sharpening *STEL*

with integrated STEM

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Introduction

Standards for Technological and Engineering Literacy (*STEL*) promotes STEM education, where technology and engineering play a critical role as subject integrators. Integration of science, technology, engineering, and mathematics (STEM) in project-based learning is an ideal approach, with benefits of enhancing student learning and 21st-century competencies. Contemporary educational reform requires science and engineering practices to be integrated and suggests that this integration should be explicit (International Technology and Engineering Educators Association [ITEEA], 2020; NRC 2012). However, teachers often experience challenges while presenting STEM content using an integrative approach. For a successful implementation of integrated STEM, teachers need to be informed about how to integrate STEM contents while also using essential pedagogical approaches. This article proposes an integrated STEM lesson tited *Designing Bugs and Innovative Technology* (*D-BAIT*) as a practical and feasible model that high school STEM teachers can adopt in their classrooms. The *D-BAIT* lesson, developed by STEM researchers within a national STEM education project, teaches high school students engineering design using biomimicry, life science, and mathematics. The paper analyzes the *D-BAIT* lesson based on *STEL* and addresses how well the lesson aligns with project-based and problem-based instruction. The *D-BAIT* lesson will inform how design instruction can be blended into science and engineering practices, which will guide STEM teachers and educators to create and implement integrated STEM lessons.

> "Standards for Technological and Engineering Literacy (STEL) *is designed to help educators better understand what technology and engineering education is and how to teach it, while also highlighting the multi-disciplinarity that is at the heart of technological and engineering literacy (ITEEA, 2020, p. 5)."*

Students engage in environmental issues and design a biomimicry-inspired solution that uses scientific inquiry and engineering design thinking.

STEL promotes interdisciplinary connections between STEM subjects and upholds technology and engineering as a disciplinary integrator for integrated STEM education.

In an integrated STEM context, students are exposed to connections across STEM disciplines, where students can learn to apply the concepts to authentic real-life problems (Nadelson & Seifert, 2017; Stohlmann, Moore, & Roehrig, 2012).

By analyzing the *D-BAIT* lesson, how design instruction can be well blended into science and engineering practices and in what way problem-focused project-based learning can be implemented in an integrated STEM lesson will be discussed. The analysis focuses on how literature and educational standards describe design-based learning, problem-based learning, and project-based learning, and how the *D-BAIT* lesson incorporates these instructional strategies. The detailed lesson plan of *D-BAIT* can be downloaded from: https://www.purdue.edu/trails/*D-BAIT*/

Technology and Engineering Design in Integrated STEM

Within *STEL*, engineering design is defined as “the systematic and creative application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems” (ITEEA, 2020, p.153). This definition indicates the interdisciplinary nature of engineering design, which lends it to facilitating subject integration within integrated STEM (ITEEA, 2000; Kelley & Knowles, 2016).

Engineering design becomes a platform for STEM practice and learning in integrated STEM; engineering and technology provide students with a context where students can test their science knowledge and apply it to a real-life situation (Brown et al., 1989; Kelley & Knowles, 2016). Furthermore, educational standards indicate that engineering-design instruction in integrated STEM incorporates societal concerns in addition to other disciplinary

knowledge and skills, which helps students increase problem-solving abilities and stimulates their 21st-century competencies, such as systems thinking, creativity, optimism, collaboration, and communication (NAE and NRC, 2009; NRC, 2012; ITEEA, 2020).

> *Effective technology and engineering design demands the application of knowledge from a range of disciplines and an appreciation of the effects of a design on society and the environment. Use of this process provides opportunities to enhance and promote necessary skills in students, often referred to as the 21st Century Skills (ITEEA, 2020, p. 57).*

The New *Standards for Technological and Engineering Literacy* (*STEL*)

Technology and engineering design in integrated STEM education can enhance students’ technological and engineering literacy and 21st-century skills. *STEL* defines technological and engineering literacy as “the ability to understand, use, create, and assess the human-designed environment that is the product of technology and engineering activity” (p.8) and a technologically and engineering literate person as the one who “understands the significance of technology and engineering in everyday life” (p. 22).

STEL presents eight core disciplinary standards. For the successful application of the core disciplinary standards, *STEL* proposes Technology and Engineering Practices, which include systems thinking,

Table 1. Technology and Engineering Core Disciplinary Standards, Contexts, and Practices

Core Disciplinary Standards	Contexts	Practices
Nature and Characteristics of Technology and Engineering	Computation, Automation, Artificial Intelligence, and Robotics	Systems Thinking
Core Concepts of Technology and Engineering	Material Conversion and Processing	Creativity
Integration of Knowledge, Technologies, and Practices	Transportation and Logistics	Making and Doing
Impacts of Technology	Energy and Power	Critical Thinking
Influence of Society on Technological Development	Information and Communication	Optimism
History of Technology	The Built Environment	Collaboration
Design in Technology and Engineering Education	Medical and Health-Related Technologies	Communication
Applying, Maintaining, and Assessing Technological Products and Systems	Agricultural and Biological Technologies	Attention to Ethics

Note. Adopted from *Standards for Technological and Engineering Literacy* (ITEEA, 2020).

creativity, making and doing, critical thinking, optimism, collaboration, communication, and attention to ethics. These eight practices were adopted from the 21st-century skills suggested by a national organization, The Partnership For 21st-Century Skills [P21] (2009), and engineering habits of mind, which were proposed by the National Academy of Engineering (NAE & NRC, 2009) as essential skills for citizens in the 21st-century.

Additionally, *STEL* presented the technology and engineering contexts where the core disciplinary standards and benchmarks can be taught or applied (Table 1).

The core disciplinary standards represent information, ideas, and processes that are common to all context areas. The eight context areas replace the "Designed World" standards found in the original *STL*. Then, as now, they are meant to encompass the broad areas of technological activity in which humans are engaged (ITEEA, 2020, p.12).

Lesson Development

The lesson, *Designing Bugs and Innovative Technology* (*D-BAIT*), was developed by the integrated STEM project named *Teachers and Researchers Advancing Integrated Lessons in STEM* (*TRAILS*) (National Science Foundation [NSF] award #DRL-1513248). TRAILS was a three-year project during the 2016-2019 school years to increase STEM disciplinary knowledge of high school students and their habits of mind in these subjects (ITEEA, 2020; NRC, 2009). The *TRAILS* team developed an exemplar lesson, *D-BAIT*, to guide science and engineering technology education (ETE) teachers to learn instructional strategies in teaching integrated STEM and creating their own lessons that they can teach in their classrooms. Scientific inquiry, engineering design, biomimicry, and 3D printing technology are key elements of the *D-BAIT* lesson. Table 2 shows the lesson overview.

D-BAIT Lesson Analysis

The *D-BAIT* lesson teaches engineering design using biomimicry, life science, and mathematics, and students practiced manufacturing from this lesson through prototyping and 3D printing. Both

Table 2. Designing Bugs and Innovative Technology (D-BAIT): Unit Objectives and Standards

Age Level	15-18
Subjects	Biology, Physics, Engineering/Technology Education
Unit Objectives	Students will be able to: ▪ Observe biological processes and organisms as a source of design inspiration. ▪ Form testable hypotheses about which aquatic insects are likely fish prey and their important features. ▪ Create a decision matrix to select the best features that meet the need of the client. ▪ Create a prototype using a 3D printer and parametric modeling software and test predictions.
Next Generation Science Standards (NGSS Lead States, 2013)	▪ **LS2-3.** Ecosystems: Interactions, Energy, and Dynamics – Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions. ▪ **LS2-5.** Ecosystems: Interactions, Energy, and Dynamics – Use mathematical representations to support claims for the cycling of matter and flow of energy among organisms in an ecosystem. ▪ **LS2-6.** Ecosystems: Interactions, Energy, and Dynamics – Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem. ▪ **LS4-4.** Biological Evolution: Unity and Diversity – Construct an explanation based on evidence for how natural selection leads to adaptation of populations.
Common Core State Standards (CCSS) Math (Grade 9-12)	▪ **N-Q.3.** Choose a level of accuracy appropriate to limitations on measurement when reporting quantities. ▪ **S-IC.2.** Decide if a specified model is consistent with results from a given data-generating process, e.g., using simulation. ▪ **G-MG.3.** Apply geometric methods to solve design problems (e.g., designing an object or structure to satisfy physical constraints or minimize cost; working with typographic grid systems based on ratios).
Standards for Technological and Engineering Literacy (Grade 9-12) (ITEEA, 2020)	Students will be able to: ▪ **STEL-1Q.** Conduct research to inform intentional inventions and innovations that address specific needs and wants. ▪ **STEL-1R.** Develop a plan that incorporates knowledge from science, mathematics, and other disciplines to design or improve a technological product or system. ▪ **STEL-2X.** Cite examples of the criteria and constraints of a product or system and how they affect final design. ▪ **STEL-2Z.** Use management processes in planning, organizing, and controlling work. ▪ **STEL-7Y.** Optimize a design by addressing desired qualities within criteria and constraints. ▪ **STEL-7AA.** Illustrate principles, elements, and factors of design. ▪ **STEL-7BB.** Implement the best possible solution to a design. ▪ **TEP-6.** Collaboration: Considers and accommodates teammate skills and abilities when working to achieve design and problem-solving goals.

engineering technology education (ETE) students and biology students worked collaboratively throughout the *D-BAIT* lesson and experienced other disciplines in an integrative way.

The *D-BAIT* unit consists of 10-12 sessions. Students learned environmental science and biology for science subject learning, and insect collection was a part of the science activity. They collected aquatic insects to investigate underwater creatures to research the natural environment and ecosystem and the swimming mechanisms of underwater creatures by investigating the aquatic insects they collected. They learned about basic taxonomy and insect classification. Students also learned about neutral buoyancy and biomimicry to apply these concepts to their prototype designs, and finally, they created fishing lure samples that mimic the functions of underwater insects and satisfy neutral buoyancy (*STEL*-1Q: Conduct research to inform intentional inventions and innovations that address specific needs and wants). An Entomology graduate student visited some classrooms to teach basic entomology to the students for understanding of the insect's movement, body shape, and adaptation.

The *D-BAIT* lesson consists of: (1) entomology introductory lesson; (2) entomology field observation and collection of aquatic insects specimens; (3) analysis of the observed data using scientific inquiry and research on aquatic entomology taxonomy and food webs; (4) introduction to design and engineering design process; (5) introduction to CAD software and 3D printing; (6) design of a fishing lure using the biomimicry concept and mathematical modeling of a prototype (buoyancy concept); (7) testing and redesigning the prototype; and (8) evaluation of prototype lures.

This model teaches common STEM practices and STEM habits of mind (ITEEA, 2020; NRC, 2009). It blends scientific inquiry and engineering design and allows students to design and test innovative design solutions using parametric modeling software and 3D printing technology (*STEL*.TEP-5: Optimism). The *D-BAIT* lesson incorporates environmental science (biology), entomology, physics, and engineering technology, which provides students with a meaningful context for learning STEM.

The lesson enacts all technology and engineering practices proposed by *STEL*, including: (1) systems thinking, (2) creativity, (3) making and doing, (4) critical thinking, (5) optimism, (6) collaboration, (7) communication, and (8) attention to ethics.

First, in the *D-BAIT* lesson, students are engaged in creating fishing lures that mimic aquatic insects using 3D printing. This activity aligns with technology and engineering practice, making and doing, and while participating in the lure-designing process, students exploit systems thinking, creativity, critical thinking, and optimism. In the *D-BAIT* lesson, students need to engage in design tasks, where scientific inquiry and engineering-design practices are integrated, and develop skills that are necessary for the design process (ITEEA, 2020). Since the design process is highly iterative and open-ended, it results in many possible solutions. During the *D-BAIT* lure-design process, students "optimize a design by addressing desired qualities within criteria and constraints" (*STEL*-7Y). They also used "conceptual, graphical, virtual, mathematical, and physical modeling to identify conflicting considerations before the entire system is developed and to aid in design decision making" (*STEL*-2T).

Kelley and Kellam (2009) noted that "systems thinking is required for solving open-ended and ill-structured problems that society faces today and such problems are prevalent in engineering design projects" (p.38). *D-BAIT* uses a "constructivist approach to teaching systems thinking within a team or group-learning environment" (Kelley & Kellam, 2009, p.40). According to Mehalik, Doppelt, and Schuun (2008), a systems design approach is an effective teaching strategy that helps students engage and gain achievement in learning. By having students research about aquatic habitats and determine water quality as indicated by insects, *D-BAIT* motivates students to begin the activity with their own needs and organize and follow the sequence of design activity, which is identified as a systems-design approach (Mehalik et al., 2008).

For a learning activity to be project-based, the project should be student-driven, a real-life challenge, central to the curriculum, focused on a driving question that derives conceptual knowledge, and involve students in a constructive investigation (Thomas, 2000). The *D-BAIT* lesson satisfies all these criteria. In the *D-BAIT* lesson, students use "management processes in planning, organizing, and controlling work" (*STEL*-2Z). They also "develop a plan that incorporates knowledge from science, mathematics, and other disciplines to design or improve a technological product or system" (*STEL*-1R). Moreover, they actively participate in the project, which is central to the curriculum and exposes students to a real-life situation.

Furthermore, the *D-BAIT* project is an authentic, real-life problem-solving activity. Students engage in environmental issues and design a biomimicry-inspired solution that uses scientific inquiry and engineering-design thinking. Researchers argue that teaching

problem-solving skills through inquiry-based real-world problems and enhancing design thinking are the most important issues in engineering-design education (Jonassen, Strobel, & Lee, 2006). By placing learners in real situation problems that they will confront in the future, engineering education can successfully prepare a competent workforce.

For the successful STEM education, Moore and colleagues (2014) proposed six major tenets: (1) motivating and engaging context; (2) mathematics and science inclusion in the context; (3) student-centered pedagogies; (4) engineering design concept; (5) teamwork and communication; (6) learning through failure and redesign (Moore et al., 2014). The *D-BAIT* lesson follows these criteria within a problem-solving and project-based context and educates students to be able to use what they learn to make decisions and solve problems in a new situation.

Lesson Implementation

To design a lure prototype, students used the CAD software program and a 3D printer. Most of the prototyping and printing parts needed engineering technology students' knowledge and skills. Biology students worked with engineering students to combine scientific inquiry with engineering design. Both biology and engineering technology teachers' different expertise were integrated into their instructions. The students considered and accommodated teammate skills and abilities when working to achieve design and problem-solving goals (TEP-6 Collaboration).

The instructional design of the TRAILS project, the *D-BAIT* lesson, also facilitated collaboration and communication skills of teachers. From classroom observations, some teacher pairs were identified to teach the *D-BAIT* lesson together throughout the unit. For the entirety of the *D-BAIT* lesson, a science teacher and an engineering teacher combined the two classes and taught not only their subjects but also the partner teacher's subjects. These teachers collaborated and communicated during the classes as well as before and after them. Even though they are teachers of different subjects, they emphasized the integration of other disciplines and constantly reminded the students of what they would learn and why they were learning together with the class of another subject. Other teacher pairs taught the *D-BAIT* lesson separately. In this case, the science teacher and the engineering teacher switched the classes and the students as needed to teach their subjects to the students of other subjects.

Student collaboration, as well as teacher collaboration, was also critical. Two to three biology students and two to three engineering technology students were grouped to work together for learning the subject knowledge, brainstorming, researching, designing the prototype, testing, evaluating, and redesigning (*STEL*-7BB: Implement the best possible solution to a design). So, the student design teams were interdisciplinary. However, in most schools, 3D printing was done only by engineering technology students. Students participated in both science and engineering practices by learning biology and technology concepts necessary to design and create the fishing lure design. Whenever requested, TRAILS researchers visited the classes on the final presentation day or field day of the fishing lure prototype testing day to give feedback.

Discussion

STEL defines the role of technology and engineering in STEM education as a subject integrator and emphasizes technology and engineering education in integrated STEM (ITEEA, 2020).

> STEL *operates from the premise that the integrated approach suggested by "STEM" is an important one and may be necessary for achieving the kind of functional literacy needed to solve our pressing societal needs.* STEL *further recognizes that technology and engineering are critical to, and must be better articulated within, STEM (ITEEA, 2000, p. 17).*

For a successful implementation of integrated STEM, teachers need to be supported with well-structured lessons that they could modify to implement, and guided by feasible instructional strategies that they could use.

Wang and colleagues (2011) claimed that STEM integration is a type of curriculum and noted that the idea of curriculum integration is derived from educators' awareness that real-world problems are not separated into isolated disciplines taught in schools. Real-world problem-solving skills cannot be taught in silos, but as Wang et al. (2011) noted, STEM integration is not just a matter of merely combining different subjects. Still, it also demands further knowledge and skills from teachers, researchers, and curriculum developers. To teach integrated STEM effectively and explicitly, how integrated STEM lessons could be delivered to the classrooms should be further researched.

Technology and engineering education involves hands-on, design-based strategies that provide students with authentic experiences of project and problem-based learning. Project-based learning is one of the key strategies of an integrated STEM lesson. The TRAILS team modified the *D-BAIT* lesson several times to connect the disciplines throughout the unit rather than teach each subject in silos, and this was possible using a project-based instruction.

STEM integration has impacts on students' content knowledge learning, problem-solving skills, and real-world application abilities. However, it still requires further research on how to integrate subjects and how to develop strategies that teachers can adopt. Teacher education may provide teachers with an opportunity to enhance their abilities to integrate STEM and awareness of connectedness between the subjects.

Finally, increasing teacher collaboration is critical for a successful implementation of integrated STEM within an authentic project-based learning environment. In an integrated STEM context, teachers can enhance their instruction with the help of teachers from other disciplines and by communicating with them (Brown, Brown, & Merrill, 2011). For the purpose of professional development, TRAILS will provide educators and researchers with a practical model of integrated STEM teacher education.

Resources

- *D-BAIT* unit plan can be downloaded from: www.purdue.edu/trails/D-BAIT/
- More lesson plans are available on the TRAILS official website: www.purdue.edu/trails/

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