocket Guide data collection tool that allowed not only student generation of a range of kinds of data on the animals and signs of animals observed in their schoolyard but also a spreadsheet that organized all of the class's observations in one document. A second strategic simplification example comes from an earlier curricular program that guided adolescents in the live tracking of hurricanes on the East Coast of the United States (see image).

8. To realize systemic change, teams must sustain their partnerships, funding, and learning activities over years or even decades.

The most challenging feature is sustaining partnerships, funding, and learning over years or even decades to realize systemic change. Instructional materials must sustain students' learning over several weeks or months to have multiple exposures and sustained engagement in sensemaking. Teachers' learning and professional development must be sustained over units and years so that teachers can take risks and make iterative improvements. Sustained learning for teachers and district leaders is also needed to moderate expectations of systematic change (it takes time and several trials). Financial investments and partners must continue so that ideas can be tested, improved, and stabilized. In BioKIDS and Egypt, our school partners and STEM faculty worked together for over a decade to realize systemic change.

Conclusions

All eight features are essential to fostering adolescents' problem-solving and designing interdisciplinary solutions. As the world's challenges with STEM foundations are complex, we must provide many varied opportunities for adolescents before college or professional careers to engage with and practice scientific investigations, engineering design, creativity, testing, critique, and sharing. Generating these solutions also requires thinking beyond traditional approaches and the narrow boundaries of current science learning. Such thinking is crucial for all our futures.

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