THE IMPACT OF INTEGRATED STEM INSTRUCTION ON STUDENTS' ENGINEERING DESIGN LEARNING AND 21ST CENTURY SKILLS

by

Jung Han

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Todd R. Kelley, Chair

Department of Technology Leadership and Innovation

Dr. Nathan Mentzer

Department of Technology Leadership and Innovation

Dr. Greg J. Strimel

Department of Technology Leadership and Innovation

Dr. J. Geoff Knowles

Bryan College

Dr. Scott Bartholomew

Brigham Young University

Approved by:

Dr. Kathryne A. Newton

This dissertation is dedicated to my savior God.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CCSS	Common Core State Standards
CoP	Community of Practice
CTA	Concurrent Think-Aloud
ET	Engineering Technology
ETE	Engineering and Technology Education
ETTE	Engineering and Technology Teacher Education
ITEEA	International Technology and Engineering Educators Association
STEM	Science, Technology, Engineering, and Mathematics
NAE	National Academy of Engineering
NGSS	Next Generation Science Standards
NRC	National Research Council
NSF	National Science Foundation
STEL	Standards for Technological and Engineering Literacy
TRAILS	Teachers and Researchers Advancing Integrated Lessons in STEM

ABSTRACT

Educational reform challenges teachers to integrate science and engineering practices in teaching the contents (Next Generation Science Standards [NGSS] Lead States, 2013; National Research Council [NRC], 2012; Lotter, Carnes, Marshall, Hoppmann, Kiernan, Barth, & Smith, 2020). However, research that reports teachers' experiences in implementing integrated STEM is limited (Dare, Ellis, Roehrig, 2018).

Intending to advance integrated STEM education through providing a practical and replicable model for schools to integrate STEM learning, this study was conducted to investigate the project *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS)*. TRAILS was a three-year project funded by National Science Foundation (NSF) (Award #DRL-1513248), which lasted during the 2016-2019 school years. A total of 30 high school science and engineering technology teachers participated in the TRAILS project for 1-3 years as an experimental group. This group of teachers participated in a two-week summer professional development and learned ways to integrate STEM knowledge and skills through their instruction. During the following school year, teachers implemented integrated STEM lessons that included science and engineering practices, through which 1157 experimental group students were exposed to an authentic, real-world STEM context. The comparison group included 18 STEM teachers and 877 students from similar environments, but they did not participate in the project and only took the surveys.

The study presented here consists of three sub-studies, which are separate from each other in research questions but connected as one larger study that explored the impact of integrated STEM instruction on students' STEM learning and 21st century skills. The first study focused on the impacts of the TRAILS model, which integrates STEM through shared practices, on student design cognition. The second study examined how teachers' self-efficacy in teaching STEM influenced students' academic achievement, 21st century skills, and STEM career awareness. The third study explored the sustainability of the TRAILS model by examining the STEM classes after the funded project ended.

The results revealed that science and engineering practices within the STEM context impacted student design cognition collectively, and teachers' self-efficacy in teaching STEM influenced students' academic performance, STEM career awareness, and 21st century skills positively. Additionally, the teachers who participated in the TRAILS project for multiple years

maintained their effectiveness in integrated STEM teaching after the project ended as measured by students' academic performances. The students also showed increases in their confidence in critical thinking, which is one of the skills needed in the 21st century.

In summary, this study supports that integrated STEM instruction enhances student engineering design learning and their 21st century skills. TRAILS provided a practical model of integrated STEM education, where teachers can increase STEM teaching efficacy and knowledge and skills to integrate STEM through professional development and community of practice. The present study suggests researchers and educators provide teachers with adequate supports, which include investing in professional developments, creating Communities of Practice (CoP), and developing instructional models of integrated STEM, for the successful implementation of integrated STEM in secondary schools.

CHAPTER 1. INTRODUCTION

1.1 Introduction

In the STEM education field, researchers and educational standards emphasize both inquiry and design and challenge teachers to integrate science and engineering in teaching the contents (NGSS Lead States, 2013; NRC, 2012). The Framework for K-12 Science Education (NRC, 2012) noted that participation in science and engineering practices helps students understand crosscutting concepts of science and engineering, which helps students acquire more meaningful worldviews. Moreover, shared practices across the STEM disciplines have been shown to increase students' skills that are necessary to advance in the 21st century, which include critical thinking, collaboration, communication, and creativity (Kelley & Knowles, 2016; Wang, Moore, Roehrig, & Park, 2011). However, the empirical studies that support the theoretical framework and construct instructional models based on teachers' real practices in their classrooms are insufficient (Dare et al., 2018; Kelley, Knowles, Han, & Trice, 2021; Pearson, 2017). Therefore, this study examined the integrated STEM project *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS)* as an empirical model of integrated STEM instruction aiming to provide STEM teachers and educators with practical and feasible approaches to support student learning in STEM (NRC, 2014; Ntemengwa & Oliver, 2018).

The goals of the TRAILS were: "1) engage in-service science and technology teachers in professional development building STEM knowledge and practices to enhance integrated STEM instruction; 2) establish a sustainable community of practice of STEM teachers, researchers, industry partners, and college student learning assistants; 3) engage grades 9-12 students in STEM learning through engineering design and 3D printing technology, and; 4) generate strategies to overcome identified barriers for high school students in rural schools and underserved populations to pursue careers in STEM fields" (TRAILS, unpublished document).

The TRAILS model specifically employed biomimicry, 3D printing, science inquiry, and engineering design as key features, where engineering design was used as a subject integrator. Focusing on the impact of the TRAILS model, three sub-studies were conducted to: 1) explore how integrated STEM instruction influences student design cognition; 2) identify the impacts of teacher self-efficacy on students' academic achievement, 21st century skills, STEM attitude, and

STEM career awareness, and; 3) investigate the STEM classes after the project ended (see Figure 1.1).

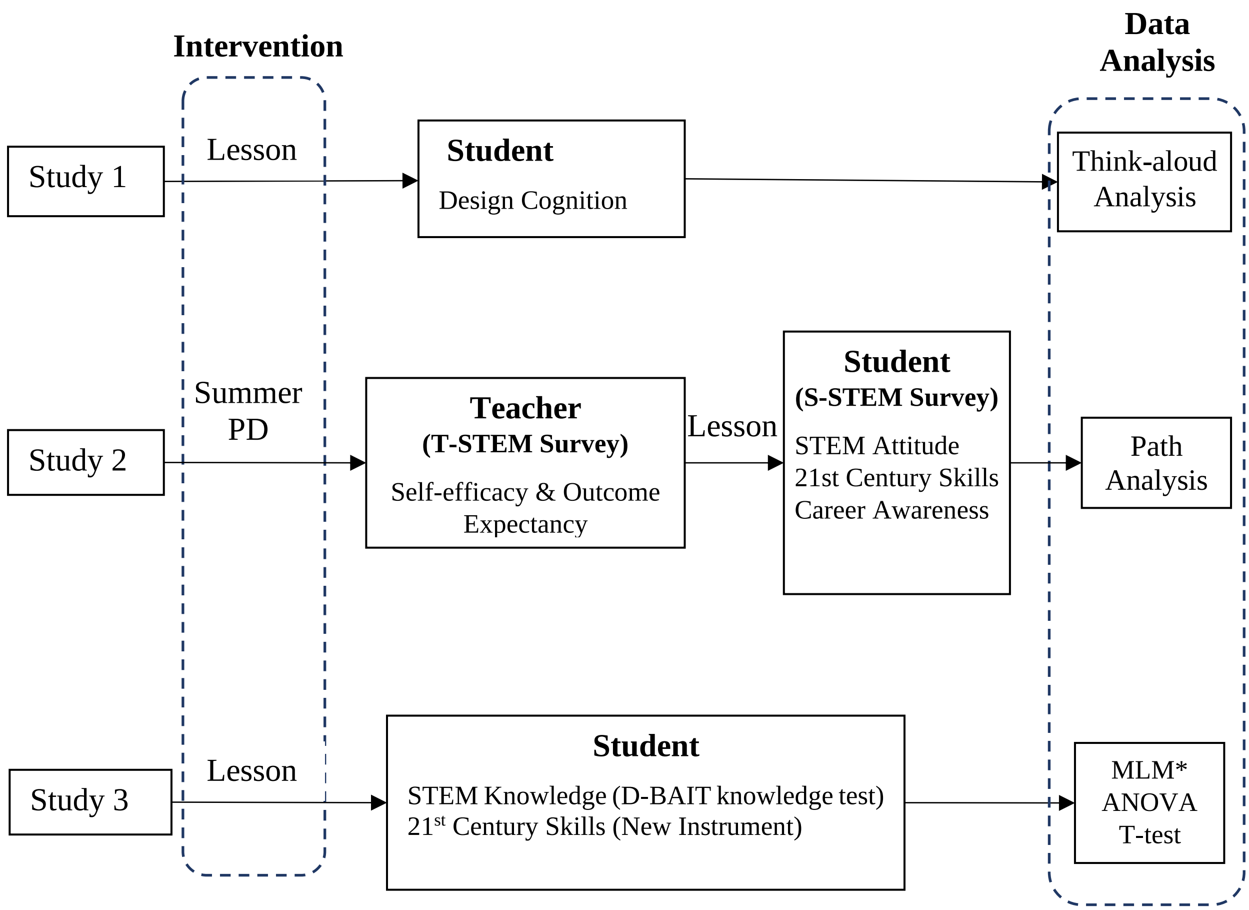

Figure 1.1. Impact of integrated STEM education. *MLM denotes Multilevel Modeling analysis.

1.2 Research Questions

The study consists of three experimental studies in the TRAILS context. The research questions for each sub-study are the following.

Study 1: STEM Integration through Shared Practices: Examining Secondary Science and Engineering Technology students' Concurrent Think-Aloud Protocols

This study investigated how scientific inquiry and engineering design shared practices promote high school students' design thinking and problem-solving skills. The study was guided by the following overarching research question and three sub-questions.

Overarching Question: During Concurrent Think-Aloud (CTA) protocol sessions, do secondary science and engineering students blend science and engineering shared practices during engineering design?

1. Do students from two different disciplines (Engineering Technology [ET] and Biology) use different design strategies during engineering design? If so, how different are those of the two groups (ET and Biology)?
2. Do students from two different disciplines (Engineering Technology [ET] and Biology) apply domain-specific knowledge and practices differently during engineering design?
3. Do students from two different disciplines (ET and Biology) demonstrate transitional patterns of design strategies differently during engineering design? If so, how different are those of the two groups (ET and Biology)?

Study 2: Factors Influence on Student STEM Learning: Teacher Self-efficacy, Student Attitude, 21st Century Skills, and Career Awareness

This investigated the factors influencing student STEM learning and examine if teacher self-efficacy and outcome expectancy beliefs affect student attitudes (self-efficacy and expectancy-value beliefs) and academic achievements in integrated STEM. The study was guided by two research questions:

1. Are teacher self-efficacy and outcome expectancy, student STEM attitudes, 21st century skills, and STEM career awareness positively associated with student STEM knowledge achievement?
2. Are there any direct and indirect effects of teacher self-efficacy and outcome expectancy on students' STEM attitudes, 21st century skills, and STEM career awareness?

Study 3: Building a Sustainable Model of Integrated STEM: Investigating Secondary School STEM Classes after Integrated STEM Project

This study investigated how teachers implement integrated STEM as a sustainable education program after participating in an integrated STEM project. To investigate whether the teachers positively influenced the academic achievements and 21st century skills of students after the conclusion of the funded program, this study had three research questions:

1. Are the students' (Year 4) STEM knowledge achievements different from those of the students (Year 1, 2, 3) who participated in the TRAILS project with program support?
2. Did the three sample teachers' students from the current year (Year 4, after program funding ended) and from previous years (Year 1, 2, 3) show the difference in their STEM knowledge achievement?
3. Did the three sample teachers' students from the current year (Year 4, after program funding ended) increase or decrease their confidence in their 21st century skills after learning integrated STEM? If so, how did they increase or decrease their 21st century skills?

1.3 Scope

The study's main goal was to identify the effectiveness of integrated STEM by investigating the impact of integrated STEM instruction on student learning and their 21st century skills.

For Study 1, which was to determine the impact of the integrated STEM instruction on student design cognition, the Concurrent Think-Aloud (CTA) protocol was employed.

For Study 2, to examine the impact of the TRAILS approach to integrate STEM on teacher self-efficacy and student learning in STEM, teacher surveys, student surveys, and student STEM knowledge tests were administered and analyzed. The assessment instruments were Teacher Efficacy and Attitudes toward STEM (T-STEM) Survey (Friday Institute for Educational Innovation, T-STEM, 201b), Student Efficacy and Attitudes toward STEM (S-STEM) Survey (Friday Institute for Educational Innovation, T-STEM, 2012a), and the *D-BAIT* STEM Knowledge Test.

For Study 3, three teachers from two schools, who implemented the integrated STEM lessons again after the TRAILS project ended, participated in the study. The *D-BAIT* STEM Knowledge Test and Student 21st Century Skills Survey (Kelley, Knowles, Han, & Sung, 2019) were conducted to investigate if the teachers maintain the effectiveness of teaching integrated STEM after the TRAILS project.

1.4 Significance

Educational reform demands teachers to integrate science and engineering practice in teaching the contents (NGSS Lead States, 2013; NRC, 2012; Lotter et al., 2020). However, blending cross-cutting concepts and creating instructional strategies that cut across the different disciplines are complex. Therefore, teachers need to be supported with well-structured lessons, which they could modify to implement, and guided by feasible instructional strategies that they could use (Wang et al., 2011).

For successful implementation of integrated STEM, engineering design-focused and project-based instruction are recommended (Asunda, 2012; International Technology and Engineering Educators Association [ITEEA], 2000; Kelley, Brenner, & Pieper, 2010; Kelley & Knowles, 2016; Mentzer, 2014; Sanders, 2012; Wang et al., 2011). Increasing teachers' awareness of integrated STEM and their teaching efficacies is also required since teachers' perceptions and beliefs impact their classroom practices (Kelley, Knowles, Holland, & Han, 2020). To enhance confidence in teaching integrated STEM, teachers should understand the multiple aspects of integrated STEM education supported by empirical evidence (Wang et al., 2011).

This study investigated the TRAILS model as a practical and feasible approach to support student learning in STEM (NRC, 2014; Ntemengwa & Oliver, 2018). The study demonstrates the impacts of integrated STEM instruction on students' design learning and 21st century skills through empirical evidence. The study will inform STEM teachers and educators of the effectiveness of science and engineering shared practices by exploring key features of TRAILS and shares perspectives and experiences of STEM teachers, which will help teachers determine the best approach to STEM integration in their classrooms, and suggests the collaboration of teachers and researchers to enhance integrated STEM education.

1.5 Assumptions

The assumptions for this study were:

1. The environments where surveys were implemented were the same.

2. Teachers and students responded to the surveys truthfully.
3. The surveys and knowledge tests are accurate measurement tools.
4. Teachers implemented TRAILS lessons truthfully including all key concepts of TRAILS.

1.6 Limitations

Some limitations of this study are:

1. Teacher samples are relatively small to generalize the results.
2. Survey responses were not reliable.
3. Likert-type surveys are not accurate measurement tools.
4. Teacher's teaching ability and school environment may influence survey results.

1.7 Delimitations

Below are the delimitations that this study includes:

1. The samples were collected only from Midwestern area.
2. Years of teaching and teaching skills are different by teachers.
3. Schools of urban areas were excluded for the purpose of the study. Most of the schools were located in rural areas, but some schools are in cities or suburban areas.

1.8 Definitions of Key Terms

Below are the important concepts of this study and the definitions:

<u>Integrated STEM Education</u>: Kelley and Knowles (2016) defined integrated STEM (science, technology, engineering, mathematics) education as "the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning" (p. 3). Similarly, Ntemngwa and Oliver (2017) defined integrated STEM instruction as "a pedagogical approach in which concepts and objectives from two or more STEM disciplines are incorporated into a single project" (p. 12).

Teacher Self-efficacy: Yoon, Evans, and Strobel (2012) defined teacher self-efficacy as "their personal belief in their abilities to positively affect students for educational attainments" (p. 26) and insisted on the importance of teacher training as teacher self-efficacy relates to their classroom behaviors, which can influence student learning.

Engineering Design: Engineering design is "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 103).

Technological and Engineering Literacy: The Standards for Technological and Engineering Literacy (STEL) (ITEEA, 2000) define technological literacy as "the ability to understand, use, create, and assess the human-designed environment in increasingly sophisticated ways over time" (p. 161).

21st Century Skills: "The P21 framework organizes 21st century skills in three basic categories: a) life and career skills; b) learning and innovation skills, and c) information, media, and technology skills. The P21 framework goes on to define these basic categories. In the learning and innovation skills category, one finds the four Cs of 21st century skills that are: a) creativity; b) critical thinking; c) communication; and d) collaboration. The following article will focus on the development of a 21st century skills survey instrument to assess students' skills within learning and innovation skills as defined by the P21 framework." (Partnership for 21st Century Skills [P21], 2009)

1.9 Participants

A total of 30 high school STEM teachers (15 science teachers, 15 Engineering Technology Education [ETE] teachers) participated in the summer professional development, and 1157 of high school students (experimental group) experienced an integrated STEM project in 46 classrooms (23 science classrooms, 23 ETE classrooms). Additionally, 18 STEM teachers (9 science teachers, 9 ETE teachers) and 877 students (449 science students, 428 ETE students) from similar school environments participated in the project as a comparison group (see Table 1.1).

Table 1.1. TRAILS Participant Students (2016-2019)

		Science	ETE	Total
Experimental	Year 1	104	142	246
	Year 2	263	115	378
	Year 3	337	196	533
	Total	704	453	1157
Comparison	Year 1	286	195	481
	Year 2	163	233	396
	Total	449	428	877

Final data from the students, who submitted the IRB consent forms from both parents and themselves, are shown in Table 1.2. There is no missing data included in the data set.

Table 1.2 Final Student Data Collection (2016-2019)

	Gender		**Ethnicity**						**Grade**					**Sum**
	Male	**Female**	**White**	**Black**	**Hispanic**	**Asian**	**Multi**	**Others**	**8**	**9**	**10**	**11**	**12**	
Exp*	605 (62%)	373 (38%)	822 (84%)	32 (3%)	78 (8%)	31 (3%)	11 (1%)	4 (0%)	6 (1%)	270 (28%)	206 (21%)	278 (28%)	218 (22%)	978 (100%)
Com**	234 (64%)	133 (36%)	264 (72%)	29 (8%)	62 (17%)	6 (2%)	6 (2%)	0 (0%)	0 (0%)	220 (60%)	66 (18%)	49 (13%)	32 (9%)	367 (100%)
Sum	839 (62%)	506 (38%)	1086 (81%)	61 (5%)	140 (10%)	37 (3%)	17 (1%)	4 (0%)	6 (0%)	490 (36%)	272 (20%)	327 (24%)	250 (19%)	1345 (100%)

*Note: the students, who did not submit IRB consent forms, were excluded from the final data collection. * denotes experimental group. **denotes comparison group.*

1.10 Summary

This study was conducted to examine the integrated STEM project *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS)* to provide empirical evidence of the effectiveness of integrated STEM. The key concepts of the TRAILS project included scientific inquiry, engineering design, biomimicry, and 3D printing technology. The TRAILS lesson used inquiry-based engineering design instruction that exposes students to authentic situated context.

The study consists of the three sub-studies. The first study focused on student design cognition using the Concurrent Think-Aloud (CTA) protocol analysis. The second study examined how the TRAILS model increased teacher self-efficacy in teaching STEM through professional development and how teachers' increased self-efficacies impact students' STEM learning. Path analysis was used to identify the relationships among teacher self-efficacy, students' academic achievement, STEM attitude, career awareness, and 21st century skills. Finally, the third study explored the impact of integrated STEM instruction on student 21st century skills and examined the sustainability of the TRAILS model to see if it is a replicable and repeatable model. T-tests were employed to examine if the students increased their 21st century skills after the integrated STEM lesson. Multilevel Modeling (MLM) analysis was also conducted to compare the academic performances of the current teachers' students to those from the previous TRAILS classes.

The study of the TRAILS project will help provide a better understanding of integrated STEM instruction on student learning and 21st century skills as well as provide teachers and educators with an instructional model for STEM integration that can be implemented in secondary schools.

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CHAPTER 2. (STUDY 1) STEM INTEGRATION THROUGH SHARED PRACTICES: EXAMINING SECONDARY SCIENCE AND ENGINEERING TECHNOLOGY STUDENTS' CONCURRENT THINK-ALOUD PROTOCOLS

A version of this chapter is accepted into The Journal of Engineering Design. Han, J. & Kelley, T. R. (2021). STEM Integration through Shared Practices: Examining Secondary Science and Engineering Technology students' Concurrent Think-Aloud Protocols. *Journal of Engineering Design.*

2.1 Abstract

To address the complete vision of the Next Generation Science Standards (NGSS Lead States, 2013) of the United States, the research focused on how scientific inquiry and engineering design shared practices promote design thinking and problem-solving skills. High school science and engineering technology students participated in the integrated STEM project, *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS)*, and learned engineering design-based integrated STEM lesson, *Designing Bugs and Innovative Technology* (*D-BAIT*). After each lesson implementation, triads of students from each class participated in a Concurrent Think-Aloud (CTA) protocol session. During the protocol session, the triads of students engaged in a design task as a team and discussed to solve a transfer problem, which required the application of STEM knowledge from the integrated STEM lesson. A total of 27 Think-Aloud datasets were collected and analyzed from the 2017-2019 school years. Data analysis captured percentages of time dedicated to each category of TRAILS key concepts, including scientific inquiry, biomimicry, and engineering design. Transitional diagrams were also generated to show the transitions between scientific inquiry, biomimicry, and engineering design. The results show that key features emerged from the dialogue of both groups (engineering technology and Biology students). Additionally, patterns from the cognitive protocols suggest that both groups used similar approaches to solving the engineering design problem.

Key words: design cognition, integrated STEM, concurrent think-aloud protocol, shared practice

2.2 Introduction

The debates surrounding the STEM workforce shortage in the United States intensified the needs to fortify this workforce, which can be accomplished through education that enhances the STEM career awareness of individuals (Camilli & Hira, 2019). In consideration of this trend, the National Research Council (NRC) developed the Framework for K–12 Science Education, which became the foundation for the Next Generation Science Standards (NGSS) of the United States. The framework was developed with extensive research on existing national documents, such as Science for All Americans (American Association for the Advancement of Science [AAAS], 1990), Benchmarks for Science Literacy (AAAS, 1994) and the National Science Education Standard (NRC, 1996). This framework and NGSS stress the infusion of engineering design into science education as the core idea and highlight the imperativeness of the shared practices of engineering and science in K-12 education (NRC, 2012; Grubbs & Strimel, 2015). Specifically, the framework uses 'the term practices instead of a term such as skills to stress that engaging in scientific inquiry [and engineering design] requires not only skills but also knowledge that is specific to each practice' (NRC, 2012, p. 30). In the framework, the importance of science and engineering practices are discussed as the following:

> Engaging in the practices of science helps students understand how scientific knowledge develops; such direct involvement gives them an appreciation of the wide range of approaches that are used to investigate, model, and explain the world. Engaging in the practices of engineering likewise helps students understand the work of engineers, as well as the links between engineering and science. Participation in these practices also helps students form an understanding of the crosscutting concepts and disciplinary ideas of science and engineering; moreover, it makes students' knowledge more meaningful and embeds it more deeply into their worldview (p. 42).

Engineering design-based instruction boosts multidisciplinary problem-solving skills and interdisciplinary and transdisciplinary collaboration (Dorst, 2015; Helmane & Briška, 2017). Since engineering design is naturally a multidisciplinary problem-solving process, which requires integrated knowledge and multiple perspectives (Dorst, 2015), students enhance problem-solving abilities while thinking like engineers to develop a solution for clients (NRC 2009, 2012). Particularly, during iterative engineering thought processes in design-based integrated STEM education, students can connect science and mathematics concepts and develop scientific and mathematical reasoning (Crismond, 2001; Guzey, Moore, & Harwell, 2016).

However, despite researchers and US educational standards stressing engineering-based instruction and science and engineering shared practices in STEM education, research on the effects that educational innovation has on the student problem-solving process, which occurs during engineering design, is limited. Moreover, problem-solving strategies may be different between science and engineering students; Lawson (1979) compared the strategies of design students and those of science students, finding that the strategies of science students were more problem-focused whereas those of architecture students were more solution-focused. Therefore, aiming to examine the influence of science and engineering practices on student design cognition and problem-solving, this study explores how the TRAILS model - blending science and engineering shared practices including scientific inquiry, biomimicry, 3D printing, and engineering design - promotes student design thinking in an integrated STEM unit context.

The current study was conducted under the integrated STEM project named *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS)* [National Science Foundation, award # DRL – 1513248]. TRAILS STEM units brought high school science and engineering technology (ET) students together to learn STEM lessons to design and test innovative engineering design solutions (International Technology and Engineering Education Association [ITEEA], 2020). TRAILS aimed to advance students' learning of STEM content and career awareness and prepared them as a possible new generation of STEM experts and problem solvers. Science and engineering technology (ET) teachers, along with STEM researchers in the TRAILS project developed integrated STEM lessons and created design tasks that were tailored to each lesson.

We hypothesized that students from different domains may have different knowledge, which can be manifested during shared practices. With this assumption, we collected CTA protocol data to investigate the student design process pattern during the inquiry-based design tasks.

2.2.1 Situated Learning and Inquiry-based Learning

Inquiry-based learning engages students in an authentic situated scientific problem-solving process. While engaging in inquiry-based learning, students experience inquiry phases, which include Orientation, Conceptualization, Investigation, Conclusion, and Discussion (Pedaste et al., 2015). In their article, A Conceptual Framework for Integrated STEM Education, Kelley and Knowles (2016) advocated inquiry-based learning that is situated in an authentic context.

> Often when learning is grounded within a situated context, learning is authentic and, therefore representative of an experience found in actual STEM practice. When considering integrating STEM content, engineering design can become the situated context and the platform for STEM learning (Kelley & Knowles, 2016, p. 4).

2.2.2 Design-based Learning in Education

Design-based instruction is embraced in STEM education for advancing student abilities to solve complex, real-world problems of the future (Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Purzer, Goldstein, Adams, Xie, & Nourian, 2015). The engineering design process is used as an effective process for project-based problem-solving activities in STEM learning (Fortus et al., 2005). Moreover, the decision-making process in a design activity has been shown to enhance 21st century skills of students, such as critical thinking, creativity, communication, teamwork, and so on (Bekker, Bakker, Douma, Van Der Poel, & Scheltenaar, 2015).

Design problems are advocated among educators for their ill-structured and complex nature. They are situated, task-specific, and require integrated knowledge, which are optimal for students to improve their problem-solving skills (Fortuset al., 2005; Jonassen, 2000; Nadelson & Seifert, 2017). Consequently, in recent years there have been strong urges for “the shift to a more ill-structured problem-based curriculum” that helps students enhance their problem-solving abilities (Nadelson & Seifert, 2017, p. 223).

2.2.3 Design-based Instruction for Learning Transfer: Science and Engineering Shared Practices

Design process can be applied to situated learning, and educational experiences in this process promote learning transfer in meaningful ways (Pearson, 2017). In an integrated STEM practice, “engineering design allows students to build upon their own experiences and provide opportunities to construct new science and math knowledge through design analysis and scientific investigation” (Kelley & Knowles, 2016, p. 5). The NGSS combine science and engineering practices and integrate engineering design throughout the document (NGSS Lead States, 2013). The eight practices of science and engineering are: 1) Asking questions (for science) and defining problems (for engineering); 2) Developing and using models; 3) Planning and carrying out investigations; 4) Analyzing and interpreting data; 5) Using mathematics and computational thinking; 6) Constructing explanations (for science) and designing solutions (for engineering); 7) Engaging in argument from evidence, and; 8) Obtaining, evaluating, and communicating information (NGSS Lead States, 2013; NRC, 2012). Figure 2.1 illustrates the relationship between situated learning, engineering practice (engineering design), and science practice (scientific inquiry). In Figure 2.1, authentic design tasks provide students with situated learning contexts as a driving gear, which have students engage in engineering design (engineering practices) using scientific inquiry (science practices). Mathematical analysis is used as a part of the analytic engineering design process (Kelley, 2010).

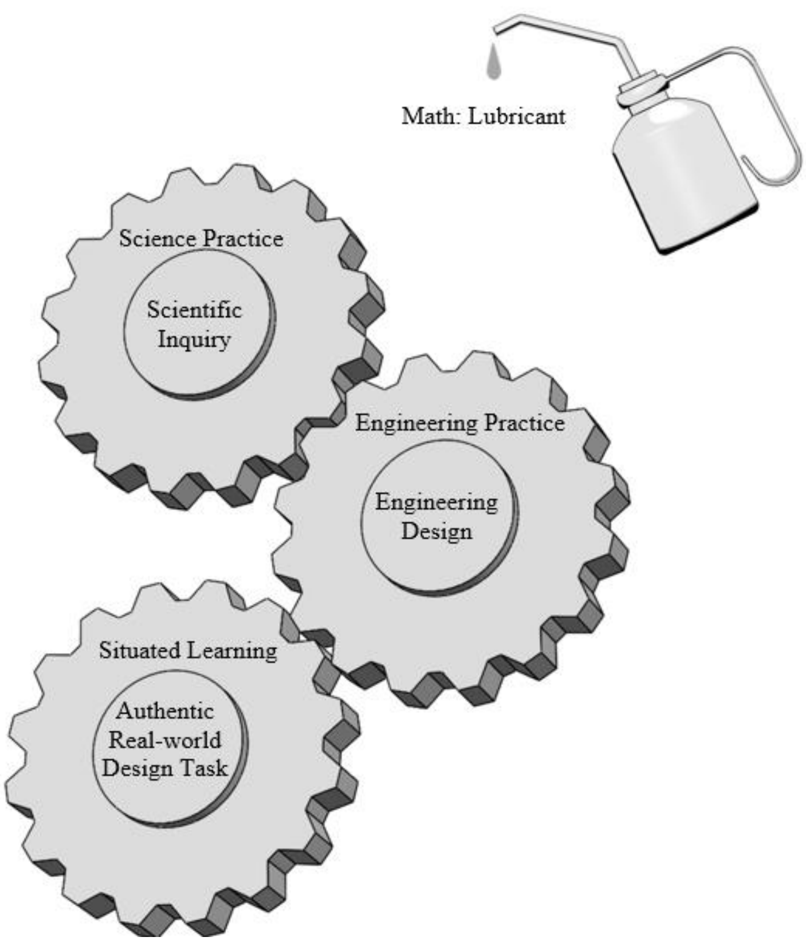

Figure 2.1. Relationship between situated learning, engineering practice (engineering design), and science practice (scientific inquiry) (Kelley, 2010, reproduced by Andrew Joon Cha, 2020).

Engineering design is an iterative and open-ended process, which provides a meaningful context for learning scientific, mathematical, and technological concepts (NGSS Lead States, 2013). Engineering design-based instruction in STEM education enables students not only to gain fundamental knowledge but also to apply knowledge to new contexts. Moreover, engineering design-based approach in STEM education stimulates students' 21st century skills, such as systems thinking, creativity, optimism, collaboration, and communication (NRC, 2009, 2012). For the current study, science and engineering technology teachers were challenged to promote students' 21st century skills by engaging them in an engineering design project in design teams, where science and engineering technology students collaborated.

In summary, design-based instruction can provide a context for students to develop and test scientific knowledge and apply it to practical problems in our world (NGSS Lead States, 2013; NRC, 2012).

2.2.4 Scientific Inquiry and Engineering Design

Scientific inquiry, engineering design, biomimicry, and 3D printing are key features of the TRAILS model. The study explores how inquiry-based learning supported by biomimicry concepts impact students' design thinking and how shared practices of science and engineering influence students' engineering design dialogue while they engage in a transfer problem using a design brief (see Figure 2.4). The transfer problem is ill-defined, providing students with real-world problem-solving situations that they can use the scientific knowledge learned from the integrated STEM lesson to solve the engineering design problem (Fortus et al., 2005).

Traditional science teaching has included the scientific method requiring "hypothesis generation and testing, deductive and inductive logic, parsimony and science's presuppositions, domain, and limits" (Gauch Jr., 2003, p. 1). In contrast, scientific inquiry involves a greater understanding of the nature of science (Bybee, 2006). "Students will engage in selected aspects of inquiry as they learn the scientific way of knowing the natural world, but they also should develop the capacity to conduct complete inquiries" (NRC, 1996, p. 23). Recent trends in science education advocate for inquiry-based experiences helping students understand how scientists think and conduct research. Therefore, K-12 science educators have moved away from using a traditional scientific method, towards open-ended inquiry creating a new paradigm of science education. (Windschitl, Thompson, & Braaten, 2008). While involving in scientific inquiry, students will gather information, analyze data, predict an answer, consider alternative results, repose the question, and repeat, all of which need iterative research and thinking processes. Table 1 displays the core elements of scientific inquiry (NRC, 1996, p. 23).

Table 2.1. Topics of inquiry proposed by the National Science Education Standards (NRC, 1996, p. 23).

Inquiry involves:	**Inquiry requires:**
• Making observations. • Posing questions. • Examining books and other sources of information to see what is already known. • Planning investigations. • Reviewing what is already known in light of experimental evidence. • Using tools to gather, analyze, and interpret data. • Proposing answers, explanations, and predictions; and communicating the results.	• Identification of assumptions. • Use of critical and logical thinking. • Consideration of alternative explanations.

Interestingly, engineering and design education, like science education, also had traditional design models that were concrete sequential, suggesting that designers move through a step-by-step process when in reality design is also iterative, open-ended, and can be informed by numerical data. Therefore, both engineering and science educators have been challenged to remove old process models and embrace new approaches to teaching authentic design and science (Lawson, 2006). benefit by learning how real engineers and technologist create new technology and how scientists uncover new science discoveries (ITEEA, 2020; NGSS Lead States, 2013).

2.3 Research Questions

Research on students' design thinking strategies and cognitive processes while engaging in the design practices has been increasing to provide deeper insights into student design cognition (Strimel et al. 2020). This research seeks to better understand high school science and engineering technology students' design capabilities and cognitive processes after experiencing science and engineering shared practices. According to Lawson (1979), to observe if shared practices influenced science and engineering students' engineering design cognitive processes differently, the study was guided by the following overarching research question and three sub-questions.

Overarching Question: During Concurrent Think-Aloud (CTA) protocol sessions, do secondary science and engineering students blend science and engineering shared practices during engineering design?

1. Do students from two different disciplines (Engineering Technology [ET] and Biology) use different design strategies during engineering design? If so, how different are those of the two groups (ET and Biology)?
2. Do students from two different disciplines (Engineering Technology [ET] and Biology) apply domain-specific knowledge and practices differently during engineering design?
3. Do students from two different disciplines (ET and Biology) demonstrate transitional patterns of design strategies differently during engineering design? If so, how different are those of the two groups (ET and Biology)?

2.4 Context of Study

The study was conducted in the context of the integrated STEM education project, *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS)* [National Science Foundation, award # DRL–1513248], which was a three-year project during the 2016-2019 academic years. The research team developed an exemplar lesson, Designing Bugs and Innovative Technology (*D-BAIT*), which integrated biology, physics, and mathematics into the engineering design process. The key concepts of the *D-BAIT* lesson are scientific inquiry, biomimicry, engineering design, and 3D printing technology. The *D-BAIT* lesson includes: 1) collecting aquatic insects to examine the water quality and learn basic taxonomy through insect classification, b) designing a fishing lure, which is inspired by the swimming mechanism of aquatic insects (biomimicry) and the concept of neutral buoyancy, using the CAD software program, and 3) manufacturing a lure prototype using 3D printing technology (Han, Kelley, Bartholomew, & Knowles, 2020). The examples of 3D printed lure designs produced by the students are displayed in Figure 2.2.

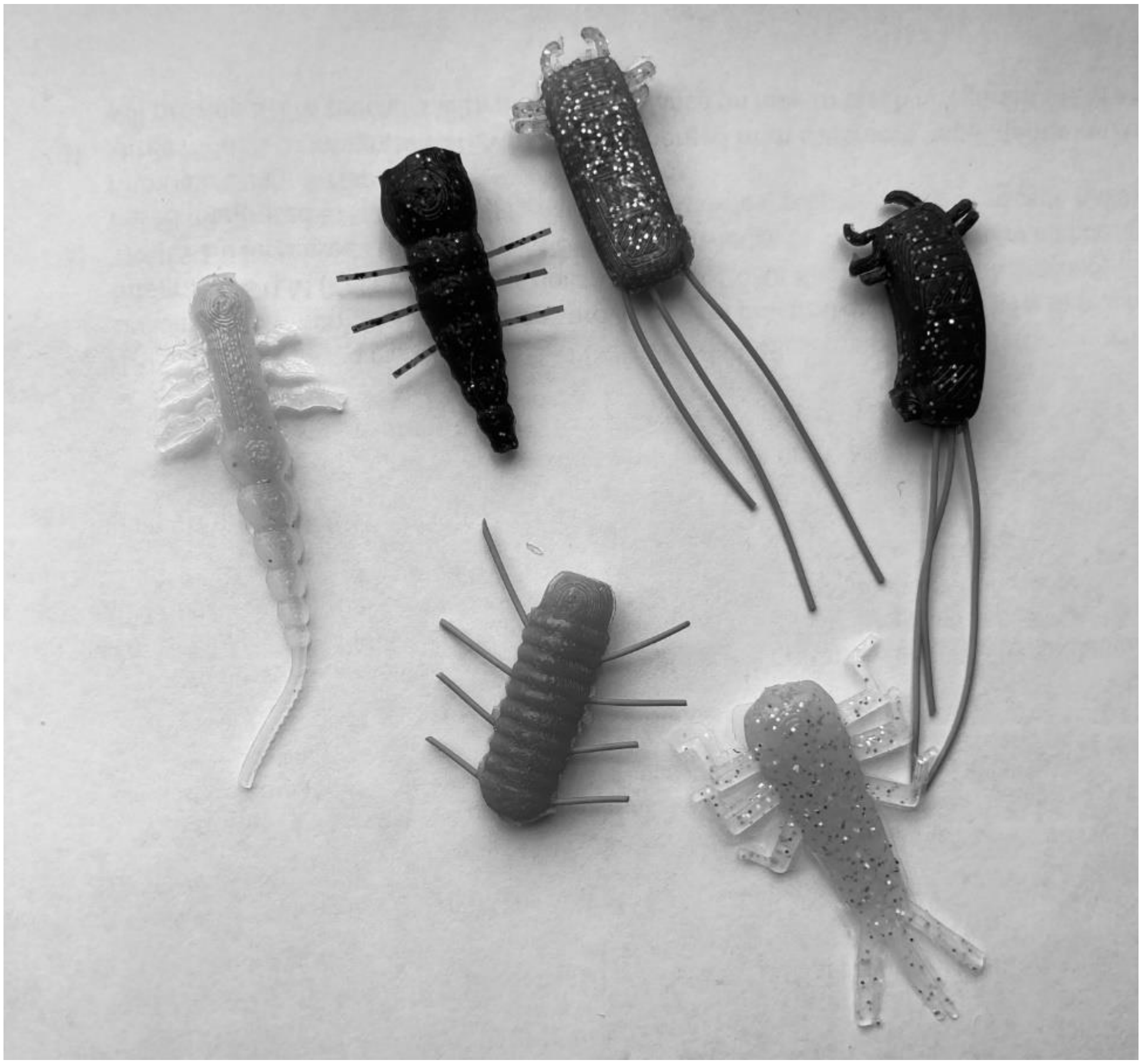

Figure 2.2. Lure Samples of High School Students.

2.4.1 Intervention

High school science and engineering technology (ET) teachers participated in the TRAILS summer professional development (PD) for two weeks, where they learned the TRAILS exemplar lesson, *D-BAIT*, and engaged in the learning experiences in the STEM unit just like their students. In the following school year, the teachers implemented the *D-BAIT* lesson in their own classrooms. Consistent with the US educational standards, such as Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) and Standards for Technological and Engineering Literacy (STEL) (ITEEA, 2020) which stress science and engineering shared practices, Science and ET teachers taught collaboratively, and the students from both science and ET classes were paired as they engaged in the STEM units (Kelley, Knowles, Holland, & Han, 2020). To ensure that the teachers taught the *D-BAIT* unit appropriately following the instruction provided during the summer PD, teacher and student interviews were conducted during and after lesson implementations. The interview responses indicate that the *D-BAIT* lesson was implemented consistently, and the students followed the course materials appropriately (Kelley, Knowles, Han, & Trice, 2021).

We expected this educational intervention- collaborative teaching and learning through shared practices- would help students understand crosscutting concepts and utilize knowledge and skills from different domains during problem-solving. In doing so, students could enhance problem-solving abilities and 21st century skills.

2.5 Methodology

2.5.1 Concurrent Think-Aloud (CTA) Protocol

Researchers identified verbal protocol analysis as a method to examine the cognitive process (Cross, 2004; Ericsson & Simon, 1984; Kelley, Capobianco, & Kaluf, 2015). Especially, CTA protocols can capture problem solving cognitions and design thinking of the designers (Kelley et al., 2015). Lloyd, Lawson, and Scott (1995) noted that "design is a combination of many types of thinking…[and] concurrent verbal reports are best at revealing particular types of thinking (specifically the short-term focus of the designer)" (237).

This study adopted CTA protocol analysis to assess student knowledge transfer from TRAILS design-based integrated STEM learning. Triads of students participated in each protocol session for collaborative problem-solving. When students are in a pair or a group conversation, they are encouraged to explicitly think and express their thoughts for collaborative problem solving (Meyer, 1991; Welch, 1999).

2.5.2 Data Collection

After each *D-BAIT* lesson implementation, triads of students were selected by the teacher and participated in the protocol session. The participants were purposefully selected based on criterion sampling (Gall, Borg, & Gall, 1996). The teachers selected each of three students who: 1) showed average performance during the lesson, 2) volunteered to participate in the video-recording protocol session, and 3) submitted university internal review board (IRB) forms of parent and student consents (Sung, Kelley, & Han, 2019). Table 2.2 displays the demographics of the participants.

Table 2.2.Participant demographics from the total sample. All students submitted IRB consent forms.

Gender		Subject		Sum
Male	Female	Science (14 teams)	ET (13 teams)	
52 (64%)	29 (36%)	42 (52%)	39 (48%)	81 (100%)

The CTA data for the current study consisted of 27 Think-Aloud data sets (ET 13, science 14), which involved 81 students from the second and third project years. Figure 2.3 displays the data collection process.

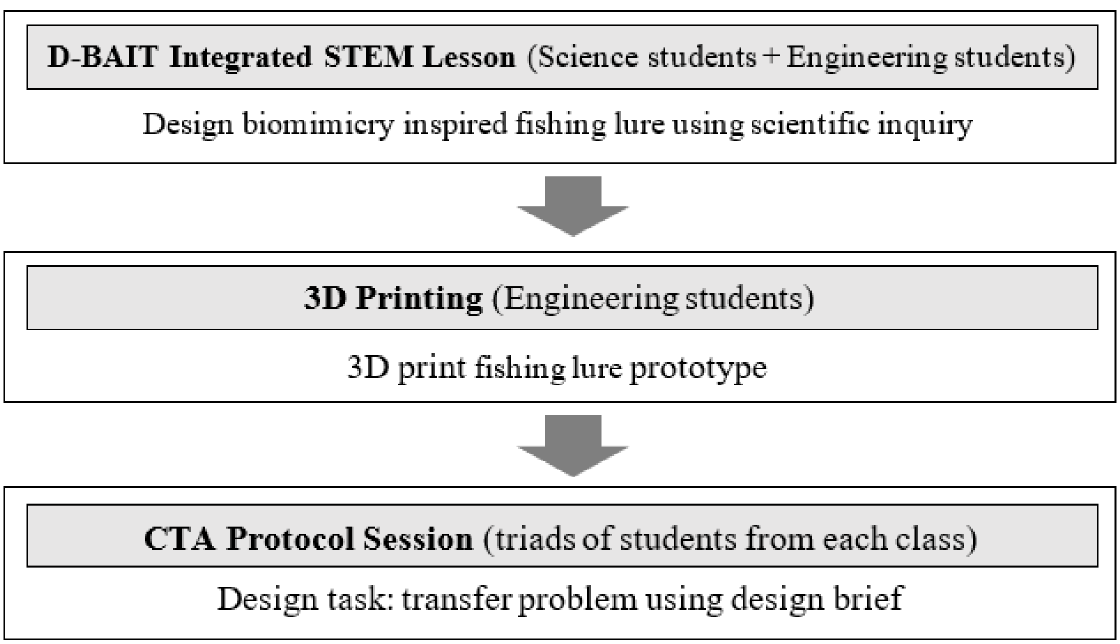

Figure 2.3. Data collection process.

2.5.3 Design Task

The research team created a design brief for the current study to assess how students transfer their connected knowledge, which they learned from the *D-BAIT* lesson to a new real-life situation (Kelley, 2020; Pearson, 2017). Triads of students engaged in each CTA session and addressed this design brief, which challenged them to create 3D printed prototypes to solve the design problem. Figure 2.4 illustrates the design brief provided to the students; this is ill-defined and contains little information on purpose to avoid restricting designers from developing their own ideas.

Underwater Robot

The Problem

Design an underwater robot for DBug harbor security company. The DBug company monitor harbors and provide their clients with underwater visual images for hulls, piers, and harbor bottom. DBug wants develop an underwater robot that explores underwater of harbor. The robot has to maneuver in all axes and be operated in restricted space where larger system cannot operate. The DBug company would like to design the robot using an innovative bio-mimicry approach. Please carefully review the constraints and criteria before creating your design solution. A partner engineering company will provide you with a waterproof camera and remotely controllable motor.

Criteria

To inspect underwater harbors, the robot should

- move in all axes under water.
- mimic an aquatic insect by shape and swimming mechanism.
- use neutral buoyancy concept to move up and down in water.

Constraint

- Use 3D printing technology to create shape and parts of the robot.
- The size of robot should no bigger than 15 x 15 x 10 inch.

Your Task

Describe how you would design an underwater robot? What kind of insects would you mimic?

What types of tests would you do to make sure that your underwater robot works?

Please describe aloud how you would start the design task - where would you begin?

Figure 2.4. Design brief (engineering design task – transfer problem).

2.5.4 Coding Scheme

The coding scheme plays a critical role as a CTA protocol analysis tool. By using a proper coding scheme, researchers can segment participants' verbal utterance into meaningful units (Grubbs, Strimel, & Kim, 2018). Following previous studies that employed Halfin's codes for investigating students' design cognition, the present study adopted seven codes from Halfin's (1973) 17 mental process codes (Kelley, Capobianco, & Kaluf, 2015; Strimel, 2014; Strimel, Bartholomew, Kim, & Liwe Zhang, 2018; Sung, 2018). Using the Delphi technique, Halfin (1973) identified 17 cognitive processes from ten high-level designers' writings, which indicate their mental process of solving technical problems. The mental process codes were revalidated later by Wicklein and Rojewski (1999) and have been used for verbal protocol analysis (Grubbs et al., 2018; Kelley, 2008; Sung, 2018; Sung et al., 2019). For the current study, the TRAILS researchers added two more codes, SI (Scientific Inquiry) and BM (Biomimicry), which are two of the four key features of TRAILS (scientific inquiry, biomimicry, engineering design, 3D printing) (see Figure 2.5). Therefore, the study utilized a total of 9 codes with three main codes (EN-Engineering Design, SI-Scientific Inquiry, BM-Biomimicry) and six Halfin's codes (DF-Defining, AN-Analyzing, DE-Designing, MO-Modeling, PR-Predicting, QH-Questioning, MA-Managing) within the engineering design (EN) process (see Table 2.3). In addition to the 9 codes, NC (No Code) was included to capture the unit of meaningless time span when students were off topic or not engaging in problem-solving dialogue.

When science concepts that students learned from the lesson appeared, such as buoyancy, mass, and volume, those parts of the dialogue were coded as SI (Scientific Inquiry). However, when students' thinking mimicked natural functions found in life sciences to inspire design solution, these protocols were code as BM (Biomimicry). For example, the quote, "we'll have a fin in the back, these flaps will move in all axes", was coded as BM. Biomimicry is "a practice that learns from and mimics the strategies found in nature to solve human design challenges" (Biomimicry Institute, n.d.).

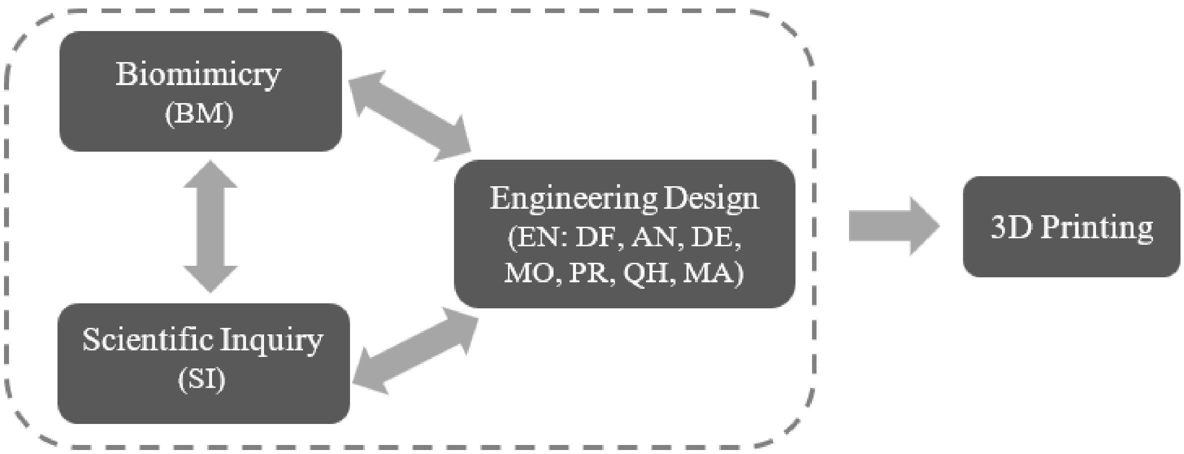

Figure 2.5. Key features of TRAILS model.

Table 2.3. Coding scheme. Adopted from original Halfin's (1973) codes (Kelley et al., 2015, Appendix 3). SI* (Scientific inquiry) and BM* (Biomimicry) are newly added codes by TRAILS researchers.

Cognitive Design Process		Code	Definition
EN (Engineering Design)	Defining	DF	The process of stating or defining a problem which will enhance investigation leading to an optimal solution. It is transforming one state of affairs to another desired state.
	Analyzing	AN	The process of identifying, isolating, taking apart, breaking down, or performing similar actions for the purpose of setting forth or clarifying the basic components of a phenomenon, problem, opportunity, object, system, or point of view.
	Designing	DE	The process of conceiving, creating inventing, contriving, sketching, or planning by which some practical ends may be affected, or proposing a goal to meet the societal needs, desires, problems, or opportunities to do things better. Design is a cyclic or iterative process of continuous refinement or improvement.
	Modeling	MO	The process of producing or reducing an act, or condition to a generalized construct which may be presented graphically in the form of a sketch, diagram, or equation; presented physically in the form of a scale model or prototype; or described in the form of a written generalization.
	Predicting	PR	The process of prophesying or foretelling something in advance, anticipating the future on the basis of special knowledge.
	Questions/Hypotheses	QH	Questioning is the process of asking, interrogating, challenging, or seeking answers related to a phenomenon, problem, opportunity element, object, event, system, or point of view. Hypothesizing is a process of stating a theory of tentative relationship between two or more variables to be tested which are aspects of a phenomenon, problem, opportunity, element, object, event, system, or point of view
	Managing	MA	The process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system.
SI*	Scientific Inquiry	SI	Scientific inquiry is an activity of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world (National Science Education Standards) (NRC, 1996).
BM*	Biomimicry	BM	Mimic natural functions to find a solution to a design problem.

2.5.5 Reliability Test

Two coders randomly selected 7 sessions from a total of 27 CTA sessions (25.9%) and coded them independently using the NVivo software. The result shows strong level of agreement with an overall agreement of 96.38% and a kappa coefficient of .8652 (McHugh, 2012).

2.5.6 Analysis Method

A total of 27 CTA protocol data was selected, coded quantitatively using Halfin's code (1973) and the NVivo12 software, and finally compiled into pie charts illustrating percentages of design strategies to compare the problem-solving strategies of students from different disciplines (science and ET).

Sequential analysis was also conducted to examine the sequential pattern of students' mental processes by investigating the transitions between scientific inquiry, biomimicry, and engineering design. For sequential analysis, the repetition of the same codes that did not show the transition from one event to the next were merged into one. For example, DE-AN-BM-**DE-DE-DE**-AN-**SI-SI**-MO was corrected to DE-AN-BM-**DE**-AN-SI-MO by merging repeating codes to avoid repeating the same events, which do not show the transition between the events (Sung, 2018). Then, the researcher compiled the consecutive codes from each CTA data file into two large files for each science group and ET group. This was done to conduct sequential analysis and compare the sequential pattern of problem-solving mental process of both groups and investigate how domain knowledge gained from integrated STEM lesson shared practices impacted their design cognition and design process.

The study used Discussion Analysis Tool (DAT) version 1.986 developed by Jeong (2003). DAT was designed to conduct various types of sequential analyses, computing frequencies and transitional probabilities between events and statistical significances. The study generated a frequency matrix, transitional probability matrix with z-scores, and transitional state diagram using DAT.

For the sequential analysis, which investigated students' mental processes of transitions between scientific inquiry, biomimicry, and engineering design, DAT generated: 1) frequencies of cognitive events represented by codes; 2) the transitional probabilities between events, and; 3) z-scores for statistical significance. Observed frequencies were converted into relative frequencies, then transitional probabilities for each pair of preceding and response event were generated. Sequential z-score indicates if the transitional probability of a sequential event pair was significantly higher or lower than the expected probability (Jeong, 2003, 2005).

The formula for z-score is

$$Z_{ij}\ (\text{Adjusted residual}) = \frac{x_{ij} - m_{ij}}{\sqrt{m_{ij}(1 - p_{+j})(1 - p_{i+})}}$$

where, $p_{+j} = \frac{x_{+j}}{x_{++}}$ and $p_{i+} = \frac{x_{i+}}{x_{++}}$

and m_{ij} represents an expected frequency and x_{ij} represents observed frequency (Bakeman, Robinson, & Quera, 1996).

2.6 Results

The results show that ET students spent more time on engineering design (76.61%) and biomimicry (10.67%) than science students (engineering design 70.83%, biomimicry 8.52%) while science students spent more time on scientific inquiry (20.65%) than ET students (scientific inquiry 12.72%). Table 2.4 summarizes the percentages of design strategies of science group and ET group. Both science and ET students spent more than 23% of the total time on the science domain (scientific inquiry, biomimicry) during the engineering design task. Pie charts visually compare the problem-solving strategies of each group (Figure 2.6).

Table 2.4. Time and percentages of design strategies.

Description (Code)	ET		Sci		Total	
	Time	% of Time	Time	% of Time	Time	% of Time
EN: (AN)	01:34.1	6.77%	01:34.2	6.40%	01:34.2	6.59%
(DE)	09:25.6	35.87%	07:53.4	31.40%	08:39.5	33.64%
(DF)	02:51.6	12.27%	02:35.7	10.94%	02:43.6	11.60%
(MA)	00:36.3	2.46%	00:33.7	2.26%	00:35.0	2.36%
(MO)	03:47.6	16.45%	04:22.6	16.86%	04:05.1	16.66%
(PR)	00:26.6	1.63%	00:28.7	2.00%	00:27.6	1.82%
(QH)	00:05.2	0.40%	00:15.4	0.97%	00:10.3	0.68%
(NC)	00:09.3	0.76%	00:00.0	0.00%	00:04.6	0.38%
BM	02:48.5	10.67%	02:13.1	8.52%	02:30.8	9.59%
SI	03:19.4	12.72%	04:54.2	20.65%	04:06.8	16.69%
Sum	25:04.1	100.0%	24:50.9	100.0%	24:57.5	100.0%

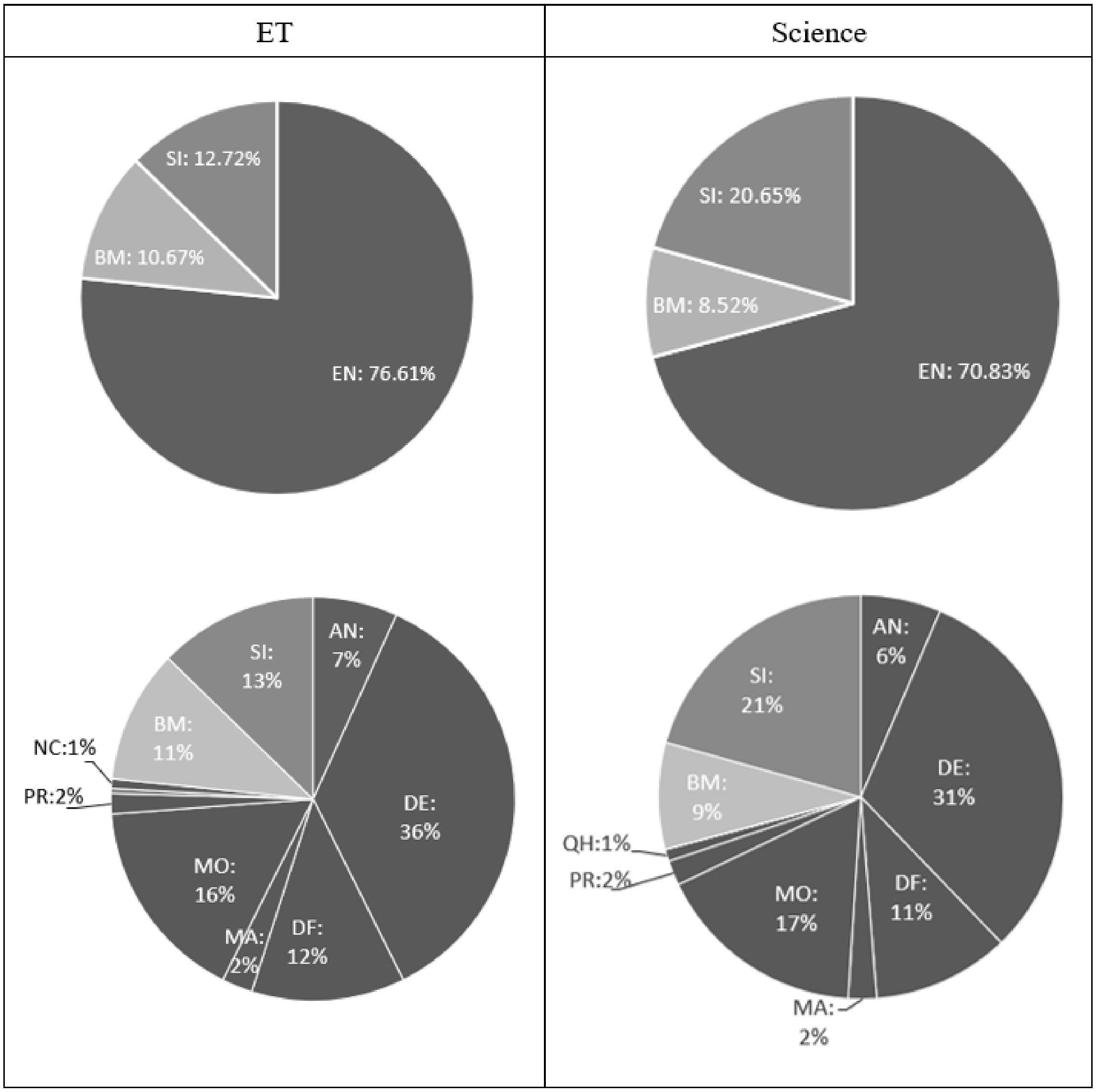

Figure 2.6. General pattern of design strategies for ET students and science students. The second pie chart in each column depicts details of engineering design category.

2.6.1 Sequential Analysis Results: ET Students

Frequency matrix for ET students generated by DAT displays ET students' overall mental process patterns represented by the transition from the given event to the target event across all the codes (see Table 2.5). Additionally, the transitional probability matrix with Z-scores indicates whether or not the transitional probabilities of each following event to each given event are significantly higher or lower than expected (see Table 2.6).

Notably, transitions between BM/DE and SI/DE show significantly higher probabilities than expected at the 0.1 of alpha level (two-tailed), which illustrates that biomimicry concepts (BM) and scientific inquiry (SI) significantly influenced student design (DE), and design (DE) generated biomimicry (BM) knowledge and scientific inquiry (SI): DE-BM (z-score = 6.31, $p < 0.01$), BM-DE (z-score = 3.84, $p < 0.01$), DE-SI (z-score = 1.71, $p < 0.10$), and SI-DE (z-score = 3.05, $p < 0.01$) (see Table 2.6).

DE (designing)/MO (modelling) and DE (designing)/AN (analyzing) transitions in the engineering design context also show significantly higher probabilities than expected with high z-scores: MO-DE (z-score = 5.16, $p < 0.01$), DE-MO (z-score = 9.96, $p < 0.01$), DF-AN (z-score = 7.94, $p < 0.01$), AN-DF (z-score = 2.44, $p < 0.01$).

Table 2.5. ET group: Frequency matrix of Given-Following (Target) codes across mental process types.

	Target (Following Codes)													
Given	BM	SI	AN	DE	MO	DF	PR	QH	MA	NC	Target	Given	%Target	%Given
BM		17	**3**	**51**	22	13	2	1	2	0	111	112	0.14	0.14
SI	15		6	**41**	17	10	1	0	3	0	93	93	0.12	0.11
AN	7	8		18	**3**	**10**	2	**3**	1	0	52	52	0.06	0.06
DE	**62**	**35**	**6**		**98**	**23**	5	2	8	2	241	244	0.30	0.30
MO	19	15	9	**74**		17	1	**5**	**14**	2	156	156	0.19	0.19
DF	5	10	**23**	33	**6**		**4**	1	5	1	88	90	0.11	0.11
PR	2	2	0	8	3	1		0	0	**1**	17	17	0.02	0.02
QH	1	**4**	2	5	**0**	0	0		0	0	12	12	0.01	0.01
MA	1	2	2	9	7	2	**2**	0		**1**	26	33	0.03	0.04
NC	0	0	1	**5**	0	1	0	0	0		7	7	0.01	0.01
Total	112	93	52	244	156	77	17	12	33	7	803 (Target Total)	816 (Given Total)		

Note: bolded figures indicate significantly higher frequencies of target event than expected in response to a given event. Underlined and bolded figures indicate significantly lower frequencies than expected in response to a given event. The frequency of responses from BM to DE (51) was significantly higher than expected while the frequency of responses from BM to AN (3) was significantly lower than expected.

Table 2.6. ET Group: transitional probability matrix.

	Target (Following Codes)									
Given	BM	SI	AN	DE	MO	DF	PR	QH	MA	NC
BM		0.15	**0.03**	**0.46**	0.20	0.12	0.02	0.01	0.02	0.00
		(1.32)	**(-1.74)**	**(3.84)**	(0.11)	(0.82)	(-0.25)	(-0.56)	(-1.32)	(-1.06)
SI	0.16		0.06	**0.44**	0.18	0.11	0.01	0.00	0.03	0.00
	(0.65)		(-0.01)	**(3.05)**	(-0.30)	(0.41)	(-0.74)	(-1.26)	(-0.46)	(-0.96)
AN	0.13	0.15		0.35	**0.06**	**0.19**	0.04	**0.06**	0.02	0.00
	(-0.10)	(0.89)		(0.69)	**(-2.57)**	**(2.44)**	(0.90)	**(2.63)**	(-0.82)	(-0.70)
DE	**0.26**	**0.15**	**0.02**		**0.41**	0.10	0.02	0.01	0.03	0.01
	(6.31)	**(1.71)**	**(-3.01)**		**(9.96)**	(-0.03)	(-0.05)	(-1.02)	(-0.74)	(-0.08)
MO	0.12	0.10	0.06	**0.47**		0.11	0.01	**0.03**	**0.09**	0.01
	(-0.71)	(-0.85)	(-0.40)	**(5.16)**		(0.62)	(-1.43)	**(1.96)**	**(3.41)**	(0.61)
DF	**0.06**	0.11	**0.26**	0.37	**0.07**		**0.05**	0.01	0.06	0.01
	(-2.37)	(-0.07)	**(7.94)**	(1.54)	**(-3.17)**		**(1.68)**	(-0.29)	(0.79)	(0.28)
PR	0.12	0.12	0.00	0.47	0.18	0.06		0.00	0.00	**0.06**
	(-0.26)	(0.02)	(-1.10)	(1.51)	(-0.19)	(-0.52)		(-0.51)	(-0.86)	**(2.25)**
QH	0.08	**0.33**	0.17	0.42	**0.00**	0.00	0.00		0.00	0.00
	(-0.57)	**(2.37)**	(1.45)	(0.86)	**(-1.71)**	(-1.14)	(-0.51)		(-0.72)	(-0.33)
MA	0.04	0.08	0.08	0.35	0.27	0.08	**0.08**	0.00		**0.04**
	(-1.51)	(-0.63)	(0.26)	(0.48)	(0.98)	(-0.33)	**(2.01)**	(-0.64)		**(1.66)**
NC	0.00	0.00	0.14	**0.71**	0.00	0.14	0.00	0.00	0.00	
	(-1.07)	(-0.96)	(0.84)	**(2.37)**	(-1.30)	(0.42)	(-0.33)	(0.00)	(-0.55)	

Note: Probabilities of events following each given event. Z-scores are indicated in parentheses. The proportion of responses from BM to DE (46%) was significantly higher than expected while the proportion of responses from BM to AN (3%) was significantly lower than expected. Bolded values indicate probabilities higher than expected (z-score > 1.65, alpha < .10, two-tailed). Values both underlined and bolded were of probabilities lower than expected (z-score < 1.65, alpha < .10, two-tailed) (Jeong, 2003, 2005).

2.6.2 Sequential Analysis Results: Science Students

Frequency matrix and transitional probability matrix with *z*-scores for science students are displayed as shown in Table 2.7 and Table 2.8. Science students also showed higher probabilities of transitions between DE/BM and DE/SI, which indicates that students employed biomimicry concepts (BM) and scientific inquiry (SI) frequently during the engineering design activity; DE-BM (*z*-score = 2.99, $p < 0.01$), BM-DE (*z*-score = 2.41, $p < 0.01$), DE-SI (*z*-score = 2.35, $p < 0.01$), and SI-DE (*z*-score = 5.01, $p < 0.01$) (see Table 2.8). Additionally, similar to the results from ET students, DE (designing)/MO (modelling) and DE (designing)/AN (analyzing) transitions within the engineering design context also show significantly higher probabilities than expected with high *z*-scores: MO-DE (*z*-score = 7.56, $p < 0.01$), DE-MO (*z*-score = 9.60, $p < 0.01$), DF-AN (*z*-score = 8.13, $p < 0.01$), AN-DF (*z*-score = 1.66, $p < 0.10$).

Table 2.7. Science Group: frequency matrix of Given-Following (Target) codes across mental process.

	Target (Following Codes)												
Given	BM	SI	AN	DE	MO	DF	PR	QH	MA	NC	Target	Given	%Target	%Given
BM		17	7	**36**	21	6	1	1	$\underline{\mathbf{0}}$	0	89	89	0.10	0.10
SI	11		7	**63**	26	13	**7**	$\underline{\mathbf{0}}$	5	0	132	133	0.15	0.15
AN	9	9		22	9	**10**	2	**4**	1	0	66	66	0.08	0.07
DE	**38**	**50**	$\underline{\mathbf{11}}$		**98**	**32**	10	5	9	2	253	256	0.29	0.29
MO	13	25	$\underline{\mathbf{7}}$	**88**		13	2	7	9	2	164	164	0.19	0.19
DF	9	**20**	**27**	23	$\underline{\mathbf{4}}$		$\underline{\mathbf{0}}$	3	**9**	0	95	95	0.11	0.11
PR	3	5	1	8	$\underline{\mathbf{1}}$	2		**3**	0	0	23	23	0.03	0.03
QH	2	4	**4**	10	$\underline{\mathbf{1}}$	0	1		1	0	23	23	0.03	0.03
MA	4	3	2	6	4	**6**	0	0		0	25	34	0.03	0.04
NC	0	0	0	0	0	0	0	0	0		0	0	0.00	0.00
Total	89	133	66	256	164	82	23	23	34	0	870 (Target Total)	883 (Given Total)		

Note: bolded values indicate significantly higher frequencies of the target event than expected in response to given event. Underlined and bolded values indicate significantly lower frequencies than expected in response to a given event.

Table 2.8. Science Group: transitional probability matrix.

	Target (Following Codes)									
Given	BM	SI	AN	DE	MO	DF	PR	QH	MA	NC
BM		0.19	0.08	**0.40**	0.24	0.07	0.01	0.01	**0.00**	0.00
		(1.06)	(0.10)	**(2.41)**	(1.21)	(-0.91)	(-0.94)	(-0.94)	**(-2.01)**	(0.00)
SI	0.08		0.05	**0.48**	0.20	0.10	**0.05**	**0.00**	0.04	0.00
	(-0.78)		(-1.08)	**(5.01)**	(0.27)	(0.18)	**(2.07)**	**(-2.06)**	(-0.08)	(0.00)
AN	0.14	0.14		0.33	0.14	**0.15**	0.03	**0.06**	0.02	0.00
	(0.95)	(-0.39)		(0.72)	(-1.13)	**(1.66)**	(0.20)	**(1.80)**	(-1.04)	(0.00)
DE	**0.15**	**0.20**	**0.04**		**0.39**	**0.13**	0.04	0.02	0.04	0.00
	(2.99)	**(2.35)**	**(-2.31)**		**(9.60)**	**(2.08)**	(1.54)	(-0.79)	(-0.34)	(0.01)
MO	0.08	0.15	**0.04**	**0.54**		0.08	0.01	0.04	0.05	0.00
	(-1.08)	(-0.02)	**(-1.78)**	**(7.56)**		(-0.73)	(-1.26)	(1.44)	(1.16)	(0.00)
DF	0.09	**0.21**	**0.28**	0.24	**0.04**		**0.00**	0.03	**0.09**	0.00
	(-0.26)	**(1.65)**	**(8.13)**	(-1.18)	**(-3.87)**		**(-1.70)**	(0.33)	**(2.97)**	(0.00)
PR	0.13	0.22	0.04	0.35	**0.04**	0.09		**0.13**	0.00	0.00
	(0.45)	(0.87)	(-0.59)	(0.57)	**(-1.80)**	(-0.12)		**(3.15)**	(-0.98)	(0.00)
QH	0.09	0.17	**0.17**	0.43	**0.04**	0.00	0.04		0.04	0.00
	(-0.25)	(0.28)	**(1.80)**	(1.50)	**(-1.80)**	(-1.57)	(0.52)		(0.11)	(0.00)
MA	0.16	0.12	0.08	0.24	0.16	**0.24**	0.00	0.00		0.00
	(0.97)	(-0.46)	(0.08)	(-0.60)	(-0.37)	**(2.53)**	(-0.84)	(-0.84)		(0.00)
NC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	(0.00)	(0.00)	(0.00)	(-0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	

Note: Probabilities of events following each given event. Z-scores are indicated in parentheses. Bolded values indicate significantly higher frequencies of the target event than expected in response to a given event. Values that are both underlined and bolded indicate significantly lower frequencies than expected in response to a given event.

2.6.3 ET vs. Science: Transitional State Diagram

DAT generates a transitional state diagram with up to six codes. Therefore, six codes of the most frequently occurred events were selected to produce the transitional state diagram. Table 2.9 and Table 2.10 show the new matrices of transitional probabilities with the six codes.

The transitional state diagrams illustrate the mental processes of science students and ET students during the design activities (see Figure 2.7). The arrows with varying densities indicate the pattern of transitions from one event to the following event with transitional probabilities between events (Jeong, 2003).

Science students employed scientific inquiry (SI) for designing (DE) more frequently (52%) than ET students (46%), with a higher probability of transition between them. ET students utilized the biomimicry concept (BM) more frequently (48%) than science students (41%), which indicates ET students employed the biomimicry concept more significantly in designing the prototype. However, the differences were small, and students from both groups showed similar patterns of mental processes during the protocol session, as seen in Figure 2.7.

Table 2.9. Transitional probability matrix with most frequently occurred six codes: ET Group.

	BM	SI	AN	DE	MO	DF
BM		0.16(1.324)	0.03(**-1.740**)	0.48(**3.840**)	0.21(0.113)	0.12(0.818)
SI	0.17(0.646)		0.07(-0.010)	0.46(**3.055**)	0.19(-0.297)	0.11(0.405)
AN	0.15(-0.105)	0.17(0.886)		0.39(0.686)	0.07(**-2.574**)	0.22(**2.442**)
DE	0.28(**6.309**)	0.16(**1.706**)	0.03(**-3.006**)		0.44(**9.961**)	0.10(-0.029)
MO	0.14(-0.710)	0.11(-0.855)	0.07(-0.399)	0.55(**5.158**)		0.13(0.618)
DF	0.06(**-2.372**)	0.13(-0.068)	0.30(**7.942**)	0.43(1.538)	0.08(**-3.168**)	

Note: Probabilities of events following each given event. Z-scores are indicated in parentheses. Z scores < −1.64, which are both bolded and underlined, reveal probabilities significantly lower than expected (p < .10). Z scores > 1.64, which are bolded, indicate probabilities significantly higher than expected (p < .10). (Jeong, 2003, 2005).

Table 2.10. Transitional probability matrix with most frequently occurred six codes: Science Group.

	BM	SI	AN	DE	MO	DF
BM		0.20(1.055)	0.08(0.105)	0.41(**2.409**)	0.24(1.208)	0.07(-0.915)
SI	0.09(-0.781)		0.06(-1.076)	0.52(**5.010**)	0.22(0.270)	0.11(0.181)
AN	0.15(0.950)	0.15(-0.388)		0.37(0.725)	0.15(-1.127)	0.17(**1.656**)
DE	0.17(**2.985**)	0.22(**2.349**)	0.05(**-2.301**)		0.43(**9.603**)	0.14(**2.083**)
MO	0.09(-1.080)	0.17(-0.017)	0.05(**-1.781**)	0.60(**7.560**)		0.09(-0.729)
DF	0.11(-0.258)	0.24(**1.654**)	0.33(**8.126**)	0.28(-1.182)	0.05(**-3.866**)	

Note: Probabilities of events following each given event. Z-scores are indicated in parentheses. Z scores < −1.64, which are both bolded and underlined, reveal probabilities significantly lower than expected (p < .10). Z scores > 1.64, which are bolded, indicate probabilities significantly higher than expected (p < .10). (Jeong, 2003, 2005).

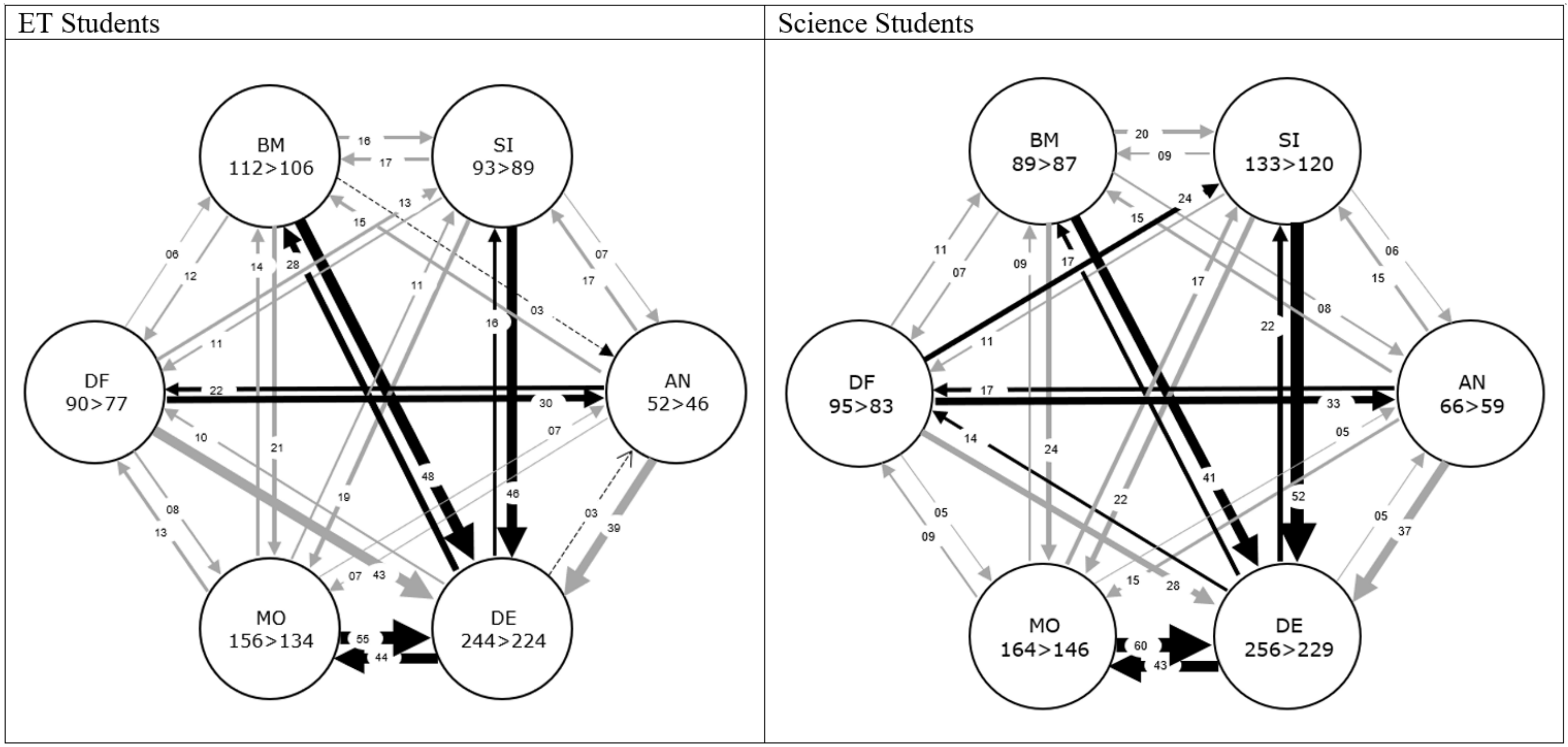

Figure 2.7. Transitional state diagrams of mental process: comparison between Science and ET students. The numerical values indicate percentage of transitional probability (analysis approach by Jeong, 2003, 2005).

2.7 Summary

The current study investigated how key features of the TRAILS model, including scientific inquiry, biomimicry, engineering design, and 3D printing impacted student design cognition and design thinking patterns.

Aiming to answer the overarching research question, *"During Concurrent Think-Aloud (CTA) protocol sessions, do secondary science and engineering students blend science and engineering shared practices while engineering design?"*, the current study explored students' design strategies manifested during the protocol sessions.

Pie charts were generated to examine the percentage of time dedicated to each category of TRAILS key concepts: scientific inquiry, biomimicry, and engineering design. Transitional state diagrams were also produced to identify the sequential patterns of students' mental processes.

The transitions displayed in the diagram illustrate that science students moved from problem space (DF) towards science inquiry (SI) with a probability significantly higher than expected (probability = 0.24, z-score = 1.654, p <0.01) while ET students did not. However, both groups showed similar patterns in that they spent about one-third of their time on scientific thinking (ET - SI 12%, BM 11%; Science - SI 20%, BM 9%) (see Figure 2.6). This result confirms that students from both disciplines utilized the domain-specific knowledge gained from integrated STEM instruction for engineering design problem-solving (sub-question 1, 2).

Furthermore, domain knowledge (SI, BM) was employed during the design process as a significant facilitator of problem-solution transition (see Figure 2.7), which indicates that experiences in specific domains from integrated STEM shared practice enabled the young designers to perceive and frame the problem leading to create design solution (DE) (sub-question 3). The numerical values for science inquiry (SI) and biomimicry (BM) to design (DE) indicated for ET students' percentage of transitional probability was 48% (BM-DE) and 46% (SI-DE). The numerical values for science inquiry (SI) and biomimicry (BM) to design (DE) indicated for science students' percentage of transitional probability was 41% (BM-DE) and 52% (SI-DE). These results indicate domain-specific knowledge gained from shared practice enhanced solution generation process as represented by design (DE). In other words, the data suggests that student protocols reveal that they moved from biomimicry (BM) and science inquiry (SI) to design (DE).

The researchers acknowledge that a judgment that the student design teams produced the proper solutions or quality designs cannot be made. This is because the protocol session did not include the final stage of prototyping: the actualization of the design solution through 3D printing (see Figure 2.5). However, the protocol analysis demonstrated that the students elaborated to find the optimal solution; they defined and analyzed the problems, identified constraints and criteria, and specified concepts and functions of the design to satisfy clients' or users' needs (Dym, Agogino, Eris, Frey, & Leifer, 2005).

2.8 Discussion and Implication

In STEM education, science and engineering shared practices enable students to combine scientific inquiry and the engineering design process, which enhances students' design thinking and creativity. The current study investigated how experiences in specific domains enable novice designers to perceive and formulate the problem and develop proper solutions (Cross, 2004) and how these domain knowledge and shared practices interfere with the engineering design process.

> "I used my skills in the design process and computer modelling to design and create the bait. The integration of the two classes aided in the design of the lure as the knowledge and ideas of the environmental science students were implemented into the design process. Blending science and engineering resulted in an increase in ideas during brainstorming and troubleshooting. It also taught me a lot about how my imagination can come to life with 3D printing" (Student reflection).

The protocol analysis of the current study shows that domain knowledge attained from the shared practice of science and engineering, which are represented as scientific inquiry, biomimicry, and engineering design, impacted three major aspects of design cognition: the problem formulation, the generation of solutions, and the utilization of design process strategies (Cross, 2001).

The findings of the current study have several potential implications. First, integrated STEM practice empowered students to utilize scientific inquiry towards everyday problem-solving. As indicated in the transitional state diagram (see Figure 2.7), both science and ET students showed higher probabilities of transitions from scientific inquiry (SI) to design (DE) while applying their knowledge to a new situation in the design brief. Second, well-integrated domain knowledge gained from integrated STEM instruction and shared practice elicited an interactive pattern between design (DE) and disciplinary knowledge (SI, BM). Student design teams processed domain knowledge (biomimicry and scientific inquiry - BM, SI) to develop the problem solution (designing - DE), indicating that shared science and engineering practice stimulated students' problem-solving abilities and enhanced design cognition by expanding their knowledge and design capacities. Finally, the study confirms that the students benefitted from integrated STEM instruction and shared practice by learning how real engineers and technologists create new technology and how scientists uncover new science discoveries (ITEEA 2020). As students experience science and engineering practice, which can be applied to real-life situations, they can understand the procedures scientists and engineers perform to improve society.

Previous literature identified that designers' performance might differ depending on their domains and prior experiences (Kolb 2014; Lawson 1979). For instance, Lawson (1979) found that science students focused more on the problem while architect students focused more on the solution, which may indicate that students from different domains use different strategies for problem-solving. However, the present study showed that students from different domains demonstrated a similar pattern of design strategies after experiencing shared practices - frequent transitions from scientific inquiry and biomimicry to engineering design. According to researchers, the creative design process requires transformation between divergent and convergent thinking (Goel, 2014), and problem and solution evolve together (Dorst and Cross 2001). This study shows that biomimicry and scientific inquiry played an important role as drivers for student design strategy. The TRAILS program goal was to implement integrated STEM content to help students become integrated thinkers and problem solver. We expected science and engineering shared practices through integrated STEM collaborative teaching and learning would help students learn crosscutting concepts. In doing so, students may employ knowledge and skills from different domains during problem-solving. Researchers noted that problem and solution frame the quality design process, and framing ability appears critical to the "high-level performance in creative design" (Dorst & Cross, 2001, p.435). The present study indicates that integrated STEM is beneficial for students as a way of practicing interdisciplinary design strategies to practice the quality design process, where framing plays a pivotal role.

Preparing students as a new generation of STEM experts and fortifying the STEM workforce are important goals of K-12 STEM education. As noted earlier in this paper, TRAILS aimed to advance students' learning of STEM content and career awareness. TRAILS created an instructional model that integrated scientific inquiry, biomimicry, engineering design, and 3D printing in order to enhance students' problem-solving abilities and increase their interests in STEM learning and career paths. Although the trends in design strategies shown in the pie charts (see Figure 2.6) display that student did not spend much time on inquiry practicing, student interviews reveal that students practiced “inquiring” as a critical factor during their design process. For example, the design teams employed scientific inquiry for their design solutions as indicated in their discussions (See the example quotes below from one CTA protocol session).

> Student 1: It's a balance- like the joints. They can go up and down and then attach to this.
>
> Student 2: The idea is pretty ok if we make oscillating joints. You can get movable joints- like they use tractors and stuff. You can make them go down with hydraulics, and we go along the body.

All in all, the implications of this study suggest researchers and educators should invest more efforts into integrated STEM education involving science and engineering shared practices.

The study has some limitations. First of all, the findings cannot be generalized since the study was case-based research with a limited sample size, which the participants cannot represent the entire population. Second, as Cross (2004) noted, “protocol analysis offers a valuable but highly specific research technique, capturing a few aspects of design cognition in detail, but fails to encompass many of the broader realities of designing in context” (Cross, 2004, p. 40). Finally, assessing mental processes is complex, and many times, it is hard to capture important features of cognitive design processes. Therefore, further studies are needed to develop effective instructional strategies to integrate STEM that students can share science and engineering practices.

Disclosure Statement

No potential conflict of interest was reported by the authors.

NSF Disclaimer

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Author Contributions

The authors confirm contribution to the paper as follows: study conception, data collection, and data analysis: Han, J.; study design and review: Kelley, T. R. All authors reviewed the results and approved the final version of the manuscript.

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CHAPTER 3. (STUDY 2) FACTORS INFLUENCING STUDENT STEM LEARNING: TEACHER SELF-EFFICACY, STUDENT ATTITUDE, 21ST CENTURY SKILLS, AND CAREER AWARENESS

A version of this chapter was previously published in The Journal for STEM Education Research. Han, J., Kelley, T. R., & Knowles, J. G. (2021). Factors Influencing Student STEM Learning: Self-Efficacy and Outcome Expectancy, 21st Century Skills, and Career Awareness. *Journal for STEM Education Research 4,* 117–137. https://doi-org.ezproxy.lib.purdue.edu/10.1007/s41979-021-00053-3

3.1 Abstract

Social, motivational, and instructional factors impact students' outcomes in STEM learning and their career paths. Based on prior research and expectancy-value theory, the study further explored how multiple factors affect students in the context of integrated STEM learning. High school STEM teachers participated in summer professional development and taught integrated STEM to students during the following school year, where scientific inquiry, biomimicry, 3D printing technology, and engineering design were integrated as instructional strategies. Surveys were conducted to measure teacher self-efficacy and outcome expectancy. Student STEM attitudes (self-efficacy and expectancy-value beliefs), 21st century skills, STEM career awareness, and STEM knowledge achievement were also measured using a survey and a custom-made knowledge test. Based on expectancy-value theory and literature, a path model was developed and tested to investigate causal relationships between these factors. The results revealed direct and indirect effects of teacher self-efficacy and outcome expectancy on students' STEM knowledge achievements. Student STEM attitudes (self-efficacy and expectancy-value beliefs), 21st century skills, and STEM career awareness also significantly influenced STEM knowledge achievement directly or indirectly.

Key words: integrated STEM education, expectancy-value theory, STEM career awareness, 21st century skills

3.2 Introduction

The national efforts for advancing science, technology, engineering, and mathematics (STEM) education is becoming stronger as our society demands a global STEM workforce (Asunda, 2012; Keirl, 2006; Kelley & Knowles, 2016; Li et al., 2019). To help students enhance their achievements in STEM learning, teachers and educators should create appropriate instructional and social learning contexts and develop strategies that positively influence student learning. For this purpose, understanding factors that influence student STEM learning is imperative.

Social, motivational, and instructional factors greatly influence students' achievements in STEM learning and their future careers. (Ketenci et al., 2020; Nugent et al., 2015; Wilson et al., 2015; Zeldin et al., 2008). Prior studies found that students' academic achievements can be impacted by domain-specific self-efficacy, attitudes, and motivation (Pajares & Graham 1999; Simon et al., 2014; Wiebe et al., 2018; Witt-Rose, 2003). However, although many studies have investigated the relationships between students' self-efficacy, motivation, and learning outcomes, few studies were reported on the multiple factors influencing student learning in STEM. In addition, studies in this area typically have been conducted on a single STEM discipline, especially science and mathematics (Wiebe et al., 2018). Furthermore, research on how self-efficacy and outcome expectancy of both teachers and students collectively affect student learning outcomes is limited. Therefore, the current study examined multiple factors influencing student STEM learning, which include teacher self-efficacy and outcome expectancy, student STEM attitudes (self-efficacy and expectancy-value beliefs), 21st century skills, and STEM career awareness.

We used expectancy-value theory as a framework to hypothesize the path model. Findings will show the direct and indirect effects of multiple factors on student achievement in the integrated STEM teaching and learning context.

3.3 Theoretical Framework

The current study is guided by expectancy-value theory (Eccles & Wigfield 2002). Expectancy-value theory has been widely used to explain student performance (Berland & Steingut, 2016; Jones et al., 2010; Jackson et al., 2019). According to Eccles and Wigfield (2002), "expectancies refer to beliefs about how one will do on different tasks or activities, and values have to do with incentives or reasons for doing the activity" (p. 110). These expectancies and values are related to individual's achievement, persistence, and choices in academic tasks (Atkinson, 1964; Eccles & Wigfield, 2002). Therefore, people who have strong beliefs about their competencies of success and efficacy tend to perform better and work on more challenging tasks (Bandura, 1994; Eccles & Wigfield, 2002).

Wiebe et al. (2018) stated that "expectancy-value theory helps frame both self-efficacy in terms of expectancies of success in a particular academic domain and outcome expectancy in terms of the value of this academic subject area to future goals" (p. 2). Bandura differentiated between efficacy expectation (beliefs about what they can do) and outcome expectation (beliefs about the likely outcomes of performance) and noted that both expectations are closely linked to academic outcomes (Trautwein et al., 2012). Previous research also revealed a significant relationship between expectancy-value beliefs and academic achievements (Bradley et al., 1999; Caraway et al., 2003; Nugentet et al., 2015; Pajares & Miller 1994; Yoon et al., 2012; Wood & Locke, 1987; Zimmerman et al., 1992). Moreover, many studies found "a dynamic, reciprocal nature of self-efficacy, expectancy outcomes, and academic career goals" (Wiebe et al., 2018, p. 2). Specifically, Wiebe et al. (2018) examined the relationships between student attitudes (self-efficacy and expectancy-value beliefs) toward all core STEM subjects and their interests in future STEM careers using the S-STEM survey (Unfried et al., 2012) and found that student attitudes (expectancy-value beliefs) and their career interests are positively associated. Teacher self-efficacy also has been emphasized as a strong predictor of student outcome and academic achievement (Nadelson et al., 2012; Ross, 1992; Tschannen-Moran & Barr, 2004; Yoon et al., 2012). Teachers' beliefs in their abilities to teach and motivate influence "the types of learning environments they create and the level of academic progress their students achieve" (Bandura, 1993, p. 117), which in turn, significantly influence student STEM interests in future STEM careers (Autenrieth et al., 2018; Brophy et al., 2008; Kelley et al., 2020). Based on expectancy-value theory and previous research findings, the present study created a hypothesized path model that displays the influence of teacher self-efficacy and outcome expectancy on student STEM attitudes, 21st century skills, STEM career awareness, and STEM knowledge achievement. The results will show the relationship between these factors and the effects of teacher self-efficacy and outcome expectancy on student learning in integrated STEM.

3.4 Literature Review

3.4.1 Self-efficacy and Outcome Expectancy

Teachers' self-efficacy can be defined as "teachers' personal beliefs in their abilities to positively affect students for educational attainments" (Yoon et al., 2012, p. 26). Prior studies provided empirical evidence that teachers' beliefs in their teaching efficacy and successful outcome influence students' self-efficacy, motivation, and performance (Cannon & Scharmann, 1996; Ross et al., 2001; Rutherford et al., 2017). Specifically, research on the relationship between teacher self-efficacy and student outcome in science learning (Bal-Taştan et al., 2018; Salgado et al., 2018) and mathematics learning (Borko & Whitcomb, 2008; Gulistan & Hussain, 2017; Perera & John, 2020) revealed that teachers' self-efficacy and expectations significantly impact students' academic achievement. According to researchers, teacher self-efficacy for successful teaching relates to content knowledge, quality pedagogy, and teaching strategies considerably (Knowles, 2017, p. 25; Rutherford et al., 2017; Stohlmann et al., 2012; Yoon et al., 2012).

Students' confidence in their abilities and perceptions of subjective values are also critical factors that influence their performances (Akey, 2006; Wigfield & Eccles, 2000). Many studies proved the positive association between student self-efficacy and academic success (Henson, 2001; Pajares, 1996; Reyes, 2010). Studies also found that student self-efficacy and expectancy-value beliefs significantly impact their career development and career choices (Ketenci et al., 2020; Lent et al., 2010; Zeldin et al., 2008). Unfried and colleagues (2015) used the term attitudes to indicate both self-efficacy and expectancy-value beliefs. They noted that students' attitudes toward STEM content, as well as their interests in STEM careers and their 21st century skills, can predict student participation in STEM-related careers. The present study also uses the term attitudes to indicate student self-efficacy in learning STEM content and their expectancy-value beliefs (Unfried et al., 2015; Wiebe et al., 2018).

3.4.2 21st Century Skills

Increasing 21st century skills through STEM education has been focused among educators (Bybee, 2010; Jang, 2016; Li et al., 2019). 21st century skills, which include critical thinking, collaboration, creativity, and communication, are necessary skills in the future (International

Technology and Engineering Educators Association [ITEEA], 2020; Partnership for 21st Century Skills [P21], n.d.). Li and colleagues (2019) posited that students can develop thinking skills in a new way in STEM education and that these new thinking skills are connected to 21st century skills.

21st century skills range from individual skills to workforce and social skills, which include skills in life and career, media and information, technology, and so on. (Kelley et al., 2019). Specifically, National Academy of Engineering (NAE & NRC 2009) proposed engineering habits of mind as essential skills in the 21st century, which include systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations. Similarly, ITEEA (2020) proposed eight technology and engineering practices adopted from 21st century skills (Partnership for 21st Century Skills [P21], n.d.) and engineering habits of mind, which include: 1) Systems thinking; 2) Creativity; 3) Making and Doing; 4) Critical thinking; 5) Optimism; 6) Collaboration; 7) Communication; 8) Attention to Ethics.

Contemporary educational standards indicate that students can enhance 21st century skills and develop confidence through the integration of STEM subjects in project-based instruction. Accordingly, teachers are required to integrate science and engineering practices in their classrooms explicitly for the students to practice real-world problem-solving and increase 21st century skills (Kelley et al., 2020; NGSS Lead States, 2013; NRC, 2012).

3.4.3 STEM Career Awareness

The term career awareness implies “one's own talents and interests or understanding the opportunities and requirements of various career fields” (Braverman et al., 2002, p. 55). There have been growing efforts to advance STEM education to increase students’ awareness of STEM careers as our society demands a competent STEM workforce (Kier et al., 2014; NGSS Lead States, 2013). Researchers claim that experiences of STEM practice through STEM education increase students’ interests in STEM-related careers and prepare them for future STEM job opportunities (Li et al., 2019; Zuo et al., 2020). Especially, as secondary school years are a critical period for students to decide their future careers, high school STEM teachers need to foster students’ STEM career awareness and job interest (Cohen et al., 2013).

STEM career-related instruction facilitates students’ interests in STEM learning and helps them be engaged in their learning activities (Salonen et al., 2018). To increase STEM career awareness, teachers are recommended to incorporate teaching strategies that students can research and solve real-world problems as scientists and engineers do. In doing so, students can enhance their understanding of the role of STEM in our society (Cohen et al., 2013; NGSS Lead States, 2013). Particularly, the Next Generation Science Standards (NGSS) present eight science and engineering practices, where students can experience what professional scientists and engineers do. The major practices of science and engineering suggested by the NGSS include: 1) Asking questions and defining problems; 2) Developing and using models; 3) Planning and carrying out investigations; 4) Analyzing and interpreting data; 5) Using mathematics and computational thinking; 6) Constructing explanations and designing solutions; 7) Engaging in argument from evidence; 8) Obtaining, evaluating, and communicating information (NGSS Lead States, 2013). By engaging in these science and engineering practices, students can acquire skills and knowledge needed for postsecondary careers, including the STEM field (NGSS Lead States, 2013).

3.4.4 Research Questions

The primary goal of the present study is to identify the factors influencing student STEM learning and determine if teacher self-efficacy and outcome expectancy beliefs affect student attitudes (self-efficacy and expectancy-value beliefs) and academic achievements in integrated STEM. A hypothesized path model was developed based on expectancy-value theory and previous research findings (see Figure 3.1). The study was guided by two research questions:

1. Are teacher self-efficacy and outcome expectancy, student STEM attitudes, 21st century skills, and STEM career awareness positively associated with student STEM knowledge achievement?
2. Are there any direct and indirect effects of teacher self-efficacy and outcome expectancy on students' STEM attitudes, 21st century skills, and STEM career awareness? Are teacher self-efficacy and outcome expectancy, student STEM attitudes, 21st century skills, and STEM career awareness positively associated with student STEM knowledge achievement?

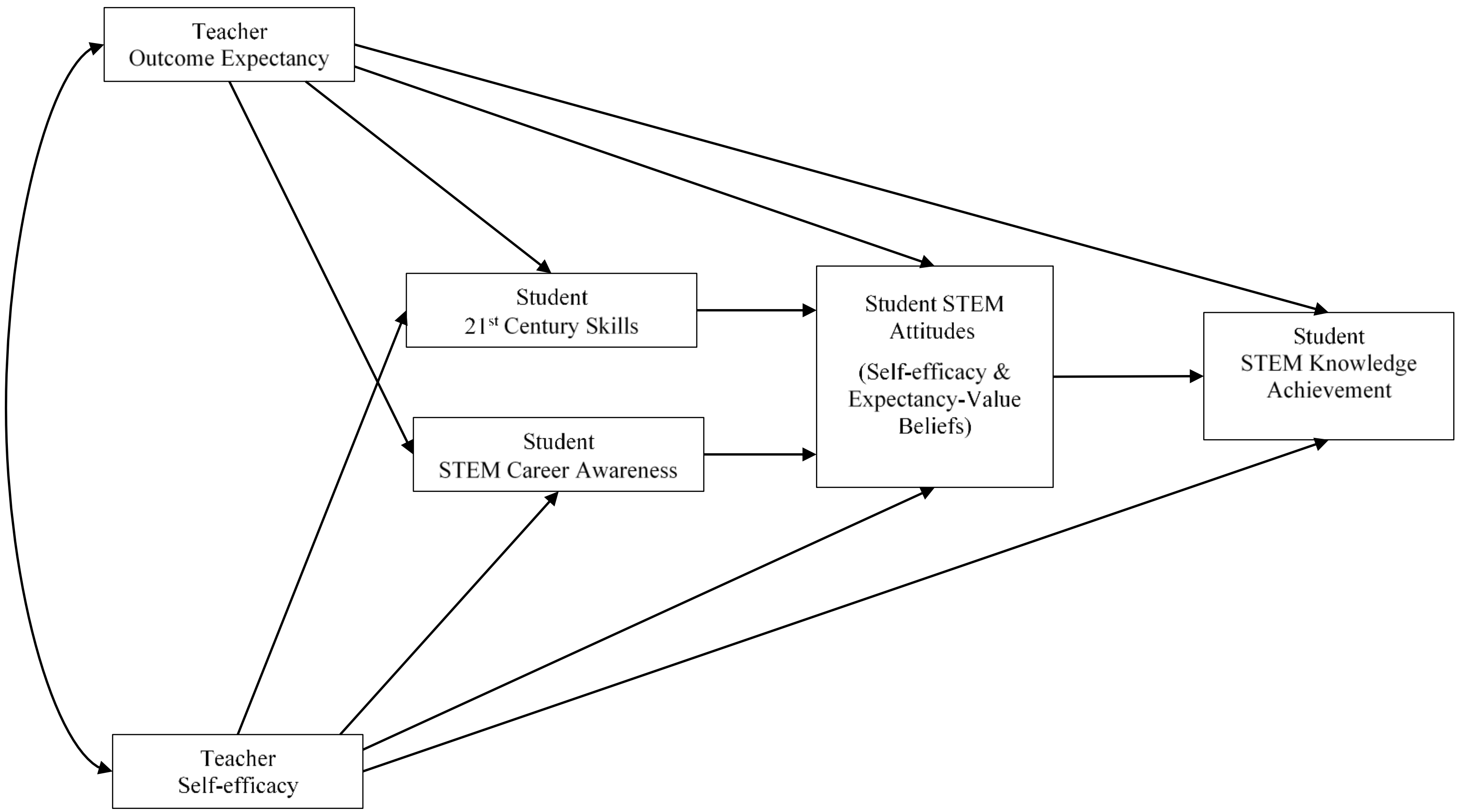

Figure 3.1. Conceptual model representing the influence of teacher self-efficacy and outcome-expectancy on students' learning in STEM.

3.5 Method

3.5.1 Context of Study

The present study was conducted within an integrated STEM project named *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS).* TRAILS was a three-year-long project funded by the National Science Foundation (Award #DRL-1513248). Researchers, educators, and industry partners cooperated to develop an integrated STEM project and supported high school STEM teachers and their students through a community of practice during the 2016-2019 school years.

The TRAILS project consisted of three cohorts: Cohort 1 was the 2016-2017 school year, Cohort 2 was the 2017-2018 school year, and Cohort 3 was the 2018-2019 school year. Cohort 1-3 high school science teachers and engineering and technology education (ETE) teachers experienced the process of integrating science, technology, engineering, and mathematics into authentic contexts through TRAILS professional development. The participating teachers were selected among the applicants following the criteria: 1) The teachers are required to be high school biology or physics teachers or engineering and technology education (ETE) teachers; 2) The teachers are required to be able to participate in the summer professional development (PD).

A total of 30 STEM teachers (15 science teachers, 15 ETE teachers) were participated in the summer professional development (PD) for two weeks during summer vacation. During the PD, teachers were introduced to an exemplar lesson developed by the research team and learned the lesson from the student's standpoint. The exemplar lesson, which was named *Designing Bugs and Innovative Technology (D-BAIT)*, employed biomimicry concepts for designing the fishing lure that mimics the functions of aquatic insects. The teachers also cogenerated their own integrated lessons as a science and engineering technology teacher pair. During the following year, the teachers taught both exemplar lesson *D-BAIT* and the custom lesson each teacher pair developed in their classrooms.

The *D-BAIT* unit consists of 10-12 sessions including: 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 (Han, Kelley, Bartholomew, & Knowles, 2020, p. 27).

3.5.2 Data Collection

The teachers completed the T-STEM survey, which consists of seven subscales including *teaching self-efficacy toward educating STEM content* and *outcome expectancy*, before and after the summer professional development. The survey scores of teachers increased after the summer PD (Kelley et al., 2020), and with the increased teaching efficacy and expectancy beliefs, they taught students during the following school year. Therefore, to see how teacher efficacy and expectancy affect student learning, we used the posttest scores (teacher scores at the point in time of teaching their students) from the T-STEM survey.

Student data were collected from high school science and ETE (engineering and technology education) students in the state of Indiana, who were enrolled in the 2016-2019 school years and experienced integrated STEM lessons from the TRAILS teachers. Students also took the S-STEM survey, which was developed to measure students' attitudes toward STEM, 21st century skills, and STEM career interest, and the *D-BAIT* STEM knowledge test two times respectively before and after they experienced integrated STEM lessons. As the S-STEM post-survey scores and the *D-BAIT* STEM knowledge posttest scores reflect student scores after they learned the *D-BAIT* lesson, these scores were used as student scores for the analysis.

All the surveys were done through the Qualtrics online survey system, and the Institutional Research Board (IRB) approval was obtained in advance.

Final data from the students, who submitted the IRB consent forms from both parents and themselves, are shown in Table 3.1.

Table 3.1. Final student data collection (2016-2019)

Gender		**Ethnicity**						**Grade**					**Sum**
Male	**Female**	**White**	**Black**	**Hispanic**	**Asian**	**Multi**	**Others**	**8**	**9**	**10**	**11**	**12**	
605 (62%)	373 (38%)	822 (84%)	32 (3%)	78 (8%)	31 (3%)	11 (1%)	4 (0%)	6 (1%)	270 (28%)	206 (21%)	278 (28%)	218 (22%)	978 (100%)

For the current study, a total of 507 data, which do not include missing data, were used for the analysis.

3.5.3 Instruments

S-STEM survey

Friday Institute for Educational Innovation (2012b) developed Student Attitudes toward STEM (S-STEM) survey for Elementary level and Middle/High School level. The present study used the S-STEM survey for Middle/High School Student level to measure high school students' STEM attitudes. The S-STEM survey contains six survey sections. The first three sections ask the students about their attitudes toward math, science, engineering and technology, respectively. The fourth section measures students' 21st century skills (21st century learning confidence). The items in the next section ask students about their interests in STEM jobs and their attitudes toward 12 different STEM career areas. The survey items in the first four subscales ask respondents to report their levels of agreement on a five-point Likert-type scale ranging from "strongly disagree" to "strongly agree". For the items in the fifth subscale, students are asked to rate on a four-point Likert-type scale with 1 being "Not at all interested," 2 "Not so interested," 3 "Interested," and 4 being "Very interested". While developing the S-STEM survey, Cronbach's alpha was used to measure internal-consistency reliability for each of the subconstructs. The first four constructs (math attitudes, science attitudes, engineering and technology attitudes, and 21st century skills) satisfied sufficient levels of reliability, 0.83 - 0.92, for both Elementary level and secondary level surveys (Unfried et al., 2015). Cronbach's alpha for the fifth subscale, interests in STEM jobs, was not reported (Friday Institute for Educational Innovation, 2012b). The items in the sixth survey section were not used for the present study. Table 3.2 summarizes the S-STEM survey.

Table 3.2. S-STEM survey summary (Friday Institute for Educational Innovation, 2012b).

Variables in the Present Study	S-STEM Survey Section	Measurement Application
STEM Attitudes (Self-efficacy & Outcome Expectancy)	Math Attitudes	Attitudes toward math – consists of items measuring self-efficacy related to math and expectations for future value gained from success in math
	Science Attitudes	Attitudes toward science – consists of items measuring self-efficacy related to science and expectations for future value gained from success in science
	Engineering and Technology Attitudes	Attitudes toward engineering and technology – consists of items measuring self-efficacy related to engineering and technology and expectations for future value gained from success in engineering and technology
21st Century Skills	21st Century Learning	Attitudes toward 21st century learning – consists of items measuring students' confidence in communication, collaboration, and self-directed learning
Career Awareness	Your Future	Interest in 12 broad categories of STEM career fields
Not Used	More About You	

STEM knowledge test

To measure the STEM knowledge of the students, the *D-BAIT* knowledge assessment was used. The *D-BAIT* knowledge test was developed by the TRAILS research team to evaluate students' STEM knowledge before and after *D-BAIT*. The *D-BAIT* knowledge test consists of 20 items within three subject domains: engineering design, physics, and biology. The full score of the STEM knowledge test was 20.

The initial *D-BAIT* STEM knowledge test was drafted by a panel of six members including an entomology professor, a biology education professor, an engineering technology teacher educator, a two-year technical college faculty, an entomology major graduate student, and a technology major graduate student. The content and face validity of the instrument were checked by two high school biology and engineering technology teachers, who had more than 15 years of teaching experience. Then the instrument was pilot tested with 429 high school students from 18 STEM classrooms. With the results, item analysis was conducted, and the final version of the *D-BAIT* knowledge test with 20 items was obtained after four items were removed (see Appendix A). After removing four items, the overall Cronbach's Alpha score of the final version of *D-BAIT* STEM knowledge test was over .70. The reliability score was also calculated using the adjusted Spearman-Brown prophecy formula (Brown, 1910; Spearman, 1910), and the score was 0.876.

T-STEM survey

For the measures of teacher self-efficacy and teaching outcome expectancy, the T-STEM Survey for technology (ETE) and science teachers was used (The Friday Institute for Educational Innovation, 2012a). According to the survey developer, they adopted the existing survey, Science Teaching Efficacy Belief Instrument (STEBI) (Enochs & Riggs 1990), for the Personal Teaching Efficacy and Beliefs (PTEB) construct and the Teaching Outcome Expectancy Beliefs (TOEB) construct. The T-STEM Survey consists of 7 subscales including: 1) teaching self-efficacy toward teaching STEM content (PTEB); 2) teacher's expectancy on student learning outcome through effective teaching (TOEB); 3) technology use by students; 4) use of STEM instructional practices, 5) teacher attitudes toward 21st century skills; 6) Teacher leadership attitudes; and 7) STEM career awareness (see Table 3.3).

For the construct reliability, developers calculated Cronbach's alpha. For the science domain, Cronbach's alpha for teaching efficacy and outcome expectancy were reported to be .908 and .814, respectively. However, the technology domain Cronbach alpha scores for both self-efficacy and outcome expectancy were not reported (Friday Institute for Educational Innovation T-STEM Survey, 2012a). Therefore, we calculated Cronbach's alpha for technology domains with our data, and the results were the following: technology teacher teaching efficacy = .915, technology teacher outcome expectancy = .800.

The survey items used a Likert-type scale with 1 being "Strongly Disagree," 2 "Disagree," 3 "Neither Agree Nor Disagree," 4 "Disagree," and 5 being "Strong Agree" (The Friday Institute for Educational Innovation 2012a). Table 3.3 demonstrates the summary of the T-STEM Survey.

Table 3.3. T-STEM survey summary: T-STEM science & T-STEM technology (Friday Institute for Educational Innovation, 2012a)

Construct	Measurement Application
*Personal Teaching Efficacy and Beliefs (Self-efficacy)	Self-efficacy and confidence related to teaching the specific STEM subject
*Teaching Outcome Expectancy Beliefs (Outcome Expectancy)	Degree to which the respondent believes, in general, student-learning in the specific STEM subject can be impacted by actions of teachers Belief in the extent to which effective teaching affects student learning in science or technology (Teaching Outcome Expectancy)
Student technology use	How often students use technology in the respondent's classes
STEM instruction	How often the respondent uses certain STEM instructional practices
21st century learning attitudes	Attitudes toward 21st century learning
Teacher leadership attitudes	Attitudes toward teacher leadership activities
STEM career awareness	Awareness of STEM careers and where to find resources for further information

*Note: * used in the present study.*

3.5.4 Data Analysis Process

The first subscale, Teacher Self-efficacy, in the T-STEM survey consists of 11 Likert-style items, and the second subscale, Teaching Outcome Expectancy Beliefs, consists of 9 Likert-style items. All items ranged from 1 (Strongly Disagree) to 5 (Strongly Agree) points. The S-STEM survey for students consists of 49 Likert-style items with five subconstructs: math attitudes, science attitudes, engineering and technology attitudes, 21st century skills, and STEM career awareness of their future. Each item's score in the first four subconstructs ranged from 1(Strongly Disagree) to 5 (Strongly Agree). The items in the fifth subconstruct (career awareness) ranged from 1 (Not at all Interest) to 4 (Very Interest) points (The Friday Institute for Educational Innovation, 2012b).

For each teacher's T-STEM score and student's S-STEM survey subscale scores, the researchers added the values across the questions for each respondent and treated the summed score as each individual's score. As the context of the present study was integrated STEM, and the students experienced integrated STEM teaching and learning, score sums of math attitudes, science attitudes, and technology attitudes in the S-STEM survey were combined to be used as student STEM attitudes score. Each student's ratings on the 21st century skills items and career awareness items - subscales in the S-STEM survey- were summed to be used as student 21st century skills score and STEM career awareness score, respectively. Each teacher's ratings on the self-efficacy questionnaire, the first subconstruct in the T-STEM survey, and Teaching Outcome Expectancy Beliefs, the second subconstruct in the T-STEM survey, were also summed to be used as teacher scores (Teacher Self-efficacy & Outcome Expectancy). Some scores (responses to the negative statements) were reversed in advance, and teacher scores were matched to their students. Table 3.4 shows all the variables and the full scores.

Table 3.4**.** Data description

Variable	Full Score
Teacher Self-efficacy	55
Teacher Outcome Expectancy	45
STEM Attitudes	130
21st Century skills (Learning Confidence)	55
STEM Career Awareness	48
STEM Knowledge Achievement	20

Note: the data were deidentified using Student ID code. There is no missing value in the data.

3.5.5 Data Analysis Method

Path analysis is known to be a useful method for identifying relationships among a set of variables as the structural model (path diagram) depicts a visual representation of relationships among variables. The procedure produces direct, indirect, and total effects represented by standardized coefficients. (Callaghan et al., 2018; Stage et al., 2004). We used the SPSS AMOS 26 software to test the hypothesized path model to investigate causal relationships between factors that could affect student learning in STEM. The path model was developed based on expectancy-value theory and previous research.

3.6 Result

Table 3.5 shows the descriptive statistics of the data, and Table 3.6 displays correlations between the variables. Figure 3.2 depicts the relationships among the factors that affect student knowledge achievement directly and indirectly in integrated STEM learning.

The test of the path model showed that the model was overall acceptable: $\chi 2$ (1) = 23.225, $p < .001$; Comparative Fit Index (CFI) = .940; Incremental Fit Index (IFI) = .942; Tucker-Lewis index (TLI) = .70; Root Mean Square Error of Approximation (RMSEA) = .115. As Figure 3.2 illustrates, teacher self-efficacy and outcome expectancy directly and indirectly affects student STEM knowledge achievement. The standardized direct effect of teacher self-efficacy on student STEM knowledge was .159 ($p < .001$). The standardized indirect effect of teacher self-efficacy and teacher outcome expectancy on student STEM knowledge achievement was .035 ($p = .009$) and .044 ($p = .002$) respectively. Additionally, student STEM attitudes showed direct effects on student knowledge achievement (B= .279, $p < .001$) while student 21st century skills (B = .093, p = .002) and STEM career awareness (B = .125, p = .003) influenced STEM knowledge achievement indirectly when mediated by STEM attitudes. All significant direct and indirect effects were indicated in Table 3.7.

Table 3.5. Descriptive statistics of the data

	N	Min	Max	Mean		*SD*	Skewness		Kurtosis	
		Statistic	Statistic	Statistic	*SE*	Statistic	Statistic	*SE*	Statistic	*SE*
STEM Knowledge	507	4	18	10.61	.151	3.408	.005	.108	-.851	.217
STEM Attitudes	507	32	130	89.35	.715	16.097	.031	108	.344	.217
21st Century Skills	507	11	55	44.39	.296	6.659	-.731	.108	1.674	.217
STEM Career Awareness	507	12	48	27.59	.277	6.241	-.254	.108	-.034	.217
Teacher Self-efficacy	507	31	55	47.41	.216	4.868	-.866	.108	-.838	.217
Teacher Outcome Expectancy	507	25	41	31.94	.167	3.761	-.032	.108	1.806	.217

Note: Min = minimum, Max = maximum, SD = standard deviation, SE = standard error.

Table 3.6. Correlation coefficients among the variables (*N* = 507)

`	1	2	3	4	5	6
1. Student STEM Knowledge	1.000					
2. Student STEM attitudes	.315**	1.000				
3. Student 21st Century Skills	.128**	.419**	1.000			
4. Student STEM career awareness	.168**	.512**	.210**	1.000		
5. Teacher Self-efficacy	.200**	.132**	.000	.129**	.1.000	
6. Teacher Outcome Expectancy	.101*	.163**	.037	.013	.076	1.000

*Note: *p < .05, **p < .01 (2-tailed).*

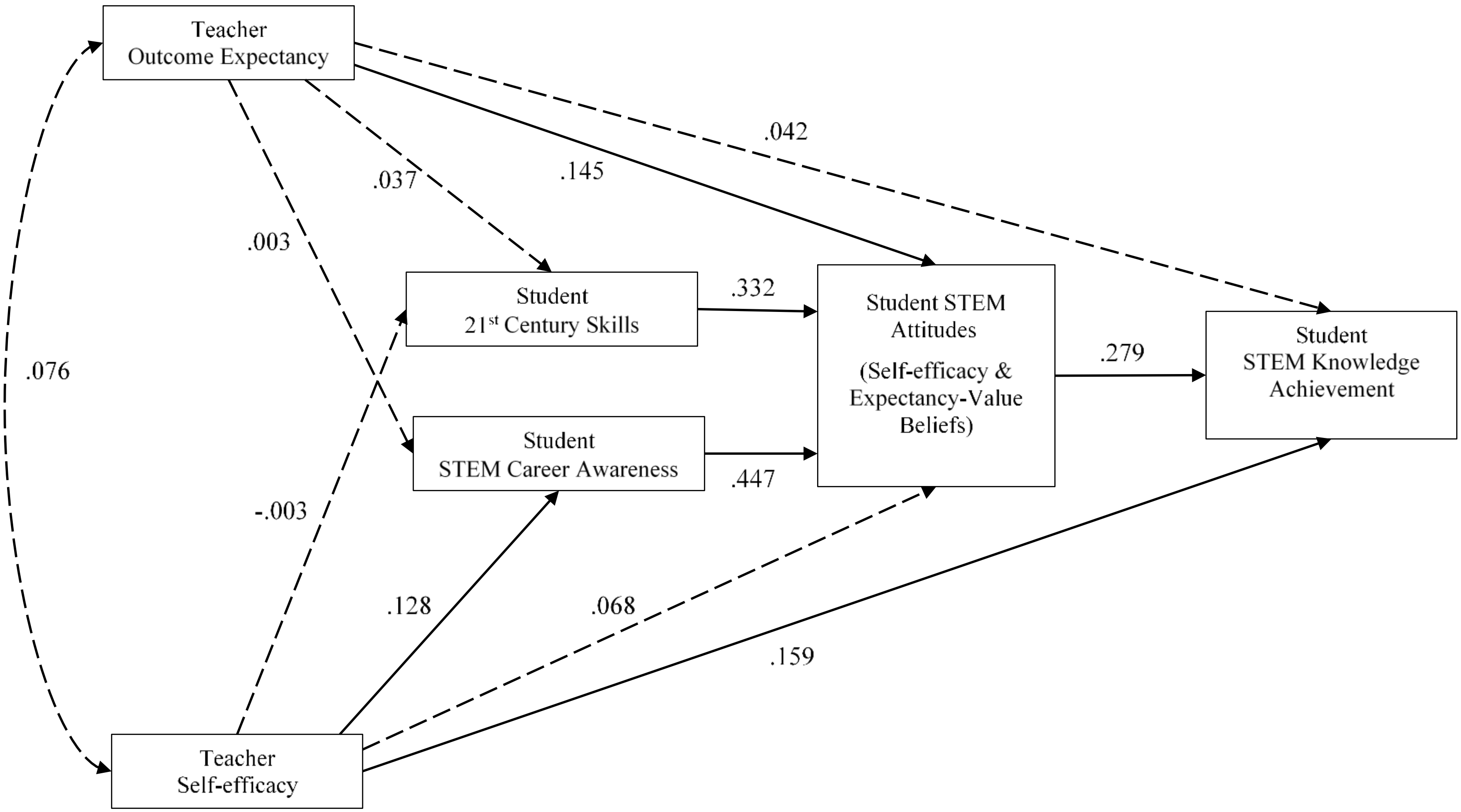

Figure 3.2. Path model of integrated STEM learning.

Note: Standardized estimates. Solid line path coefficients are significant at p < .05 while the dotted line path coefficients are nonsignificant.

Table 3.7. Standardized direct, indirect, and total effects in the SEM model

Predictor	Criterion	Direct effect	Indirect effect	Total effect
Teacher Self-efficacy	Student STEM Knowledge	.159**	.035**	.194**
Teacher Self-efficacy	Student 21st Century Skills	-.003		-.003
Teacher Self-efficacy	Student STEM Attitudes	.068	.056*	.124*
Teacher Self-efficacy	Student STEM Career Awareness	.128**		.128**
Teacher Outcome-expectancy	Student STEM Knowledge	.042	.044**	.086**
Teacher Outcome-expectancy	Student 21st Century Skills	.037		.037
Teacher Outcome-expectancy	Student STEM Attitudes	.145**	.014	.159**
Teacher Outcome-expectancy	Student STEM Career Awareness	.003		.003
Student STEM Attitudes	Student STEM Knowledge	.279**		.279**
Student 21st Century Skills	Student STEM Knowledge		.093**	.093**
Student 21st Century Skills	Student STEM Attitudes	.332**		.332**
Student STEM Career Awareness	Student STEM Knowledge		.125**	.125**
Student STEM Career Awareness	Student STEM Attitudes	.447**		.447**

*Note: *p < .05, **p < .01 (two-tailed). Bootstrap approximation obtained by constructing two-sided bias-corrected confidence intervals.*

3.7 Summary

The study investigated how multiple factors of both students and teachers influence students' STEM learning with the two guiding questions as the following.

1. Are teacher self-efficacy and outcome expectancy, student STEM attitudes, 21^{st} century skills, and STEM career awareness positively associated with student STEM knowledge achievement?
2. Are there any direct and indirect effects of teacher self-efficacy and outcome expectancy on students' STEM attitudes, 21^{st} century skills, and STEM career awareness?

For the first research question, the results reveal significant direct effects of teacher self-efficacy on students' STEM knowledge achievement (B = .159, p < .001). Student STEM attitudes also significantly influenced student STEM knowledge achievement (B = .279, p < .001). Even though no significant direct effects of teacher outcome expectancy on student STEM knowledge achievement were found, it indirectly influenced student achievement by affecting their STEM attitudes. Additionally, indirect effects of 21^{st} century skills (.093) and STEM career awareness (.125) on STEM knowledge achievement were found to be significant when mediated by STEM attitudes. For the second research question, teacher outcome expectancy show significant direct effect on student STEM attitudes (B = .145, p < .001). Teacher self-efficacy show significant direct effect on student STEM career awareness (B = .128, p < .001) and indirect effect on STEM attitudes (.056). Both teacher self-efficacy and outcome expectancy did not show significant effects on student 21^{st} century skills.

The findings of this study indicate that self-efficacy and expectancy-value beliefs are critical for both teachers and students in teaching and learning integrated STEM. The standardized path diagram depicts the collective effects of teacher factors and student factors on student STEM attitudes and knowledge achievement (See Figure 3.2 and Table 3.7).

3.8 Discussion

Aiming to identity the factors that influence students' learning in STEM, the current study investigated the relationships among teacher self-efficacy and outcome expectancy, student STEM attitudes (self-efficacy and expectancy-value beliefs), 21st century skills, and STEM career awareness in an integrated STEM education context. According to the findings, the current study reinforces previous literature that teachers' self-efficacy and expectancy beliefs are critical factors for enhancing students' attitudes and performance, which sheds light on the importance of the teachers' roles in student learning. Integrating different subjects into one project is a relatively new way of teaching and learning. Consequently, the effect of teachers self-efficacy and student attitudes (self-efficacy and expectancy-value beliefs) on students' achievement in an integrated STEM context was not researched as much as that of in general classrooms. The findings of the current study are consistent with the previous literature, which found that teachers' beliefs in their teaching efficacy and success are strong predictors of students' self-efficacy, motivation, and academic performance (Cannon & Scharmann, 1996; Muijs & Rejnold, 2001; Podell & Soodak, 1993; Ross, 1992; Ross et al., 2001; Rutherford et al., 2017; Shahzad & Naureen, 2017; Tschannen-Moran & Barr, 2004; Yoon et al., 2012). This result indicates the significance of educating teachers since teacher self-efficacy for successful teaching relates to content knowledge, quality pedagogy, and teaching strategies considerably (Knowles, 2017, p. 25; Rutherford et al., 2017; Stohlmann et al., 2012; Yoon et al., 2012). Through professional development, teachers can construct a community of practice, where they could enhance knowledge, instructional skills, and pedagogical approaches (Kelley et al., 2020; Knowles et al., 2018).

Additionally, the present study draws attention to the importance of affective domains in STEM education (ITEEA, 2020; NGSS Lead States, 2013). Affective domain includes attitudes, interest, motivation, social skills, and so on, and researchers and instructional developers have been claimed to include affective domain in curriculum and instruction. However, the way of placing an affective domain within a curriculum can be different depending on the context, and many teachers lack attention to an affective domain (Hansen, 2009; Reigeluth, 1999). Therefore, teacher training programs that prepare teachers to teach students affective skills are recommended. For example, project-based instructions help students develop social and interpersonal skills (Hansen, 2009; Li et al., 2019). By learning how to incorporate project-based instruction in their teaching, teachers can enhance students' attitudes, self-efficacy beliefs, and motivation to learn (Abdullah et al., 2010; Markham, 2011; Mataka & Kowalske, 2015). To teach integrated STEM, further research is needed to develop instructional strategies which are "focusing teaching and learning across all three domains of learning: cognitive, affective, and psychomotor" (ITEEA 2020,

p. 4; Griffith & Nguyen, 2006). Since integrated STEM education involves complex teaching strategies and requires insights into students' educational and psychological needs, which are different from general education, further discussions based on more empirical research are required.

3.9 Implication

The current study provides some theoretical and practical implications. First, the present study contributes to the research in expectancy-value theory framework with empirical evidence. Consistent with previous studies, the current study demonstrates that self-efficacy and outcome expectancy of both teachers and students are significant predictors of student STEM knowledge achievement as a direct factor or a mediator (Bradley et al., 1999; Caraway et al., 2003; Nadelson et al., 2012; Nugentet et al., 2015; Ross, 1992; Tschannen-Moran & Barr, 2004; Pajares & Miller, 1994; Yoon et al., 2012; Wood & Locke, 1987; Zimmerman et al., 1992). As noted earlier, teachers' self-efficacy and beliefs can influence the successful outcome of students' performance (Bal-Taştan et al., 2018; Borko & Whitcomb, 2008; Gulistan & Hussain, 2017; Perera & John, 2020; Salgado et al., 2018), and students with strong competencies of success and efficacy beliefs tend to perform more challenging tasks and succeed more frequently (Bandura, 1994; Eccles & Wigfield, 2002). This finding confirms expectancy-value theory that expectations and task-value beliefs are linked to the achievement-related choice and performance of individuals (Eccles & Wigfield, 2002). Second, this study indicates that students' STEM knowledge achievement is influenced not only by a single factor but also by multiple factors of both teachers and students. Although many studies have investigated the relationships between students' self-efficacy, motivation, and learning outcomes, few studies were reported on the multiple factors influencing student learning in STEM (Wiebe et al., 2018). Therefore, this study may provide implications by adding empirical evidence to the prior research. Specifically, as the path model illustrates, teacher self-efficacy and outcome expectancy are linked to student achievement directly or indirectly through student career interests and attitudes. Moreover, students' 21st century learning confidence and interests in future STEM careers significantly influenced their attitudes toward STEM, which in turn affected their academic achievement in STEM. Even though no significant direct effects of students' STEM career awareness and 21st century skills on their STEM knowledge achievement were found, indirect effects of STEM career awareness and 21st century skills mediated by STEM attitudes (student self-efficacy and outcome expectancy) were detected. These results imply that multiple factors interplay and finally affect student STEM knowledge achievement collectively. Finally, the present study focused on all core STEM disciplines: science, technology, engineering, and mathematics. As prior studies of the relationship between motivation and achievement have been conducted mostly on science or mathematics alone, the present study addresses the gap in this area by using the S-STEM survey focusing on student attitudes (expectancy-value beliefs) toward all STEM subjects (Wiebe et al., 2018).

3.10 Limitation

This study has some limitations. Although construct validities of the instruments were confirmed, the respondents' honesty, which is required for self-report surveys, cannot be verified. Additionally, as the current study investigated the relationships between the factors of both teachers and students, teacher career awareness and 21st confidence may also need to be considered to draw conclusions that better discuss the findings. Finally, the variables of student STEM attitudes include both self-efficacy and expectancy-value beliefs while teacher variables include teacher self-efficacy and outcome expectancy separately. Following the instrument developers and previous studies, we used STEM attitudes, which indicate "a composite of both self-efficacy and expectancy-value beliefs" (Unfried et al., 2015, p. 23; Wiebe et al., 2017). This may not fully explain the effect of each specific factor, self-efficacy and expectancy-value beliefs.

Conflicts of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Author Contributions

The authors confirm contribution to the paper as follows: study conception, data collection, and data analysis: Han, J.; study design and review: Kelley, T. R., and Knowles, G. All authors reviewed the results and approved the final version of the manuscript.

NSF Disclaimer

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CHAPTER 4. (STUDY 3) BUILDING A SUSTAINABLE MODEL OF INTEGRATED STEM: INVESTIGATING SECONDARY SCHOOL STEM CLASSES AFTER INTEGRATED STEM PROJECT

4.1 Abstract

This study investigates the sustainability of an integrated STEM program after participation in a funded integrated STEM project. Two US high school science teachers and an engineering technology teacher sustained implementation of an integrated STEM curriculum after the conclusion of the funded program, TRAILS. Students' academic achievements after the integrated STEM lesson were compared to those who previously participated in the project. The results reveal that the students showed no difference from the previous TRAILS students in terms of academic achievements as measured by STEM knowledge score increases, which may indicate that the teachers maintained implementation fidelity and effectiveness. Additionally, 21st century skills survey was newly conducted to examine students' growth in confidence in 21st century skills after they were taught integrated STEM. The students showed increases in their confidence in critical thinking, which also indicates that the students benefitted from these teachers' instruction despite the conclusion of the funded program and absence of support. Based on the findings from teachers' experiences of multiple years of integrated STEM teaching, the study discusses how to better support teachers for successful implementation of integrated STEM curriculum as a sustainable education program in secondary schools. This paper will also discuss the importance of building a Community of Practice (CoP) for successful implementation of integrated STEM.

Keywords: integrated STEM, sustainability, shared practice, Community of Practice

4.2 Introduction

With growing attention towards integrated STEM education K-12 in the United States, developing instructional strategies and curricular materials to build sustainable models of integrated STEM has become critical. For this purpose, researchers suggest providing teachers with opportunities to participate in professional development, where they can develop STEM curriculum and increase the perception and understanding of STEM fields while simultaneously teaching 21st century competencies (Guzey, Harwell, & Moore, 2014; Kelley, Knowles, Holland, & Han, 2020; Kelley, Knowles, Han, & Trice, 2021). Creating a sustainable Community of Practice to support STEM teachers is also recommended (Kelley & Knowles, 2016; Kezar & Gehrke, 2017). In a Community of Practice, teachers can share their concerns and deepen their knowledge by exchanging expertise with other teachers and experts on an ongoing basis (Wenger, McDermott, & Snyder, 2002).

To teach STEM effectively in secondary schools, researchers presented the following key approaches within a well-designed integrated program: a) STEM content integration, b) inquiry-based instruction, c) project- and problem-based instruction, d) real-world problem solving, e) collaboration, f) design-based instruction, and g) digital technologies (Kelley & Knowles, 2016; Nadelson & Seifert, 2017; Nguyen, Nguyen, & Tran, 2020). With the goal of building a sustainable and replicable model of integrated STEM education program, the current study examined an integrated STEM project, TRAILS), which incorporated inquiry- and design-based learning using 3D printing technology. Specifically, the study investigates STEM classes after the project had ended (with both financial and professional development support ended) to examine if the TRAILS program provided the teachers with a practical model of integrated STEM education that motivates them to continue teaching integrated STEM.

During the 2016-2019 school years, TRAILS researchers, local industry partners, and graduate students partnered with the teachers and created a Community of Practice by providing teachers with professional development and supporting them to construct STEM knowledge and skills in an authentic STEM context. Three STEM teachers, who participated in the TRAILS project for multiple years and decided to teach the TRAILS lessons again after the conclusion of the TRAILS project, participated in the current study and implemented the integrated STEM lesson again during the 2019-2020 school year. 21st century skills pre- and post-surveys and STEM knowledge test were implemented with students of the three participating teachers. The academic achievements of the participating students measured by the STEM knowledge test, whose teachers attempted to maintain effective integrated STEM instruction even without the funding after the project had ended, will be compared to those who participated in the TRAILS project in previous years. From the TRAILS model, how teachers and students benefit from shared practices of science and engineering in integrated STEM will be addressed, and how to better support teachers in implementing integrated STEM will be discussed.

4.2.1 Research Questions

This study investigates how teachers implement integrated STEM as a sustainable education program after participating in an integrated STEM project. To investigate whether the teachers positively influenced the academic achievements and 21st century skills of students after the conclusion of the funded program, this study examines three research questions.

1) Are the students' (Year 4) STEM knowledge achievements different from those of the students (Year 1, 2, 3) who participated in the TRAILS project with program support? (RQ1)
2) Did the three sample teachers' students from the current year (Year 4, after program funding ended) and from previous years (Year 1, 2, 3) show the difference in their STEM knowledge achievement? (RQ2)
3) Did the three sample teachers' students from the current year (Year 4, after program funding ended) increase or decrease their confidence in their 21st century skills after learning integrated STEM? If so, how did they increase or decrease their 21st century skills? (RQ3)

4.3 Literature Review

4.3.1 Integrated STEM Context: Shared Practices

Integrated STEM education provides a context for scaffolding multiple facets of STEM knowledge, which can be applied to authentic real-world problems (Han, Kelley, Bartholomew, Knowles, 2020; Kelley & Knowles, 2016; Nadelson & Seifert, 2017; Stohlmann, Moore, & Roehrig, 2012). Instructional activities in the integrated STEM context facilitate students' learning of science through engineering design. By using engineering design and technology, students can test their science knowledge and apply it to a real-life situation (Brown, Collins, & Duguid, 1989; Kelley & Knowles, 2016; NGSS Lead States, 2013).

Integrated STEM education is "the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning" (Kelley & Knowles, 2016, p. 3). Researchers and the US educational standards, such as Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) and Standards for Technological and Engineering Literacy (STEL) (ITEEA, 2020) emphasize connections between and across STEM disciplines and argue for integrating crosscutting concepts of STEM in school curricula (Bybee, 2010; Kelley & Knowles, 2016). Specifically, Next Generation Science Standards (NGSS) stress interdependence of STEM disciplines and require teachers to integrate science and engineering in an explicit way by sharing practices of the two disciplines. The shared practices of science and engineering addressed by NGSS include: 1) asking questions and defining problems; 2) developing and using models; 3) planning and carrying out investigations; 4) analyzing and interpreting data; 5) using mathematics and computational thinking; 6) constructing explanations and designing solutions; 7) engaging in argument from evidence, and; 8) obtaining, evaluating, and communicating information (NGSS Lead State, 2013, Appendix F). Standards for Technological and Engineering Literacy (STEL) also noted interconnectivity of STEM and stressed infusing technology and engineering practices into integrated STEM. According to STEL, technology and engineering practices include systems thinking, creativity, making and doing, critical thinking, optimism, collaboration, and attention to ethics (ITEEA, 2020). The core ideas that connect STEM disciplines and share practices are scientific inquiry and engineering design (Apedoe, Reynolds, Ellefson, & Schunn, 2008; Han, Kelley, Bartholomew, & Knowles, 2020; Kelley & Knowles, 2016; NGSS Lead State, 2013; National Research Council [NRC], 2011). According to researchers and the US educational standards, engineering design is a subject integrator in integrated STEM, and engineering and technology can be a vehicle for science learning by realizing scientific inquiry (ITEEA, 2020; Kelley & Knowles, 2016; NGSS Lead States, 2013).

In summary, integrated STEM allows scientific inquiry to be realized by technology and engineering design using authentic design tasks, and mathematical thinking plays a significant role as a helper in this process (Han, Kelley, Bartholomew, & Knowles, 2020; Kelley, 2010). However, although integrated STEM education is innovative and beneficial for student learning, teaching integrated STEM curriculum is complex as it requires not only content integration, but also "teaching and learning across all three domains of learning: cognitive, affective, and psychomotor" (ITEEA 2020, p.4) (see Figure 4.1).

4.3.2 Benefits of Integrated STEM Education

The goals of integrated STEM education are to help students prepare for STEM careers, build STEM literacy, increase interest and engagement in STEM, and develop 21st century competencies (Pearson, 2017).

Integrated STEM education helps learners develop problem-solving abilities by connecting subjects and real-world problems. While engaging in inquiry-based real-world problems, students enhance design thinking, which is required for a competent STEM workforce in the future (Dare, Ellis, & Roehrig, 2018; Jonassen, Strobel, & Lee, 2006; Kelley & Knowles, 2016; Moore, Stohlmann, Wang, Tank, Glancy, & Roehrig, 2014). By integrating engineering and technology into science learning, students can develop and test their scientific knowledge and apply it to real-world problems in everyday situations (Brown et al., 1989; Kelley & Knowles, 2016). Kelley and Knowles (2016) posited that "science education can be enhanced by infusing an engineering design approach because it creates opportunities to apply science knowledge and inquiry as well as provides an authentic context for learning mathematical reasoning for informed decisions during the design process" (p.5).

Additionally, within the integrated STEM context, students can develop 21st century skills such as creativity, critical thinking, communication, and collaboration by addressing complex problems in our world (Bellanca & Brandt, 2010; Dare et al., 2018). According to National Research Council (NRC) (2011), 21st century skills include the ability to: 1) solve the complex problems, 2) think critically about the tasks, 3) effectively communicate with people using a variety of techniques, 4) work collaboratively with others, and 4) acquire new skills and information on one's own (p.1).

Moreover, integrated STEM instructions influence students positively on affective outcomes as well as cognitive outcomes by increasing the motivation to learn (Nadelson & Seifert, 2017; NRC, 2014), interests in STEM careers (Shahali, Halim, Rasul, Osman, & Zulkifeli, 2016), and attitudes toward STEM (Guzey et al., 2014; Han, Kelley, & Knowles, 2021). Standards for

Technological and Engineering Literacy (STEL) also noted that integrating technology and engineering into science and mathematics education will enhance student learning not only in the cognitive domain (Anderson & Krathwohl, 2001) but also in the affective domain (Bloom, Krathwohl, & Masia, 1964) and psychomotor domain (Bixler, 2011) by increasing technological competencies. Based on Bloom's (1956) Taxonomy of Educational Objectives, which consist of six major categories (Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation), STEL addressed three domains of learning to the technology and engineering and the applicable levels of each domain (see Figure 4.1).

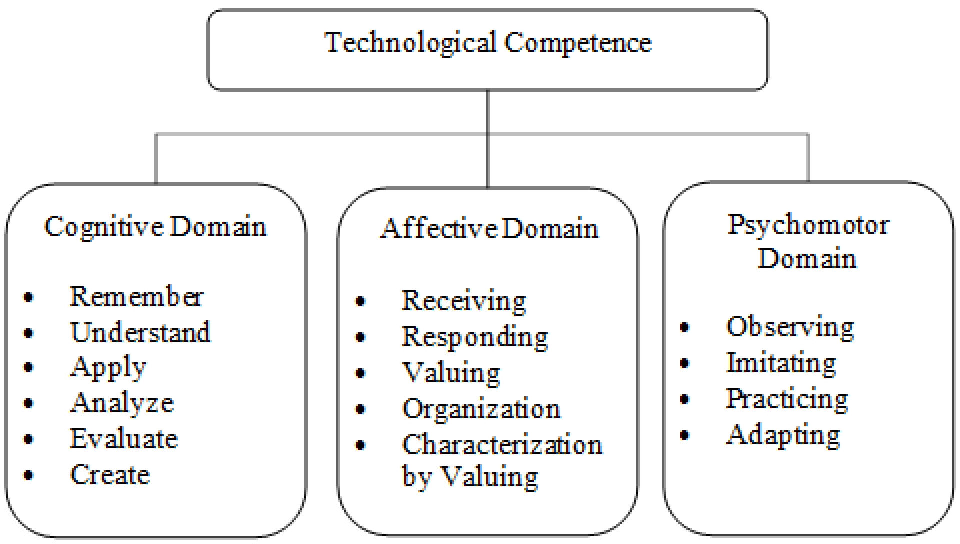

Figure 4.1. Three Domains of Learning to the Technology and Engineering (ITEEA, 2020, p.121-122).

However, although efforts to integrate STEM in authentic contexts are increasing dramatically, further work remains to connect these disciplines in a deliberate way and apply STEM knowledge to real-world problems, since making connections across STEM disciplines in an integrated context still often remains implicit (Kelley & Knowles, 2016; NAE and NRC, 2009).

4.3.3 Challenges of Integrated STEM Implementation

For successful integrated STEM education, it is necessary to address the challenges that teachers confront in implementing integrated STEM and reduce the barriers to teach integrated

STEM (Dare et al., 2018; Ejiwale, 2013; Kelley et al., 2021; Wang, Moore, Roehrig, & Park, 2011). Some barriers from advancing integrated STEM that researchers identified are the following: (a) poor preparation and shortage in supply of qualified teachers, (b) lack of investment in teacher professional development (PD), (c) poor preparation and inspiration of students, (d) lack of connection with individual learners in a variety of ways, (e) insufficient support from the school system, (f) insufficient research collaboration across STEM fields, (g) poor content preparation, (h) poor content delivery and methods of assessment, (i) insufficient laboratory facilities and instructional media, and (j) lack of hands-on training for students (Ejiwale, 2013). Kelley and Knowles (2016) also identified some barriers that hinder integrated STEM education, which include rigid departmental agendas and requirements, inflexible content standards, and end-of-year exams.

To overcome the barriers to integrated STEM education, providing teachers with adequate support through collaboration of school administrators, local communities, and educational policy makers is critical (Dare et al., 2018; Kelley & Knowles, 2016). Providing teachers with opportunities to participate in professional development, where they can increase confidence and knowledge and learn how to integrate contents and STEM practices in instruction is also important (Kelley & Knowles, 2016; Kelley et al., 2020; Nadelson & Seifert, 2017; Shernoff, Sinha, Bressler, & Ginsburg, 2017). Moreover, increasing teacher self-efficacy through Community of Practice is pivotal. By increasing teacher self-efficacy, teachers' comfort levels and their motivations to teach STEM content will also increase (Han, Yelling, Mentzer, & Kelley, 2021; Nadelson, Seifert, Moll & Coats, 2012). Studies also show that teachers can increase their self-efficacy by participating in a Community of Practice as part of their professional development (Ekici, 2018; Kelley et al., 2020; McCollough, Jeffery, Moore, & Champion, 2016).

4.4 TRAILS Model for Integrated STEM

TRAILS (National Science Foundation [NSF] Award #DRL-1513248) aimed to build a sustainable and replicable model of integrated STEM education by providing teachers with adequate support including quality educational curriculum, professional development, and on-going support from a Community of Practice. The TRAILS project integrates science, technology, engineering, and mathematics in an authentic way to enhance student learning, and utilizes engineering design as the key to integrating STEM. High school science teachers and engineering and technology education (ETE) teachers participated in the summer professional development (PD) to be trained for teaching integrated STEM lessons during the following school year. Through professional development, TRAILS provided science and ETE teachers with practical and feasible approaches to support student learning in STEM (Kelley et al., 2020; NRC, 2014; Ntemengwa & Oliver, 2018).

The TRAILS project consisted of three cohorts: Year 1 was the 2016-2017 school year, Year 2 was the 2017-2018 school year, and Year 3 was the 2018-2019 school year, collaborating with a total of 30 teachers (15 science teachers, 15 ETE teachers) and 978 students (978 experimental group students) from 17 schools in suburban and rural school settings throughout the state of [Name of STATE] (experimental group with IRB consent forms submission). Every summer, high school science and ETE teachers participated in a two week, over 70 hours of professional development and developed integrated STEM lessons for their students as a science-ETE teacher pair. The teachers also engaged in an exemplar integrated STEM unit *D-BAIT* developed by the TRAILS team to teach this lesson to their students the following school year. Engineering design is the situated context in the TRAILS project and was used as a platform for integrated STEM (Brown et al., 1989; Kelley & Knowles, 2016). In the *D-BAIT* lesson, teachers experienced engineering design activities, which included engineering design brainstorming, aquatic specimen collection and identification, CAD instruction, 3D printing prototypes, and fishing lure prototype field testing. After participating in the *D-BAIT* lesson, science and ETE teachers were partnered, and each teacher pair created their own integrated STEM lesson with the help of the TRAILS research team. In the following academic school year, teachers delivered the *D-BAIT* lesson and the custom lesson they developed during the professional development to their classrooms.

The *D-BAIT* unit consists of 10-12 sessions, including biomimicry, life science, mathematics, engineering, and students practice manufacturing from this lesson through prototyping and 3D printing (see Figure 4.2 and Table 4.1). Students investigate water quality with the water insects they collected and research underwater creatures and their aquatic movements. Students also learn neutral buoyancy and biomimicry to apply these concepts to their prototype designs. Then students create fishing lure samples that mimic the functions of underwater insects and satisfy neutral buoyancy. For the entirety of the *D-BAIT* lesson, the biology teacher and the engineering teacher were encouraged to partner and teach both science and ETE classes collaboratively.

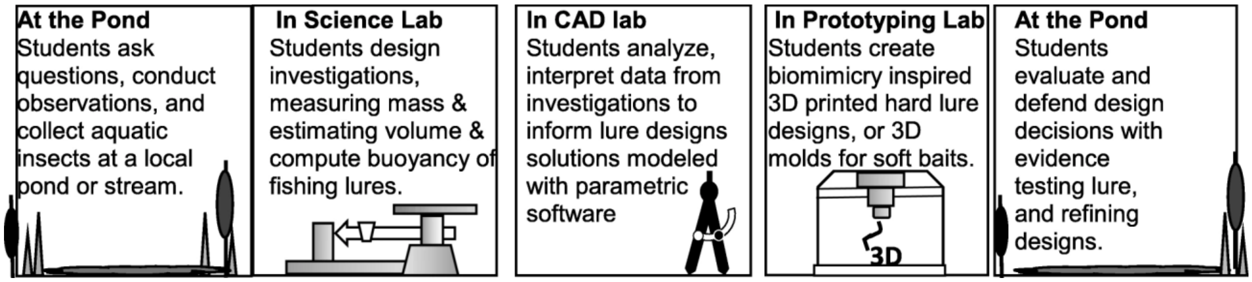

Figure 4.2. *D-BAIT* Lesson Activities: Science and Engineering activities (Kelley et al., 2020, p.7).

Table 4.1. TRAILS Science and Engineering Activities for Students' 21st Century Skills.

Learning Activity	**Entomological Science Inquiry Lab**	**Additive Manufacturing (3D Printing) of a Fishing Lure**	**Design Analysis of Lure Prototype**
Lesson Description	Aquatic entomology field lab to collect insects. Mathematical exercise to estimate insect diversity. Assess water quality using sampled insects.	Parametric modeling software is used to create CAD designs for visualizing 3D models.	Finite Element Analysis (FEA) features used within CAD parametric modeling software to generate simulations to test the strength of materials, calculate the volume of materials, and calculate buoyancy factors.
Creativity	Students create individual inquiry questions regarding insects to investigate through observations.	Students create unique design solutions applying characteristics of insects collected in the field to make an innovative fishing lure design.	Students develop and implement prototype testing investigations to assess prototype performance and overall analysis of design.
Critical Thinking	Students think about how insects become food for fish and how insects are indicators of water quality.	Students are challenged to determine how to use innovative technologies to simulate insect motion, as observed in the inquiry investigation.	Students generate testable hypotheses, investigate prototype solutions, and use features within innovative technology to generate evidence of proof of concept.
Communication	Students record observations using field n otes, videos, and digital photos to create a final lab report.	Students generate multi-view CAD drawings providing key prototype specifications necessary to manufacture the prototype solution.	Students document fair test investigations providing numerical data evidence to assess lure design performance.
Collaboration	Through a Community of Practice, students report out individual findings to entire science and technology classes.	Students share final design drawings across technology and science classes indicating how science inquiry observation data is used to create design solutions.	Students will share design analysis investigation findings with all stakeholders within the Community of Practice.

4.5 The Present Study

The present study was conducted during the 2019-2020 school year (Year 4) to investigate how teachers implement integrated STEM after professional development and funded support has ended.

After the three-year-long TRAILS projected ended, some teachers taught integrated STEM lessons, including the *D-BAIT* lesson again. Among them, three teachers (2 Science, 1 ETE) from two high schools, who participated in TRAILS for all three years (Year 1, 2, 3), volunteered to participate in this study during the 2019-2020 school year (Year 4). Table 4.2 displays the demographics of the three participating teachers and their students.

Table 4.2. Year 4 Demographics of teachers and their students.

	Students						
Teacher	Total	Male	Female	White	Black	Hispanic	Asian
Charlotte Ames	16	4	12	15	1	0	0
Mark Zion	15	15	0	9	2	4	0
Corey Adams	19	8	11	18	0	1	0
Total	50	27	23	42	3	5	0

Note: the teacher's names are pseudonyms.

4.5.1 Lesson Implementation

Before this present study, the researchers conducted a multiple case study during the last year of the TRAILS project (Year 3) to capture how integrated STEM can be delivered to classrooms by science-ETE teacher pairs after they were trained at the PD. As the teachers were provided freedom in terms of how to implement the integrated STEM lessons, they customized their own implementation plans, which they thought were optimal for their classrooms and school structure. From this previous case study that examined STEM teachers' approaches to implementing integrated STEM, the researchers identified the emergence of three distinct integrated STEM implementation models (Kelley et al., 2021, p.43). (See Table 4.3)

Table 4.3. Three Models of Integrated STEM Implementation (Kelley, Knowles, Han, & Trice, 2021, p. 40).

Model 1	Model 2	Model 3
STEM Content Inclusion	**STEM Content Integration**	**STEM Content and Practices Integration**
• Content is integrated in one classroom • One teacher adds one or more additional STEM domain content within the classroom • The approach is often called multidisciplinary	• Each domain teacher shared STEM content from domain • Each domain teacher teaches content, equipping student to become experienced with key practices and knowledge • Two or more STEM domains information and practices are shared across classrooms • Students become 'experts' sharing STEM knowledge	• Content and practices are shared within a Community of Practice • STEM knowledge and practices inform process taken by students • For example, science inquiry, engineering design, and computational thinking are informed by the integration process (crosscutting)

The three models identified are important to understand how teachers implement integrated STEM while overcoming barriers. Even though each model has advantages and disadvantages, teachers found their own way to teach integrated STEM best fit their students, schedule, and school structure (Kelley et al., 2021). Now, as these three models of implementation were captured during the TRAILS project, we wondered how the teachers implement integrated STEM after the project and how these implementation models will be modified based on their previous experience of teaching integrated STEM during the project.

For the current study (Year 4), the researchers visited one participant school two times to observe how teachers implement integrated STEM after the TRAILS program ended. The class observed was an integrated STEM class that consisted of twenty biology students and eighteen engineering technology students.

The biology teacher, Corey Adams, and the ETE teacher, Mark Zion, had been teaching the *D-BAIT* lesson since the 2016-2017 school year (Year 1). As they participated in the TRAILS project for all three years (Year 1, 2, and 3), the current year was the fourth of the integrated STEM unit implementation. During the TRAILS project, they were supported by the research team with summer PD, follow-on sessions, and web meetings. Also, they could exchange ideas with other STEM teachers from other schools during the summer PD. However, this year (Year 4) they implemented *D-BAIT* again without the help and funding support they received from previous years.

During the TRAILS project, Corey Adams and Mark Zion taught two integrated STEM lessons: one exemplar lesson, *D-BAIT*, and one custom lesson, Bumblebot, which they developed collaboratively during the PD. In the first and second year of participation in the TRAILS project, they taught the two classes separately (Model 2), but in the third year, they taught both science and ETE classes together for the *D-BAIT* lesson (Model 3). When they taught the integrated STEM lesson separately (Model 2), they switched the classes and the students as needed to teach their subjects to the students of other subjects. This year, they taught together for the *D-BAIT* lesson again (Model 3) and separately for the custom lesson (Model 2). All the teaching materials were the same as the previous years.

The present study focused on the *D-BAIT* lesson. Corey Adams and Mark Zion taught the *D-BAIT* lesson together four times a week for an entire three weeks of instruction, and through the collaboration of the two teachers, biology students and ETE students worked together throughout the *D-BAIT* unit and learned both disciplines in an integrative way.

During the first and second sessions of the *D-BAIT* lesson, students learned basic entomology and environmental science, such as aquatic habitats, food webs, adaptations, evolution, ecosystem, food chain, and so on (Kelley et al., 2020). On one observation day, which was the third day of the *D-BAIT* lesson, students collected aquatic insects to investigate underwater creatures to research natural environment and ecosystem. The next day, the teachers invited a Purdue University entomology Ph.D. student for an entomology lesson, which indicates that the teachers tried to create a Community of Practice in their classrooms to enhance STEM teaching. In doing so, teachers could share their concerns and deepen their knowledge by exchanging expertise with other teachers and experts (Wenger et al., 2002). During the entomology session, students learned basic taxonomy and insect classification to understand the insect’s body shape and their adaptabilities. They also learned biomimicry concepts by investigating the water insects they collected and apply the function of the underwater insect movements to create fishing lure sample prototypes. In this process, the teachers used the TRAILS resources, such as the insect identification index, TRAILS website, and entomology videos created by the TRAILS team. Later, the students used this knowledge when they designed fishing lure prototypes that mimic natural fishing lures.

To design a lure prototype, students used the CAD software program and a 3D printer, and most of the prototyping and printing parts were done by ETE students. Biology students worked with ETE students to combine scientific inquiry with engineering design, and both biology and ETE teacher's different expertise were integrated into their instruction.

Since the teachers taught the *D-BAIT* lesson together throughout the unit, they could collaborate and communicate during the classes as well as before and after. Even though they were teachers of different subjects, they were observed to emphasize the integration of other disciplines and were constantly reminding the students of what they would learn and why they were learning two domains of subjects together with another class of a different subject.

Student collaboration, as well as teacher collaboration, also seemed critical. About 2-3 biology students and 2-3 ETE students were grouped to work together for learning the subject knowledge, brainstorming, researching, designing the prototype, testing and evaluating, and redesigning. Since the students learned the lessons and completed the activities together throughout the unit, they regularly met in a large media room, which is the biggest room in the school.

4.6 Methods

4.6.1 Instruments

TRAILS Knowledge Test

The research team created the *D-BAIT* STEM knowledge test to evaluate student STEM content knowledge achievement through the integrated STEM lesson *D-BAIT*. The initial *D-BAIT* STEM knowledge test was developed by a panel of six experts from entomology, technology, biology education, and engineering technology teacher education. Content and face validity were checked with two high school teachers. The instrument was pilot tested with 429 high school students, and item analysis was conducted. The final *D-BAIT* knowledge test consists of 20 multiple-choice items with five subject domains, including biomimicry, engineering design, physics, entomology, and food webs. The overall Cronbach's Alpha score obtained from the item analysis was over 0.7 (Han, Kelley, & Knowles, 2021).

21st Century Skills Survey

The 21st Century Skills Survey consists of 30 items within four subconstructs: critical thinking, collaboration, communication, and creativity (see Table 4.4). The five Likert-type score ranges from strongly disagree to strongly agree. Content validity was checked with a panel of experts from STEM fields (three STEM education faculty members, one two-year community college faculty, two graduate students from STEM majors). Face validity was checked two times with three high school students. The survey instrument was pilot tested with 276 high school students, and exploratory factor analysis was conducted. The Cronbach's alpha reliabilities across the four subscales were: Collaboration = 0.826; Communication = 0.749; Creativity = 0.751; and Critical Thinking = 0.876 (Kelley, Knowles, Han & Sung, 2019).

Table 4.4. 21st Century Skills Survey.

	I am confident in my ability to:
Critical Thinking	revise drafts and justify revisions with evidence
	develop follow-up questions that focus on or broaden inquiry
	create new, unique, surprising products
	identify in detail what needs to be known to answer a science inquiry question
	evaluate reasoning and evidence that support an argument
	create ideas geared to the intended client or user
	develop follow-up questions to gain an understanding of the wants and needs of client or product users
	combine different elements into a complete product
	understand the questions that lead to critical thinking
	justify choices of evaluation criteria
	gather relevant and sufficient information from different sources
Collaboration	be polite and kind to teammates
	acknowledge and respect other perspectives
	follow the rules for team meetings
	make sure all team members' ideas are equally valued
	offer assistance to others in their work when needed
	improve my own work when given feedback
	use appropriate body language when presenting
	come physically and mentally prepared each day
	follow rules for team decision-making
Communication	use time, and run meetings, efficiently
	organize information well
	track our team's progress toward goals and deadlines
	complete tasks without having to be reminded
	present all information clearly, concisely, and logically
Creativity	understand how knowledge or insights might transfer to other situations or contexts
	find sources of information and inspiration when others do not
	help the team solve problems and manage conflicts
	adapt a communication style appropriate for the purpose, task, or audience
	elaborate and improve on ideas

4.6.2 Data Analysis

Academic performances (*D-BAIT* STEM knowledge test scores after the *D-BAIT* lesson) of the current year's (Year 4) students were compared to those of previous years' (Year 1, 2, and 3) students that participated in the TRAILS project. Data from 42 classrooms (former participant classrooms = 39, current participant classrooms = 3) with 757 students (former participant students = 702, current participant students = 55) were collected from 2016-2019 school years during the TRAILS project and 2019-2020 school year of the current study. Considering the cluster effect of the data (intraclass correlation coefficient [ICC] = 0.319) as students were nested within each class, we used Multilevel Modeling (MLM) analysis using the HLM 8.0 Software instead of single-level analysis. For the nested data, single-level analysis can violate the independence of observations and reduce statistical power. On the other hand, MLM analysis can use clustered samples dependent on each other within the group they are nested (Finch, Bolin, Kelley, 2019; Raudenbush & Bryk, 2002).

Additionally, an analysis of variance (ANOVA) test was conducted using the SPSS software to see if the three teachers showed the difference among implementation years (Year 1, 2, 3, 4) in terms of their students' STEM knowledge achievement.

Students' growth in confidence in 21st century skills was also examined using the new instrument developed by the TRAILS team. The students participated in the present study (Year 4) took the 21st Century Skills pre- and post-survey before and after they learned integrated STEM. To examine the influence of integrated STEM instruction on students' (Year 4) confidence in 21st century skills, a matched pairs T-test was conducted using the SPSS software. A matched pairs T-test is frequently used to examine the change from pre- to post-survey to identify the effects of intervention (Duran, Höft, Lawson, Medjahed, & Orady, 2014; Xie, & Reider, 2014).
Institutional Review Board (IRB) consent forms were collected by the teachers using Purdue University protocol.

4.7 Results

4.7.1 Multilevel Modeling Analysis (MLM) (RQ1)

All assumptions for MLM adequacy were checked and the data were confirmed to be appropriate for the MLM analysis. The outcome variable, *D-BAIT* STEM knowledge test score (student STEM knowledge achievement), showed to be a normal distribution. Level-1 residuals and Level-2 residuals were independently and normally distributed with a common variance. For the MLM analysis, restricted maximum likelihood estimation (REML) was used, and the level-2 predictor was uncentered.

A total of 757 students (38.2 % female students and 61.8 % male students) were nested in 42 classrooms (23 science classes and 19 ETE classes) (See Table 4.5). The number of students nested in each class ranged from 5 to 64 (M = 18, SD = 11.579). The mean score of the *D-BAIT* STEM knowledge test score was 10.55 (SD = 3.63). The *D-BAIT* STEM knowledge test score was set as the dependent variable, and the level-2 predictor (Year) was set as the independent variable. The categorical level-2 variable, Year, was dummy coded: 0 = previous years (Year 1, 2, 3). 1 = current year (Year 4) (See Table 4.6).

Table 4.5. Demographics of the MLM Data.

Science	ETE	Male	Female	White	Black	Hispanic	Asian	Other	Sum
479 (63.3%)	278 (36.7%)	468 (61.8%)	289 (38.2%)	645 (85.2%)	27 (27%)	57 (57%)	19 (2.5%)	9 (1.2%)	757 (100%)

Table 4.6. Variables and Descriptive Statistics.

Variables		Frequency (%)	*M*	*SD*	Min	Max	Skewness	Kurtosis
Student Level	**Level 1**							
Dependent	*D-BAIT* Score	757	10.550	3.630	1	18	0.030	0.293
Classroom Level	**Level 2**							
	Year (Current Year = 1, Previous Years=0)	42						

Classroom Variance in STEM Knowledge Achievement (Unconditional Model)

The summary of the Unconditional model is the following:

Level-1 Model:

$DBAITSCORE_{ij} = \beta_{0j} + r_{ij}$

Level-2 Model:

$\beta_{0j} = \gamma_{00} + u_{0j}$

Mixed Model:

$DBAITSCORE_{ij} = \gamma_{00} + u_{0j} + r_{ij}$

Where, $DBAITSCORE_{ij}$ = *D-BAIT* score (STEM knowledge achievement) for student i in class j, β_{0j} = group mean, r_{ij} = level 1 residual, γ_{00} = grand mean, and u_{0j} = level 2 residual (group effect).

From the unconditional model, intraclass correlation coefficient (ICC) was calculated to examine the classroom variance. The formula for the ICC is:

ICC = $\tau^2 / \sigma^2 + \tau^2$

Where τ^2 = between group variance, and σ^2 = within group variance.

The ICC indicates that about 31.9 % of the total variation in the STEM knowledge achievement (*D-BAIT* score) is associated with the classroom difference ($\tau_0^2 = 4.3917$, $\chi^2(41) = 349.9787$, $p < 0.001$).

Conditional Model with Classroom Level Predictor

The difference between the classrooms from the current year (Year 4) and those from the previous years (Year 1, 2, 3) in terms of student STEM knowledge achievement (*D-BAIT* knowledge test score) was examined through a conditional model with the classroom-level predictor, Year (Year 1, 2, 3 = 0, Year 4 = 1).

The summary of the conditional model is the following:

Level-1 Model:

$DBAITSCORE_{ij} = \beta_{0j} + r_{ij}$

Level-2 Model:

$\beta_{0j} = \gamma_{00} + \gamma_{01}*(YEAR4_j) + u_{0j}$

Mixed Model:

$DBAITSCORE_{ij} = \gamma_{00} + \gamma_{01}*YEAR4_j + u_{0j} + r_{ij}$

Table 4.7 displays the summary of the MLM results. The conditional mean (grand mean) of student STEM knowledge achievement (*D-BAIT* test score) varies across classrooms (τ_0^2 = 4.0430, χ^2 (40) = 318.9200, p < 0.001) (Jeong & Choi, 2020; Suárez & Wright, 2019). However, lesson implementation year was not found to be a significant predictor of student STEM knowledge achievement (γ_{01} = 2.5222, t (40) = 1.959, p = 0.057), which indicates that the students of the current year (Year 4) did not show a difference in their academic performances compared to the students from the previous years (see Figure 4.3).

Compared to the unconditional model (τ_0^2 = 4.3917), 7.9 % of variance is reduced by adding level 2 predictor, Year 4, to the conditional model (τ_0^2 = 4.0430) (Raudenbush & Bryk, 2002).

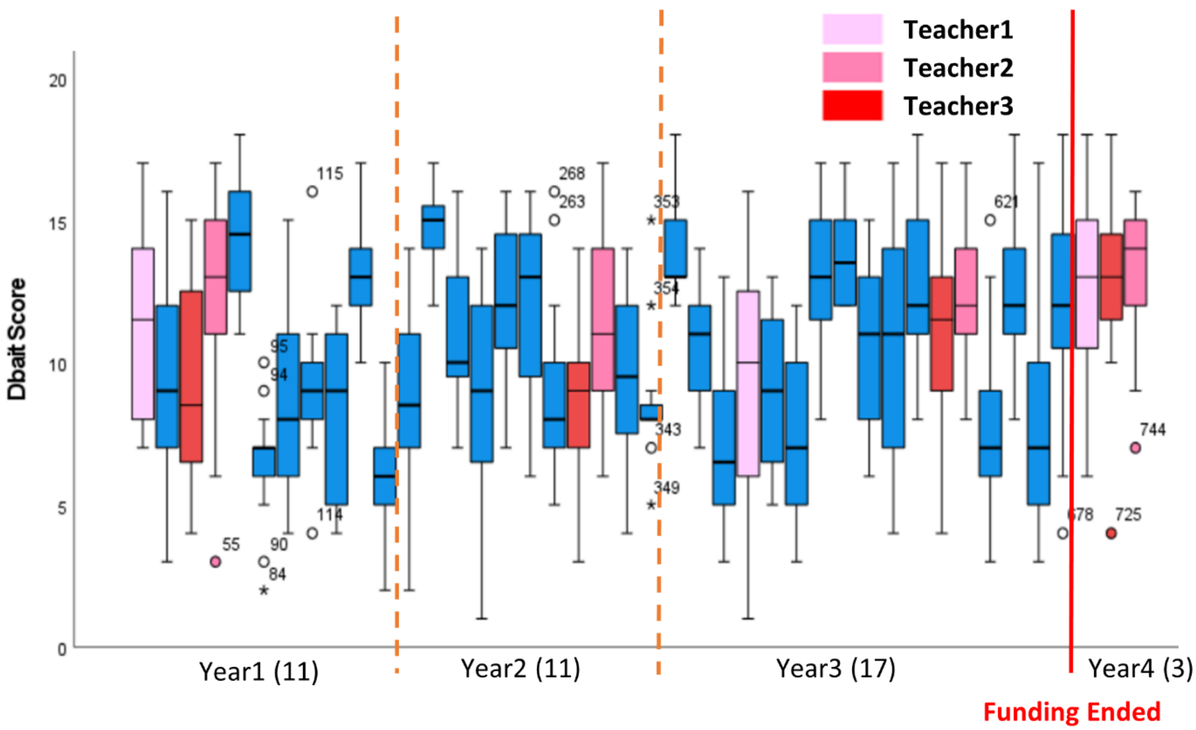

Figure 4.3. Distribution of *D-BAIT* STEM Knowledge Scores across Classrooms by Years

Note: Year 1, 2, 3 = previous years (during TRAILS). Year 4 = current year (after TRAILS). Number of classes are in parentheses.

Table 4.7. MLM Models and Results.

	Unconditional Model		Conditional Model	
Fixed Effect	Estimate	*SE*	Estimate	*SE*
Intercept (β_0)				
Intercept (γ_{00})	10.5416***	0.3475	10.3562***	0.3483
Year4 (γ_{01})			2.5222	1.2878
Variance Estimates	Variance		Variance	
Between-Classroom				
Intercept (τ_0^2)	4.3917***		4.0430***	
Within-classroom (σ^2)	9.3817		9.3842	

*Note: * p < 0.05, ** p < 0.01, *** p < 0.001.*

4.7.2 ANOVA (RQ2)

To examine if the three teachers show the difference between during and after the TRAILS program in terms of their students' STEM knowledge achievement (RQ 2), ANOVA test was conducted. Equality of variances of the dependent variable (*D-BAIT* score) across groups (Year 1, 2, 3, 4) was assumed based on Levene's test result (p = .173). Table 8 displays the descriptive statistics of the three teachers' students. The results indicate that the three teachers' students from Year 4 (After TRAILS) show better academic performances than those from Year 1 ($p < 0.001$), Year 2 ($p < 0.001$), and Year 3 ($p < 0.01$) (see Table 9 and Table 10).

Table 4.8. *D-BAIT* Score Descriptive Statistics of the Focus Group Teachers' Students

	N	Mean	*SD*	Skewness		Kurtosis	
				Statistic	*SE*	Statistic	*SE*
Year 1	52	10.40	3.637	-0.118	0.330	-1.009	0.650
Year 2	50	9.92	3.238	0.259	0.337	-0.590	0.662
Year 3	98	11.17	3.343	-0.480	0.244	0.024	0.483
Year 4	50	12.88	3.088	-0.836	0.337	0.683	0.662
Total	250	11.10	3.467	-0.299	0.154	-0.578	0.307

Table 4.9. ANOVA Test Result.

Source	Sum of Squares	*df*	Mean Square	*F*
Between Groups	253.766	3	84.589	7.596***
Within Groups	2739.530	246	11.136	
Total	2993.296	249		

Note. *** $p < 0.001$

Table 4.10 Multiple Comparison (Post Hoc Test).

I (Year)	J (Year)	Mean Difference (I-J)	*SE*	95% Confidence Interval Lower Bound	Upper Bound
Y1	Y2	0.484	0.661	-0.82	1.79
	Y3	-0.770	0.573	-1.90	0.36
	Y4	-2.476***	0.661	-3.78	-1.17
Y2	Y1	-0.484	0.661	-1.79	82
	Y3	-1.253*	0.580	-2.40	-0.11
	Y4	-2.960***	0.667	-4.27	-1.65
Y3	Y1	0.770	0.573	-0.36	1.90
	Y2	1.253*	0.580	0.11	2.40
	Y4	-1.707**	0.580	-2.85	-0.56
Y4	Y1	2.476***	0.661	1.17	3.78
	Y2	2.960***	0.667	1.65	4.27
	Y3	1.707**	0.580	0.56	2.85

Note. Fisher's Least Significant Difference (LSD) was used. Y1 = Year 1, Y2 = Year 2, Y3 = Year 3, Y4 = Year 4. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4.7.3 T-test (RQ3)

T-test was conducted to examine the current year's students' 21st century skills score increases from pre- to post-survey (Year 4). The student data with both pre- and post-survey scores were included in the data set for the analysis. Table 4.11 displays the descriptive statistics, and each pair shows pre/post-test scores of each category, critical thinking, collaboration, communication, and creativity. The ranges of Skewness and Kurtosis are between -2 and +2, which is the acceptable range to assume normal distribution of the data (Gravetter, Wallnau, Forzano, & Witnauer, 2020; Sharma & Ojha, 2020). The result shows significant increases in the critical thinking category (t (49) = 3.237, p = 0.002). The other three categories (collaboration, communication, creativity) did not show a statistically significant difference between pre- and post-survey scores ($p > 0.05$) (see Table 4.12).

Table 4.11. Pre/Post Survey Results Descriptive Statistics.

		Mean	*N*	Ste. Deviation	Std. Error	Skewness	Kurtosis
Pair 1	Post Crit	44.660	50	5.017	.709	-0.140	0.245
	Pre Crit	42.480	50	4.904	.694	-0.189	-0.537
Pair 2	Post Col	39.000	50	3.922	.555	-0.628	0.281
	Pre Col	38.440	50	4.146	.586	-0.206	-0.814
Pair 3	Post Com	19.780	50	3.112	.440	-0.375	-0.707
	Pre Com	20.340	50	2.973	.421	-1.000	1.852
Pair 4	Post Creat	20.000	50	2.748	.389	-0.639	0.074
	Pre Creat	20.180	50	2.723	.385	-0.412	-0.364

Note: Crit = Critical Thinking. Col = Collaboration. Com = Communication. Creat =Creativity.

Table 4.12. Pre/Post Survey T-test Results

		Mean	Std. Deviation	Std. Error	*t*	*df*	Sig. (2-tailed)
Pair 2	PostCrit - PreCrit	2.18	4.762	.674	3.237	49	.002
Pair 3	PostCol - PreCol	.56	3.980	.563	.995	49	.325
Pair 4	PostCom - PreCom	-.56	3.252	.460	-1.218	49	.229
Pair 5	PostCre - PreCre	-.18	2.336	.330	-.545	49	.588

4.8 Summary

Aiming to build a sustainable model of integrated STEM education, the present study investigated the implementation of an integrated STEM curriculum after the TRAILS project. The students of the three teachers, who implemented integrated STEM instruction after three years of participation in the project, showed no difference from the previous TRAILS students in terms of STEM knowledge achievement (RQ1). Moreover, the students who the three teachers taught during Year 4 (after TRAILS) showed better academic performances than those who these teachers taught during Year 1 to Year 3 (during TRAILS) (RQ2). This result may indicate that teachers maintained and even improved their teaching in terms of student STEM knowledge achievement even after the project ended. Finally, students showed increases in their confidence in critical thinking, which is one of the skills needed to prepare for the 21st-century workforce (RQ3).

However, as the Chi-Square result from the MLM analysis shows (τ_0^2 = 4.0430, χ^2 (40) = 318.920, p < 0.001), significant variation in student STEM knowledge achievement (*D-BAIT* knowledge test score) remains unexplained, which indicates that there exist additional classroom-level predictors that can explain the remaining variance in the intercept. Therefore, further analysis is needed to identify the classroom level predictors that influence student STEM knowledge achievement. For example, classroom teacher's teaching skills, behaviors, and teaching experience as well as socioeconomic status (SES) at the school level may need to be further investigated (Armor, Marks, & Malatinszky 2018; Huang & Moon 2009; Nye, Konstantopoulos, & Hedges 2004; Perry & McConney 2010).

4.9 Discussion

TRAILS aimed to provide a sustainable integrated STEM model with Communities of Practice which teachers could maintain successfully even after the funding ended. For this purpose, TRAILS had initial goals: 1) Engage in-service science and technology teachers in professional development building STEM knowledge and practices to enhance integrated STEM instruction; 2) Establish a sustainable Community of Practice of STEM teachers, researchers, industry partners, and college student "learning assistants"; 3) Engage grades 9-12 students in STEM learning through engineering design and 3D printing and scanning technology, and ; 4) Generate strategies to overcome identified barriers for high school students in rural schools and underserved populations to pursue careers in STEM fields.

Integrated STEM instruction exposes learners to meaningful contexts, where students can enhance 21st century skills and motivation to learn STEM content (Nadelson & Seifert, 2017; NRC, 2014). However, barriers exist that limit the integration of STEM subjects in secondary education, which include lack of support from the school system and university faculties (Ejiwale, 2013; Kelley et al., 2021). Although educational standards and researchers place high importance in purposeful and explicit connections between different subjects and contents for STEM education (NAE & NRC, 2009; NGSS Lead State, 2013; Wang et al., 2011), teachers often find it difficult integrating STEM deliberately in their classrooms.

To help teachers develop instructional strategies to integrate STEM subjects, teacher training through professional development is critical. As Nadelson and Seifert (2017) posited, a professional knowledge and confidence is paramount for teachers in successfully implementing integrated STEM in their classrooms (Nadelson & Seifert, 2017).

Science and engineering technology education (ETE) teacher collaboration is also critical. According to the National Academy of Engineering (NAE) Grand Challenges (GC) Committee, engineers are required to partner with scientists and explore scientific inquiries to understand our environment and improve our world (NAE, 2016). US Educational standards also require science and engineering practice to be shared (NGSS Lead State, 2013; ITEEA, 2020) for successful STEM education implementation. In the TRAILS project, teachers participated in two weeks of professional development and developed integrated STEM lessons for their students as a science-ETE teacher pair. After PD, they collaborated again as science-ETE teacher pairs to teach integrated STEM curriculum and demonstrated different types of collaboration and subject integration (Kelley et al., 2021). For example, when the three focus teachers participated in the TRAILS project for three years, they taught both science and ETE class *D-BAIT* units collaboratively (Model 2) for the first and second year (Year 1 and Year 2), and in the third year (Year 3) they combined both classes and taught together throughout the unit (Model 3). In the present year (Year 4), after the conclusion of the project, the teachers taught the *D-BAIT* unit in this way again (Model 3), which they may have decided to be the best way for them to teach integrated STEM. However, this may not have been possible if the schools did not have the space, such as an LGI (Large Group Instruction) room, for the two classes to be gathered to do the activities together. Also, if the school did not support teachers to teach collaboratively, collaborative teaching models (Model 2 and Model 3) may not be possible to be delivered.

School administrations also play a pivotal role for teachers implementing integrated STEM. For instance, one school administration supported the teacher pair by allowing them to arrange a parent meeting session at the start of the school year, in which they could introduce integrated STEM education and the TRAILS project. On the presentation day, the administrators, in addition to the TRAILS research team, attended the student presentation and demonstrated their interest in integrated STEM education by providing positive verbal feedback directly to the students and the teachers on their integrated STEM projects.

Furthermore, building a sustainable Community of Practice is critical for integrated STEM education to be successful (Kelley & Knowles, 2016; Kezar & Gehrke, 2017). To build a Community of Practice for TRAILS STEM teachers, the TRAILS leadership team recruited over

20 STEM experts for teacher professional development in all three years of the project. These experts came from workforce at the intersections across biomimicry, education, STEM research, and advanced manufacturing to present on the following topics: 3D scanning for design innovation, additive manufacturing, and applied research to advance STEM knowledge. These presentations provided knowledge with which TRAILS teachers could provide authentic contexts to educate their students on current STEM practices and content; the practices were placed in the TRAILS learning activities and lessons planned by the teachers. (TRAILS Annual Report, unpublished document). In Year 4, after the funding had ended, the teachers we observed maintained their Community of Practice network and invited a TRAILS leadership team member, an entomology major graduate assistant, to their classroom as a guest speaker. They also participated in a state-wide STEM conference and presented their experiences from the TRAILS project. The TRAILS leadership team also tried to provide consistent support to teachers and arranged the follow-up sessions in Year 4. During a follow-up session- Indiana STEM education workshop- a total of 16 TRAILS teachers from Year 1-3 returned to campus, and 5 TRAILS teachers presented TRAILS lessons to a total of 80 in-service STEM secondary teachers from all over Indiana. In addition, after the conclusion of the TRAILS project, 10 TRAILS teachers reunited on the summer of 2019 to help format, refine, and build supplementary TRAILS curriculum and teacher resources. All these efforts reflect what Kezar and Gehrke (2017) emphasized for Sustaining Communities of Practice Focused on STEM Reform: a) leadership development, distribution, and succession planning; (b) a viable financial model; (c) a professionalized staff; (d) feedback and advice mechanisms; (e) research and assessment; and (f) an articulated community strategy (p. 323).

In summary, the current study shows that the experiences of participating in professional development and three years of integrated STEM implementation in a science-ETE teacher pair, enabled teachers to continue teaching integrated STEM effectively after the funded project end. Teachers increased teaching efficacy in STEM and the knowledge and ability to create integrated STEM lessons in professional development and Community of Practice, empowering teachers to implement an integrated STEM curriculum. Collaboration with a partner teacher and administrative support also facilitated teachers to implement new instructional strategies in teaching STEM.

For successful implementation of integrated STEM in secondary schools, teachers need to build a cohesive understanding of STEM education and the process of integrating science, technology, engineering, and mathematics in authentic contexts. Additionally, inquiry-based learning, project- and problem-based instruction, real-world problem solving, cooperative learning, design-based learning, and digital technologies should be included in integrated STEM (Kelley & Knowles, 2016; Nguyen, Nguyen, & Tran, 2020). The teachers, who were able to continue to teach integrated STEM after the project, had three years of experience in the project, which may have reinforced their understanding and abilities to implement integrated STEM. As the present study shows, the teachers who had multiple years of support from the TRAILS project maintained their teaching effectiveness, and the students benefitted from these teachers' instruction by increasing their STEM knowledge and confidence in critical thinking. Therefore, for successful implementation of integrated STEM, teachers should be provided with ongoing help including administrative support and investment in professional development, through which they can enhance their STEM knowledge and self-efficacy in a Community of Practice (Dare et al, 2018; Kelley & Knowles, 2016; Wenger et al., 2002). Furthermore, we need to listen to the beliefs, challenges, and understandings of teachers about integrated STEM education (Dare et al., 2018). For both teachers who bring integrated STEM to their classrooms for the first time and who implement integrated STEM on a regular basis, we need to provide them with continued support for a successful and sustainable integrated STEM education.

4.10 Conclusion and Recommendations

Based on multiple years of teacher implementations, the present study concludes integrated STEM as a sustainable educational program that can be implemented in secondary school classrooms. Specifically, the participating teachers of the current study sustained integrated STEM teaching and maintained their teaching efficacy and fidelity despite the barriers identified from previous literature. To overcome barriers and advance integrated STEM education, we recommend the following strategies:

1) Invest more into
    a. teacher professional development (PD) (Ejiwale, 2013; Kelley et al., 2020).
    b. school facilities, such as an LGI room for two or more classes to learn collaboratively in as well as 3D printing equipment for students to experience advanced manufacturing systems (Kelley et al., 2021).

2) Increase supports from school administrators to help teachers plan for integrated STEM implementation with more autonomy (Kelley et al., 2021).
3) Build Communities of Practice for teachers, researchers, STEM experts, industry partners, and local community experts to engage in integrated STEM to facilitate students' learning in STEM (Kelley et al, 2020; Kelley et al., 2021).
4) Develop online platforms for teacher collaboration and student collaboration, such as Microsoft TEAMS.
5) Share resources for teachers that can be provided within sustained websites including lesson plans, how-to videos, professional CoP expert networks.

Specifically, by using online collaboration platforms, teachers may overcome restrictions on the time and place of different classrooms to communicate and collaborate. As integrated STEM needs collaborative efforts of many people, not only teachers and students but also researchers, STEM experts, and integrated STEM CoP members, using online collaborative platforms such as Microsoft TEAMS will enable collaboration between them regardless of their availabilities. We admit that many teachers cannot implement integrated STEM since they do not have partner teachers to collaborate and flexibility in availabilities and resources. Therefore, we recommend utilizing collaborative platforms that enable communications and collaboration between teachers as well as students, both in-school and out of school, and without the restriction of time and space (Lansmann, Schallenmüller, & Rigby, 2019; Leonardi, Huysman, & Steinfield, 2013).

4.11 Limitation

The study has some limitations. First, as only three teachers and their students participated in the study, a relatively small number of the samples from these classes may not provide enough evidence to support the quantitative data analysis results. Additionally, class observations were conducted only two times. The observations were implemented in the 2019 fall semester, and further observations were not possible because of the COVID-19 pandemic since the following 2020 spring semester. As a result, the classroom implementation focused only on the *D-BAIT* lesson, and the custom lessons, which were also integrated STEM lessons that the teachers developed during the TRAILS summer PD, were not investigated. Therefore, the researchers recommend referring to the previous multiple case study, where the current participant teachers were also investigated, for more information of classroom implementation (Kelley et al., 2021) as it provides more information that is based on additional class observations and teacher interviews during the final year (Year 3) of the TRAILS project.

Disclosure Statement

No potential conflict of interest was reported by the authors.

NSF Disclaimer

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Author Contributions

The authors confirm contribution to the paper as follows: study conception, data collection, and data analysis: Han, J.; study design and review: Kelley, T. R., and Knowles, G. All authors reviewed the results and approved the final version of the manuscript.

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CHAPTER 5. SUMMARY, CONCLUSION, AND DISCUSSION

5.1 Summary of the Research

The present study was implemented to explore the impact of integrated STEM instruction on students' engineering design learning and 21st century skills through investigating the project *Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS).*

Three studies were conducted to examine the effectiveness of the TRAILS approach to integrate STEM. The first study focused on student design cognition using the CTA protocol analysis. Students from both science and ETE classes showed higher probabilities of transitions between scientific inquiry (SI) and design (DE) during the engineering design problem-solving task. This result indicated that integrated STEM shared practices enhance students' abilities to utilize scientific inquiry to solve design problems. The second study examined how the TRAILS model increased teacher self-efficacy in teaching STEM through professional development and how teachers' increased self-efficacy impacts students' STEM learning. Path analysis was used to identify the relationship among teacher self-efficacy, students' academic achievement, STEM attitude, career awareness, and 21st century skills. The results showed that teacher self-efficacy and student attitudes played a significant role in facilitating students' academic achievement in STEM. The third study explored the impact of integrated STEM instruction on student 21st century skills and examined the sustainability of the TRAILS model to see if it is a replicable and repeatable model. T-test was employed to examine if the students increased their 21st century skills after the integrated STEM lesson, and the results revealed that students increased critical thinking, which is one of the four 21st century skills. Multilevel Modeling (MLM) analysis was also conducted to compare the academic performances of the focus teachers' students to those from the previous TRAILS classes. The focus teachers, who participated in the TRAILS project and community of practice for multiple years, maintained their effectiveness in teaching integrated STEM, which indicated the importance of providing teachers with adequate and sustained support with a practical model of integrated STEM.

5.2 Conclusion

The main goal of the study was to investigate the impacts of integrated STEM instruction on student design cognition, academic achievement, and 21st century skills by exploring the TRAILS project.

In conclusion, integrated STEM helped students enhance design learning and 21st century skills. Teachers also increased STEM teaching efficacy through a community of practice and collaborative teaching in an integrated STEM context. TRAILS integrated STEM approach helped teachers and students create a community of practice, where teachers increase self-efficacy in teaching STEM and students can enhance design cognition and 21st century skills in authentic situated contexts. The present study will inform STEM researchers and educators that the shared practices of the TRAILS approach provide a feasible and sustainable model of integrated STEM instruction to create advanced integrated STEM models.

5.3 Discussion

Developing educational programs and curricula that increase students' disciplinary knowledge, inquiry, and 21st century skills, which include problem-solving abilities, critical thinking, and creativity, has been the focus of STEM education (English, 2016; English & Gainsburg, 2016). In particular, project- and problem-based design instruction is advocated as a great instructional strategy for teaching integrated STEM (Nadelson & Seifert, 2017; NRC 2012). Specifically, engineering design in integrated STEM provides an authentic, real-world, and situated context where students can enhance 21st century skills needed to prepare for the global workforce (Kelley & Knowles, 2016). As researchers posited that design is a vehicle that facilitates scientific knowledge and real-world problem-solving skills (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2005), developing effective and feasible instructional strategies that employ engineering design as a key to integrate STEM is imperative. Therefore, TRAILS lessons embraced inquiry-based design instruction, which enables students to develop contextual knowledge and design thinking.

The present study assessed the impact of integrated STEM instruction on student design learning and 21st century skills in a variety of ways and examined if TRAILS provided teachers with a practical model of integrated STEM. The sustainability of integrated STEM education was also investigated through exploring the STEM classes after the TRAILS project ended. In study 1, science and ETE students showed similar patterns of cognitive strategies, which demonstrates the interplay between science inquiry and engineering design during the design task after they experienced integrated STEM that shares the science and engineering practices. Study 2 confirms the impact of integrated STEM on teacher self-efficacy and student learning as well as the collective effect of teacher self-efficacy and student career awareness and 21st century skills on student attitude and academic achievement in STEM. Study 3 assessed the sustainability of the integrated STEM model by examining the classes that implemented the TRAILS lessons again after the project ended; the results indicated that teachers who participated in the TRAILS project for multiple years sustained integrated STEM education successfully after the TRAILS project ended and the students increased STEM knowledge and 21st century skills.

In summary, integrated STEM education helped students develop 21st century skills and innovative design thinking. Teachers also benefited from integrated STEM education and community of practice. In the integrated STEM context, teachers could enhance their instruction with the help of teachers from other disciplines and communication with them (Brown, J., Brown, R., & Merrill, C., 2011; Fulton & Britton, 2011; Kelley, Knowles, Han, & Trice, 2021). Through the professional development and community of practice, TRAILS teachers enhanced teaching efficacy and knowledge and skills to integrate STEM. Moreover, teachers who participated in the TRAILS project for multiple years sustained integrated STEM education successfully even after the TRAILS project ended.

To conclude, teaching problem-solving skills through inquiry-based real-world problems and enhancing design thinking is an important goal of integrated STEM education (Jonassen et al., 2006; Kelley & Knowles, 2016). By sharing perspectives and experiences of STEM teachers, we can help teachers determine the best approach to STEM integration in their classrooms and create an environment that fosters students' engagement, motivation, and creativity (Honey, Pearson, G., & Schweingruber, 2014). The present study will inform STEM researchers and educators of the TRAILS model to create advanced integrated STEM models.

5.4 Recommendations

Further research is needed to include various elements that can address the complexity of teaching integrated STEM. Research is recommended to address the following topics.

1. More research that provides substantive evidence of learning outcomes is recommended (English, 2016; Honey et al., 2014).
2. Many researchers proposed the importance of metacognitive processing in learning. More research on design instructions in integrated STEM, through which learners can develop metacognitive abilities, is needed (Brown, Collins, & Duguid, 1989; Collins, Brown, & Holum, 1991; Lajoie, Guerrera, Munsie, & Lavigne, 2001).
3. Not only content and pedagogical methods but also sequencing of learning activities and the sociology of learning also should be considered for successful teaching of integrated STEM (Collins et al., 1991).
4. Research that investigates the relationship between cognitive component of learning and affective and conative components factors (Jonassen, 2000) in integrated STEM education is also recommended.

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APPENDIX A. D-BAIT STEM KNOWLEDGE TEST ITEM ANALYSIS RESULTS

Item	Difficulty		Discrimination		Cronbach's Alpha
No	Score	Index	Score	Index	if Item Deleted
1	0.67	Easy	0.44	Very good	0.68
2	0.58	Moderate	0.42	Very good	0.69
3	0.14	Very difficult*	-0.06	Poor**	0.71
4	0.10	Very difficult*	0.03	Poor**	0.70
5	0.44	Moderate	0.45	Very good	0.68
6	0.32	Difficult	0.31	Good	0.69
7	0.42	Moderate	0.42	Very good	0.69
8	0.45	Moderate	0.54	Very good	0.68
9	0.78	Easy	0.38	Good	0.68
10	0.44	Moderate	0.50	Very good	0.68
11	0.42	Moderate	0.55	Very good	0.68
12	0.51	Moderate	0.40	Good	0.69
13	0.53	Moderate	0.59	Very good	0.67
14	0.51	Moderate	0.29	Marginal	0.70
15	0.52	Moderate	0.50	Very good	0.68
16	0.25	Difficult	0.42	Very good	0.68
17	0.51	Moderate	0.41	Very good	0.69
18	0.58	Moderate	0.52	Very good	0.68
19	0.46	Moderate	0.28	Marginal	0.70
20	0.53	Moderate	0.62	Very good	0.67
21	0.29	Difficult	0.42	Very good	0.68
22	0.53	Moderate	0.47	Very good	0.68
23	0.33	Difficult	0.19	Poor**	0.70
24	0.11	Very difficult*	-0.06	Poor**	0.71
Average	0.43	Moderate	0.38	Good	0.69

Note: Item 3, 4, 23, and 24 were removed as these showed low scores in difficulty and item discrimination.

APPENDIX B. D-BAIT UNIT PLAN

<table>
<tr><th colspan="2">Recommended Instructor Preparation</th></tr>
<tr><td colspan="2">

Cut bottom out of 5-gal bucket before starting. Bottom and lid are not needed.
Fill vials approx. 80% full of alcohol or hand sanitizer. Each group of students will have vials to preserve insects.
Clear plastic containers are used to observe aquatic insects. They should be very transparent. Ice cube trays are for sorting insects.
During field observations, students may work in teams with one transparent container for observation per team.
If there is no field component as Lesson Plan #2, use these materials to obtain living insects before Lesson #1.

</td></tr>
<tr><th colspan="2">Lesson Plan 1: Which insects become food for fish?</th></tr>
<tr><td>Lesson Focus</td><td>

What kinds of food do fishes eat?
Do you think insects can be great food for fish? Why? Then, can we use this information to create artificial baits?

Optional: What can insects tell us about water quality?
</td></tr>
<tr><td>Total Time Required</td><td>1-2 hours</td></tr>
<tr><td>Lesson Objectives</td><td>Students will be able to:

Understand how some insects are adapted to breathe, move, feed, and hide underwater.
Understand how anglers may use biological knowledge.
Hypothesize which types of insects are likely fish prey.

</td></tr>
<tr><td>Equipment and Materials</td><td>
<table>
<tr><th>Tools and Materials</th><th>Quantity Needed</th></tr>
<tr><td>Transparent plastic containers (1-5 gal.)</td><td>[number/ group, or class]</td></tr>
<tr><td>Plastic bucket (5 gal.), bottom cut off</td><td>1 / group</td></tr>
<tr><td>Aquarium net</td><td>1 / group</td></tr>
<tr><td>Ice cube trays</td><td>1 / group</td></tr>
<tr><td>Forceps</td><td>1-2 / group</td></tr>
<tr><td>Magnifying glasses</td><td>1-2 / group</td></tr>
<tr><td>Vials (4-8 dram)</td><td>3-4 / group</td></tr>
<tr><td>70% Isopropyl Rubbing alcohol or hand sanitizer</td><td>1 32 oz. bottle / class</td></tr>
<tr><td>Aquatic insect identification guide</td><td></td></tr>
</table>
</td></tr>
</table>

Special Notes on Materials:	• Cut bottom out of 5-gal bucket before starting. Bottom and lid are not needed. • Fill vials approx. 80% full of alcohol or hand sanitizer. Each group of students will have vials to preserve insects. • Clear plastic containers are used to observe aquatic insects. They should be very transparent. Ice cube trays are for sorting insects.
Lesson Procedures:	1. One-hour lecture on the main aquatic insect groups and how they live. Focus on adaptations that allow them to breathe underwater, move, feed, and hide. 2. Discuss scientific inquiries. Main topics will be observation, hypotheses to explain observations, falsifiability and repeatability, predictions and testing, refining hypotheses. 3. Discuss which types of insects are likely prey for fish. What are the reasons for choices—what are the important features of these insects? How could we test these hypotheses? Given unlimited time and resources, how could we test these hypotheses? 4. Field observation: observe insects and those of adaptations. a. Travel as a group to a nearby safe shallow body of water. b. Press bottomless five-gallon bucket into substrate in ~1 foot of water. c. Stir water in bucket to dislodge insects from bottom, rocks, plants. d. Sweep aquarium net several times through the water. e. Drop insects into separate clear plastic container half full of pond/stream water. f. Repeat in different habitats, ex.: different substrates, depths, plants, etc. g. Cover clear plastic container and observe insects. It may be easier to observe some insects if they are moved with the dip net or forceps to a basin in the ice cube tray. Based upon their body shape, what do you think they eat? How do they move? Use the Insect Body Adaptations table (appendix F) to help guide this activity. Optional Activity: Biological Indicators a. Students will divide into groups and collect their own samples. Use biological indicator flash cards to determine water quality as indicated by insects. *Note*: If this field component is not possible (e.g., no accessible or safe body of water available), the instructor may use the tools and

<table>
<tr><td></td><td>materials to collect insect samples beforehand and bring these to the class. Changes in water temperature and depleting oxygen mean that some insects will not live long so as soon before class time as possible is best. In class, use an aquarium net to remove one type of insect from the larger bucket and place in smaller clear plastic container or one section of an ice cube tray. Use live insects in containers to pass around class if containers are small and sealable, or to have students come to view at a break in the class.</td></tr>
<tr><td colspan="2">Lesson Plan 2: How do we select the best features from design solutions?</td></tr>
<tr><td>Lesson Focus:</td><td>Imagine you are an engineer; how would you generate innovative ideas? How would you assess existing solutions to select the best features?</td></tr>
<tr><td>Total Time Required:</td><td>1 hour</td></tr>
<tr><td>Lesson Objectives:</td><td>Students will be able to:
Identify the client’s needs and constraints of the problem.
Generate ideas to design the best bait prototype through brainstorming.
Utilize benchmarking using existing bait products in the market.
Assess benchmarking products using the decision matrix.</td></tr>
<tr><td>Equipment and Materials</td><td><table><tr><th>Tools and Materials</th><th>Quantity Needed</th></tr><tr><td>Examples of commercially available fishing lures</td><td></td></tr><tr><td>Fishing line or string</td><td></td></tr><tr><td>Plastic tub filled with water</td><td>1 / class</td></tr><tr><td>Decision matrix printout</td><td>1 / student</td></tr></table>If using real lures, be aware that the hooks are very sharp. It may be good idea to remove the hooks or cover the points in tape.</td></tr>
<tr><td>Lesson Procedures:</td><td>(Number and describe the steps or procedures to follow. Include information about how to introduce students to new content and how to review and summarize key information.)
Teacher provides the material detailing the design brief.
Teacher asks what the context, criteria, and constraints of the design problem are.
Student teams brainstorm to generate possible solutions.</td></tr>
</table>

<table>
<tr><td></td><td>
4. Student teams refine generated ideas and make a list of solutions.
5. Teacher explains that engineers might look at existing bait designs to understand current bait design features.
6. Student teams study fishing bait market products.
7. Student teams test fishing bait product on the water by pulling them through the water to better understand their action, depth range, natural mimicking characteristics to insects or other creatures.
8. Students create a decision matrix to select the best features for the bait.
    a. List products on the columns.
    b. Fill out decision criteria on the rows.
    c. Weight percentages with each row criteria.
    d. Assess the products and calculate total scores.
9. Students will choose the best solution from the decision matrix.
Optional Activity # 1: How do we predict the bait’s movement in the water?
a. Students will learn about forces that cause organisms to float, sink, or hover in water, as well as how to make lures neutrally buoyant (See Appendix A).
Optional Activity # 2: Buoyancy and displacement
1. Students will learn how about forces that cause organisms to float, sink, or hover in water, as well as how objects from bobbers to boats float. (See Appendix A).
Note: If it is not possible to use real examples of lures, images and videos of lures can be found online.
• Student Resources: Decision matrix template
</td></tr>
<tr><th colspan="2">Lesson Plan 3: How can we create a fishing lure to mimic an insect?</th></tr>
<tr><td>Lesson Focus</td><td>How do engineers prove their ideas? Can you explain a complex object without its visualization?</td></tr>
<tr><td>Total Time Required</td><td>1 hour</td></tr>
<tr><td>Lesson Objectives:</td><td>Students will be able to:
• Create unique design solutions applying the result of the decision matrix with the observation of the insect specimen collected in the field.
• Visualize the 3D prototype of soft baits using the parametric modeling software.</td></tr>
</table>

<table>
<tr><td></td><td>Print the designed lure mold for creating prototypes using a 3D printer.</td></tr>
<tr><td>Equipment and Materials</td><td><table><tr><th>Tools and Materials</th><th>Quantity Needed</th></tr><tr><td>Computer with parametric software</td><td>1 / group or 1 / student</td></tr></table>
Special Notes on Materials:
If you are unfamiliar with parametric software, you can follow this simple guide.</td></tr>
<tr><td>Lesson Procedures:</td><td>Student teams brainstorm design ideas on paper.
Student teams design the bait prototype using the parametric modeling software.
Student teams note the volume and weight of the bait prototype from the parametric modeling software and predict how the bait will behave in the water.
If students need to create prototype using a mold, student teams create the bait mold for creating prototype using the liquid plastic.
Once student teams finish designing the bait (mold) design, teacher examines its completeness to avoid collapse during the printing of the 3D object.</td></tr>
<tr><td colspan="2">Lesson Plan 4: How do we test the model prototype?</td></tr>
<tr><td>Lesson Focus</td><td>Students will learn how to test and assess their prototypes.</td></tr>
<tr><td>Total Time Required</td><td>1-2 hours</td></tr>
<tr><td>Lesson Objectives:</td><td>Students will be able to: (list 2-3 that apply directly to the lesson)
Produce the fishing bait prototype using 3D printer or the bait mold.
Test the depth of lure dive, lure motion, and the attractiveness for fish.
Research and report on the design of products and processes
Share the process of integration with science, technology, engineering, and mathematics to solve a real-world problem.</td></tr>
<tr><td>Equipment and Materials</td><td>Tools and Materials
3D Printer
Liquid plastic for casting soft baits (optional)</td></tr>
</table>

Lesson Procedures:	1. Create the fishing bait using 3D printer directly or the bait mold.
	2. Student teams calculate the weight of the prototype regarding buoyancy.
	3. If students use a mold with plastic liquid, teacher carefully explains the instructions and safety guidelines.
	    a. Generally, 3D printers allow solid objects, not flexible objects.
	    b. If students use a mold, prepare plastic liquid.
	    c. Inject plastic liquid into the mold using an injector (piston).
	    d. Place the mold in the microwave and run 2 minutes.
	4. Students will examine the bait prototype in water: depth of lure dive, lure motion, attractiveness for fish.
	5. Students will write a report detailing and reflecting on the design process.
	6. Teacher asks what types of knowledge and skills the students used during this project.
	7. Students will discuss the integration of STEM knowledge and skills.

APPENDIX C. MLM OUTPUT

Program:	HLM 8 Hierarchical Linear and Nonlinear Modeling
Authors:	Stephen Raudenbush, Tony Bryk, & Richard Congdon
Publisher:	Scientific Software International, Inc. (c) 2019

The maximum number of level-1 units = 757
The maximum number of level-2 units = 42
The maximum number of iterations = 100
Method of estimation: restricted maximum likelihood
The outcome variable is POSTDBAIT

Unconditional Model

Level-1 Model
$POSTDBAI_{ij} = \beta_{0j} + r_{ij}$
Level-2 Model
$\beta_{0j} = \gamma_{00} + u_{0j}$
Mixed Model
$POSTDBAI_{ij} = \gamma_{00} + u_{0j} + r_{ij}$

Final Results - Iteration 5
Iterations stopped due to small change in likelihood function

$\sigma^2 = 9.38174$
τ
INTRCPT1, β_0 4.39169

Random level-1 coefficient	Reliability estimate
INTRCPT1, β_0	0.866

The value of the log-likelihood function at iteration 5 = -1.965622E+03

Final estimation of fixed effects:

Fixed Effect	Coefficient	Standard error	*t*-ratio	Approx. *d.f.*	*p*-value
For INTRCPT1, β_0					
INTRCPT2, γ_{00}	10.541550	0.347538	30.332	41	<0.001

Final estimation of fixed effects
(with robust standard errors)

Fixed Effect	Coefficient	Standard error	*t*-ratio	Approx. *d.f.*	*p*-value
For INTRCPT1, β_0					
INTRCPT2, γ_{00}	10.541550	0.343355	30.702	41	<0.001

Final estimation of variance components

Random Effect	Standard Deviation	Variance Component	*d.f.*	χ^2	*p*-value
INTRCPT1, u_0	2.09564	4.39169	41	349.97836	<0.001
level-1, r	3.06296	9.38174			

Deviance = 3931.243745
Number of estimated parameters = 2

Conditional Model

Level-1 Model

$POSTDBAIT_{ij} = \beta_{0j} + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}*(YEAR4_j) + u_{0j}$

Mixed Model

$POSTDBAIT_{ij} = \gamma_{00} + \gamma_{01}*YEAR4_j + u_{0j} + r_{ij}$

Final Results - Iteration 6
Iterations stopped due to small change in likelihood function

σ^2 = 9.38419
τ
INTRCPT1, β_0 4.04298

Random level-1 coefficient	Reliability estimate
INTRCPT1, β_0	0.856

The value of the log-likelihood function at iteration 6 = -1.961665E+03

Final estimation of fixed effects:

Fixed Effect	Coefficient	Standard error	*t*-ratio	Approx. *d.f.*	*p*-value
For INTRCPT1, β_0					
INTRCPT2, γ_{00}	10.356221	0.348302	29.733	40	<0.001
YEAR4, γ_{01}	2.522198	1.287754	1.959	40	0.057

Final estimation of fixed effects
(with robust standard errors)

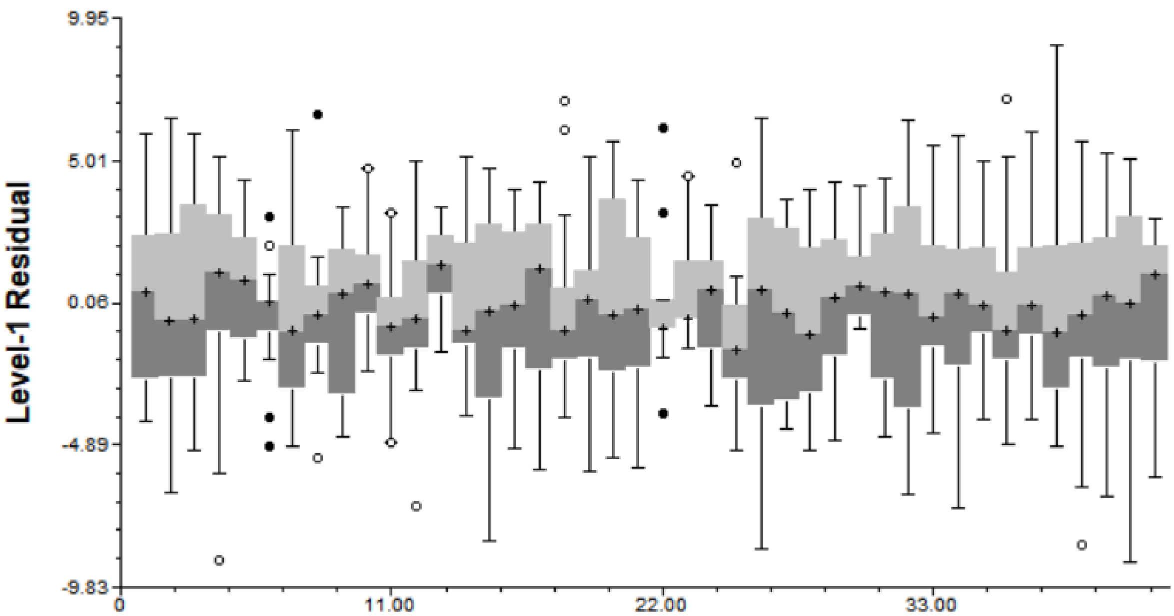
Fixed Effect	Coefficient	Standard error	t-ratio	Approx. $d.f.$	p-value
For INTRCPT1, β_0					
INTRCPT2, γ_{00}	10.356221	0.352887	29.347	40	<0.001
YEAR4, γ_{01}	2.522198	0.361517	6.977	40	<0.001

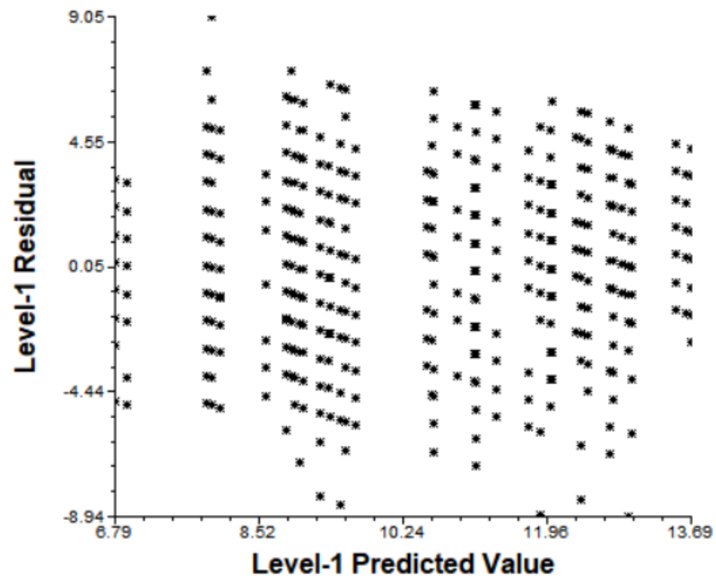
Final estimation of variance components

Random Effect	Standard Deviation	Variance Component	$d.f.$	χ^2	p-value
INTRCPT1, u_0	2.01072	4.04298	40	318.92003	<0.001
level-1, r	3.06336	9.38419			

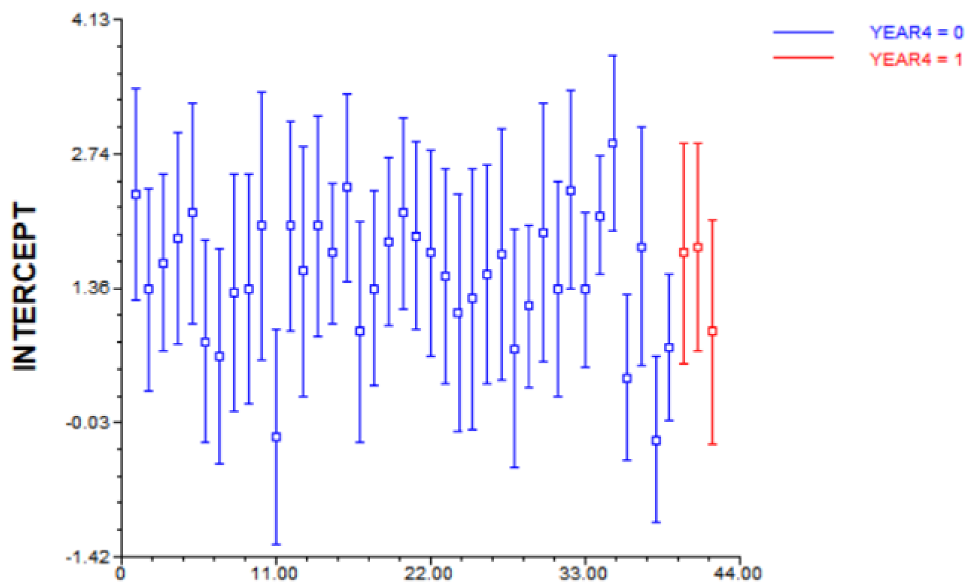
Deviance = 3923.329920
Number of estimated parameters = 2

Assumption Check





Level-2 EB Coefficient Confidence Intervals



APPENDIX D. D-BAIT KNOWLEDGE TEST

Note: After Item analysis, item 3,4, 23, 24 were removed from the final version. Coded in red.

Directions: For each of the questions below, choose the BEST answer.

BIOMIMICRY

1. If a client asks you to design a lure to catch a newly discovered species of fish, how can Biology knowledge be best used to inform your design ideas?

A) Investigate what is a main food source for the fish

B) Investigate what insects and other animals live in the area

C) Determine where in the body of water the fish lives

D) Discover the most common predators of the species of fish

2. Why do fishing lures that mimic an adult mayfly not work as well throughout the year as fishing lures that mimic crayfish?

A) Crayfish are larger, slower, and therefore a better meal for fish

B) Fish expect to find crayfish all year but don't expect to find adult mayflies all year

C) Adult mayflies are more difficult for fish to eat because they can fly

D) Adult mayflies are more difficult for fish to see than crayfish

3. When an engineer designs a fishing lure using a biomimicry approach, he or she should focus on ________________________?

A) mimicking the look of real aquatic insects

B) learning what attracts predacious fish to aquatic insects

C) calculating how far aquatic insect lures can be cast

D) designing hooks that look like insect legs

4. Which of the following is the best **biomimicry** approach to designing? A designer tries to mimic nature by focusing on _________________?

A) shape

B) color

C) texture

D) function

5. Which of the following is the best example of a biomimicry approach to design?

A) The fastener Velcro® designed inspired by cockleburs.

 = 

B) A cell tower inspired by tree.

 = 

C) The Beijing 2008 Aquatic Center- inspired by bubbles.

 = 

D) A cover for a home power utility box inspired by rock.

 = 

ENGINEERING DESIGN

6. When a lure designer reviews existing designs of manufactured lures to identify key design features, he or she is using which engineering design technique?

A) a decision matrix

B) brainstorming

C) benchmarking

D) forming

E) norming

7. When a designer uses a table with weighted design constraints and criteria to evaluate the best possible solution for a client, he or she is using what engineering design technique?

A) a decision matrix

B) brainstorming

C) benchmarking

D) forming

E) norming

8. When a designer seeks to understand clients' needs, criteria, and constraints, he or she is in which stage of the engineering design process?

A) Defining problem

B) Benchmarking

C) Prototyping

D) Modeling

E) Evaluating

9. In engineering design, what is the purpose of drawing sketches in the notebook?

A) To record the ideas

B) To evaluate the ideas

C) To share ideas with others

D) To generate more ideas

E) All the above

10. <u>After</u> identifying a client's needs and define constraints within the design problem, a designer should begin to:

A) prototype

B) benchmark

C) brainstorm

D) optimize

E) create a decision matrix

BUOYANCY

11. A condition experienced by an object underwater where the upward force of buoyancy is equal to the downward pull of gravity is known as________________________?

A) Displacement

B) Density

C) Archimedes' Principle

D) Neutral Buoyancy

E) A and C

12. The upward force that allows an object to float in a fluid and is equal to the weight of the amount of fluid displaced by the object is known as ______________________?

A) Displacement

B) Density

C) Gravity

D) Buoyancy

E) None of these

13. An object denser than water will _(X)_ in water. An object less dense than water will _(Y)_ in water. An object with the same density as water will _(Z)_ in water.

	(X)	(Y)	(Z)
A)	Sink	Float	Float
B)	Sink	Float	Sink
C)	Sink	Float	Neither sink nor float
D)	Float	Sink	Neither sink nor float
E)	Float	Sink	Sink

14. A Purdue astronaut is conducting experiments on the moon. She places a tennis ball in a beaker of pure water. The tennis ball floats:

A) Lower than it would on earth

B) Higher than it would on earth

C) The same as it would on earth

D) Away into space.

Answer notes: it will float higher. The force of buoyancy is equal to the mass of the volume of water displaced, but the downward force of gravity on the ball is lessened.

15. Referring the picture below, when the golf ball is placed in the beaker, what happens to the digital scale reading?

A) Increase weight

B) Decrease weight

C) Remain the same

16. A fish in water wants to move upward without swimming upward. The fish can control buoyancy by ________________.

A) Increasing volume

B) Increasing weight

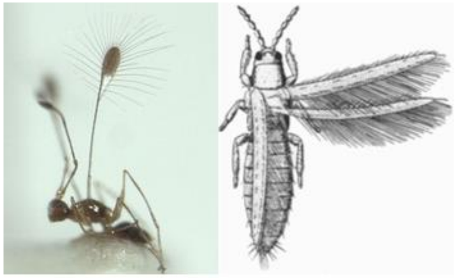
C) Increasing density

D) Decreasing volume

E) C and D

ENTOMOLOGY

17. Several groups of very small insects such as tiny wasps and thrips have greatly reduced wings. Larger insects are capable of directed flight towards an objective even against moderate winds, while these smaller insects are not able to fly against even light winds. What constraint is causing the tiny insects not also have normally-sized wings relative to their size?



Fairyfly wasp Thrips

A) Larger structures are heavier

B) Larger structures cost more in energy and materials

C) Smaller insects do not have the strength to flap larger wings

D) Larger wings would cause excessive cooling because of their large surface area

E) A and C

Answer notes: This is a transfer question. This happens because biological structures have a cost. Human-made artefacts are made with safety tolerances, but not 100X stronger than they need to be, because this would waste resources. In the same way, biological materials and energy are better spend elsewhere, if wings don't allow insects to fly where they want to. Instead, the 'cheap' hairs along the wings are enough to catch the breeze and disperse. This ties in with the reduced antennae of aquatic insects, which are reduced for the same reason, and I will include this idea of cost in the lecture. Another interesting parallel: one of the images on the Biomimicry Institute's front page is of a milkweed seed, which used the same cheap hairs for dispersal.

18. In what way(s) do aquatic insects breathe underwater?

A) Breathing at the surface

B) Splitting water molecules into oxygen and hydrogen

C) Carrying air with them underwater

D) Breathing oxygen directly from the water

E) A, C, and D

Answer Notes: breathing tubes, gills, carry air bubbles

19. What body features do all insects share?

A) Six legs and two pairs of wings

B) A head of one segment, thorax of three segments, and abdomen of eleven segments

C) Six legs and twenty segments

D) Six legs and a one year life cycle

E) 6 – 8 legs and two kinds of eyes

20. Natural selection results in the selecting individuals or species that:

A) are more perfect

B) are more complex

C) can acquire traits in response to their environment

D) are best adapted to their environment

E) are red in tooth and claw

21. Which of the following is the best measure of an organism's evolutionary fitness?

A) how long it lives

B) the amount of care it receives from its parents

C) the number of mutations it acquires in its lifetime

D) its size compared to other members of the same species

E) the number of fertile offspring it produces

FOOD WEBS

22. What can be inferred about populations of top predators based on the amount of energy passed on to each trophic level?

A) Populations are lower because total energy is increased at each trophic level.

B) Populations are lower because total energy is reduced at each trophic level.

C) Populations are higher because total energy is increased at each trophic level.

D) Populations are higher because total energy is reduced at each trophic level.

23. Consider the organisms occupying the various trophic levels of a food web. Omnivores:

A) only eat dead organisms and waste products of other organisms.

B) have species that are dedicated carnivores and other species that are dedicated herbivores.

C) are individuals that eat organisms at several different trophic levels.

D) always exist at the third trophic level.

24. Adaptive change refers to changes that cause organisms to

A) maintain internal stability.

B) detect and respond to things in their environment.

C) modify their behaviors to gather more food.

D) produce more offspring.

E) become larger and stronger.

Open-Response Assessment

Directions: The following section of open response questions will provide a description of an observation, experiment, or scenario. You must carefully read this description and in some cases study provided pictures and respond to the questions based upon your knowledge of the principles presented.

Biology

Topic: Adaptations of teeth and jaws for Herbivores/Carnivores/Omnivores

The teeth in an animal skull can tell us whether the animal was a carnivore, herbivore, or omnivore. The different types of teeth are:

Incisors: middle teeth in the front

Canine teeth: longer pointed teeth to the sides of the incisors

Cheek teeth: pre-molars and molars, side and back teeth

Herbivore – Herbivores are prey animals that need to rapidly ingest food when they have the opportunity so they can avoid being eaten by predators.

The teeth of herbivores can be identified by:

Incisors: large, well-developed for cutting plants

Canine teeth: resemble the incisors in form and function, flat and non-pointed, many herbivores do not have upper incisors or canines, instead they have a hard, flat upper palate that serves as a "cutting board" for the lower incisors to cut through plant stems

Cheek teeth: large and wide for grinding and chewing plants, do not overlap, instead they make surface contact to provide a grinding surface

Carnivore – Carnivores are predators and tend to bite, tear and gulp down food without any chewing action.

The teeth of carnivores can be identified by:

Incisors: smaller and less developed

Canine teeth: large, long and pointed for piercing and holding prey

Cheek teeth: sharp and pointed for cutting and tearing flesh, upper cheek teeth overlap the lower teeth providing scissor-like action to cut meat

Open Response Question 1: Based on this information about herbivores and carnivores, what would the teeth of an omnivore look like? Why?

Omnivores have a combination of carnivore and herbivore characteristics. Many omnivores are either predominantly meat eaters or predominantly plant eaters. This can be determined by looking at their cheek teeth to see if they are more sharp and pointed like a carnivore's, or more large, wide, and flat like a herbivores

Make an inference about whether the animal below was an herbivore, a carnivore, or an omnivore. Be sure to justify your inference by addressing:

- the shape of the teeth
- the location of the teeth


(raccoon)

Omnivore because:

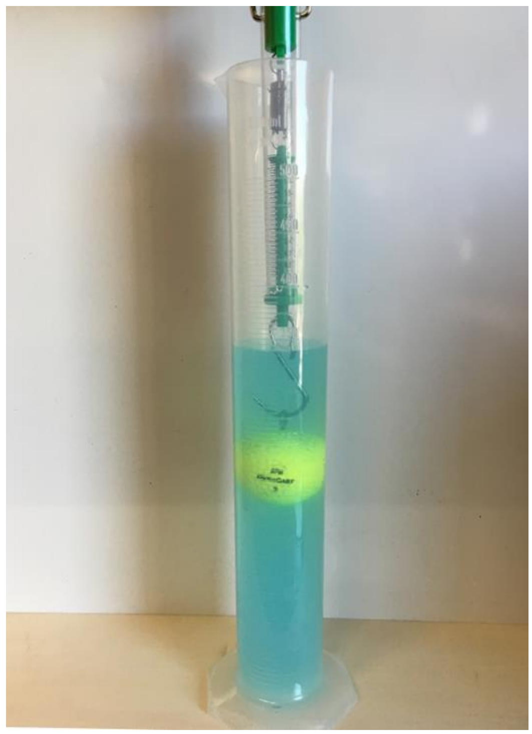
Incisors: fairly large and well developed for cutting plant material

Canine teeth: long and pointed for killing and holding prey

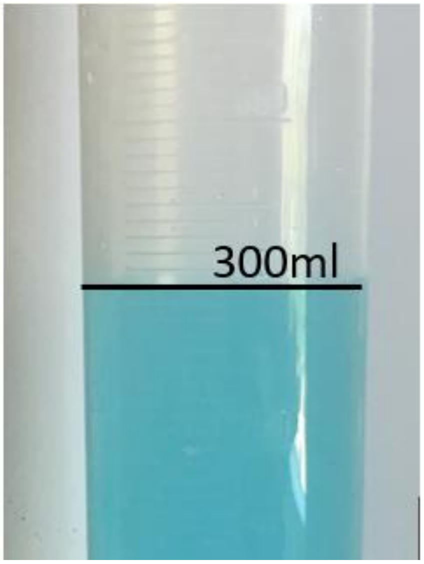
Cheek teeth: combination of sharp, scissor-like cheek teeth for shearing meat and teeth with rounded edges for grinding and crushing plant material

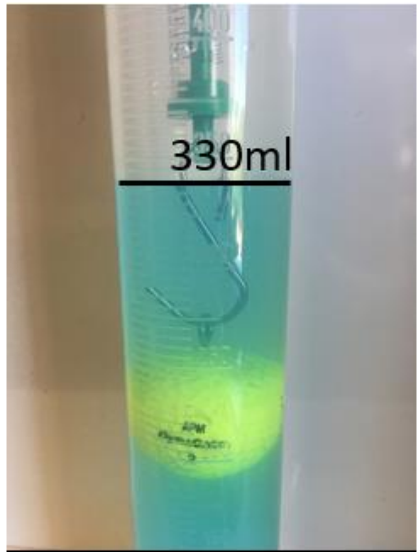
Directions: The following section of open response questions will provide a description of an observation and experiment. You must carefully read this description and respond to the questions based upon your knowledge of the principles presented.

Open Response Question 2-A: The pictures below are showing a golf ball placed in water. What forces are acting on the golf ball before and after placing in the golf ball in water? **Name the forces and directions in your explanation.**



Open Response Question 2-B: Read the water levels on the pictures below. Explain the reason why the water level changed. What information can be inferred through this example?





<Before placing a golf ball in water>   <After placing a golf ball in water>

Open Response Question 2-C: Below the pictures are showing spring scale indicators measuring weight of a golf ball. The left is weighted outside of water (approximately 45 g) while the right is weighted the same ball in water (close to 0 g). Explain the reason why the spring scale indicates different weights of the golf ball.

<Weighted out of water>   <Weighted in water>

APPENDIX E. STUDENT STEM SURVEY (S-STEM)

This survey is designed for high school students to measure changes in students' confidence and efficacy in Science, Technology, Engineering, & Math (STEM) subjects, 21st century learning skills, and interest in STEM careers. This survey will help inform schools and researchers about how to improve STEM programs. There are no right or wrong answers and all responses are kept confidential.

Please enter your student code provided to you. This will help us link survey data for research. You will enter the same code on all of your surveys.

Directions:

There are lists of statements on the following pages. Please click one answer bubble to mark how you feel about each statement. The answers range from: Strongly Disagree, Disagree, Neither Agree nor Disagree, Agree, Strongly Agree.

As you read the sentence, you will know whether you agree or disagree. Click on the circle that describes how much you agree or disagree. Even though some statements are very similar, please answer each statement. This is not timed; work fast, but carefully. There are no "right" or "wrong" answers! The only correct responses are those that are true for you. Whenever possible, let the things that have happened to you help you make a choice.

PLEASE FILL IN ONLY ONE ANSWER PER QUESTION OR STATEMENT

Math

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1. Math has been my worst subject.	○	○	○	○	○
2. I would consider choosing a career that uses math.	○	○	○	○	○
3. Math is hard for me.	○	○	○	○	○
4. I am the type of student to do well in math.	○	○	○	○	○
5. I can handle most subjects well, but I cannot do a good job with math.	○	○	○	○	○
6. I am sure I could do advanced work in math.	○	○	○	○	○
7. I can get good grades in math.	○	○	○	○	○
8. I am good at math.	○	○	○	○	○

Science

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
9. I am sure of myself when I do science.	○	○	○	○	○
10. I would consider a career in science.	○	○	○	○	○
11. I expect to use science when I get out of school.	○	○	○	○	○
12. Knowing science will help me earn a living.	○	○	○	○	○
13. I will need science for my future work.	○	○	○	○	○
14. I know I can do well in science.	○	○	○	○	○
15. Science will be important to me in my life's work.	○	○	○	○	○
16. I can handle most subjects well, but I cannot do a good job with science.	○	○	○	○	○
17. I am sure I could do advanced work in science.	○	○	○	○	○

Engineering & Technology

Please read this paragraph before you answer the questions.

Engineers use math, science, and creativity to research and solve problems that improve everyone's life and to invent new products. There are many different types of engineering, such as chemical, electrical, computer, mechanical, civil, environmental, and biomedical. Engineers design and improve things like bridges, cars, fabrics, foods, and virtual reality amusement parks. Technologists implement the designs that engineers develop; they build, test, and maintain products and processes.

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
18. I like to imagine creating new products.	○	○	○	○	○
19. If I learn engineering, then I can improve things that people use every day.	○	○	○	○	○
20. I am good at building and fixing things.	○	○	○	○	○
21. I am interested in what makes machines work.	○	○	○	○	○
22. Designing products or structures will be important for my future work.	○	○	○	○	○
23. I am curious about how electronics work.	○	○	○	○	○
24. I would like to use creativity and innovation in my future work.	○	○	○	○	○
25. Knowing how to use math and science together will allow me to invent useful things.	○	○	○	○	○
26. I believe I can be successful in a career in engineering.	○	○	○	○	○

21st Century Learning

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
27. I am confident I can lead others to accomplish a goal.	○	○	○	○	○
28. I am confident I can encourage others to do their best.	○	○	○	○	○
29. I am confident I can produce high quality work.	○	○	○	○	○
30. I am confident I can respect the differences of my peers.	○	○	○	○	○
31. I am confident I can help my peers.	○	○	○	○	○
32. I am confident I can include others' perspectives when making decisions.	○	○	○	○	○
33. I am confident I can make changes when things do not go as planned.	○	○	○	○	○
34. I am confident I can set my own learning goals.	○	○	○	○	○
35. I am confident I can manage my time wisely when working on my own.	○	○	○	○	○
36. When I have many assignments, I can choose which ones need to be done first.	○	○	○	○	○
37. I am confident I can work well with students from different backgrounds.	○	○	○	○	○

Your Future

Here are descriptions of subject areas that involve math, science, engineering and/or technology, and lists of jobs connected to each subject area. As you read the list below, you will know how interested you are in the subject and the jobs. Fill in the circle that relates to how interested you are.

There are no “right” or “wrong” answers. The only correct responses are those that are true for
you.

	Not at all Interested	Not So Interested	Interested	Very Interested
1. Physics: is the study of basic laws governing the motion, energy, structure, and interactions of matter. This can include studying the nature of the universe. (aviation engineer, alternative energy technician, lab technician, physicist, astronomer)	○	○	○	○
2. Environmental Work: involves learning about physical and biological processes that govern nature and working to improve the environment. This includes finding and designing solutions to problems like pollution, reusing waste and recycling. (pollution control analyst, environmental engineer or scientist, erosion control specialist, energy systems engineer and maintenance technician)	○	○	○	○
3. Biology and Zoology: involve the study of living organisms (such as plants and animals) and the processes of life. This includes working with farm animals and in areas like nutrition and breeding. (biological technician, biological scientist, plant breeder, crop lab technician, animal scientist, geneticist, zoologist)	○	○	○	○
4. Veterinary Work: involves the science of preventing or treating disease in animals. (veterinary assistant, veterinarian, livestock producer, animal caretaker)	○	○	○	○
5. Mathematics: is the science of numbers and their operations. It involves computation, algorithms and theory used to solve problems and summarize data. (accountant, applied mathematician, economist, financial analyst, mathematician, statistician, market researcher, stock market analyst)	○	○	○	○
6. Medicine: involves maintaining health and preventing and treating disease. (physician’s assistant, nurse, doctor, nutritionist, emergency medical technician, physical therapist, dentist)	○	○	○	○
7. Earth Science: is the study of earth, including the air, land, and ocean. (geologist, weather forecaster, archaeologist, geoscientist)	○	○	○	○

8. Computer Science: consists of the development and testing of computer systems, designing new programs and helping others to use computers. (computer support specialist, computer programmer, computer and network technician, gaming designer, computer software engineer, information technology specialist)	○	○	○	○
9. Medical Science: involves researching human disease and working to find new solutions to human health problems. (clinical laboratory technologist, medical scientist, biomedical engineer, epidemiologist, pharmacologist)	○	○	○	○
10. Chemistry: uses math and experiments to search for new chemicals, and to study the structure of matter and how it behaves. (chemical technician, chemist, chemical engineer)	○	○	○	○
11. Energy: involves the study and generation of power, such as heat or electricity. (electrician, electrical engineer, heating, ventilation, and air conditioning (HVAC) technician, nuclear engineer, systems engineer, alternative energy systems installer or technician)	○	○	○	○
12. Engineering: involves designing, testing, and manufacturing new products (like machines, bridges, buildings, and electronics) through the use of math, science, and computers. (civil, industrial, agricultural, or mechanical engineers, welder, auto-mechanic, engineering technician, construction manager)	○	○	○	○

Thank you for taking this survey! Please click on the forward button below to submit your survey.

APPENDIX F. TEACHER STEM SURVEY (T-STEM)

Note: "Technology" is changed to "Science" for Science teachers

This survey is designed for technology education teachers to measure attitudes and beliefs about teaching and practices. There are no right or wrong answers and all responses are kept confidential.

Science Teaching Efficacy Belief Instrument

Please indicate the degree to which you agree or disagree with each statement below by selecting the option that best applies to you.

	Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
1. When a student does better than usual in science, it is often because the teacher exerted a little extra effort.	○	○	○	○	○
2. I am continually finding better ways to teach science.	○	○	○	○	○
3. Even when I try very hard, I don't teach science as well as I do most subjects.	○	○	○	○	○
4. When the science grades of students improve, it is most often due to their teacher having found a more effective teaching approach.	○	○	○	○	○
5. I know the steps necessary to teach science concepts effectively.	○	○	○	○	○
6. I am not very effective in monitoring science experiments.	○	○	○	○	○
7. If students are underachieving in science, it is most likely due to ineffective science teaching.	○	○	○	○	○

	Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
8. I generally teach science ineffectively.	○	○	○	○	○
9. The inadequacy of a student's science background can be overcome by good teaching.	○	○	○	○	○
10. The low science achievement of some students cannot generally be blamed on their teachers.	○	○	○	○	○
11. When a low achieving child progresses in science, it is usually due to extra attention given by the teacher.	○	○	○	○	○
12. I understand science concepts well enough to be effective in teaching elementary science.	○	○	○	○	○
13. Increased effort in science teaching produces little change in some students' science achievement.	○	○	○	○	○
14. The teacher is generally responsible for the achievement of students in science.	○	○	○	○	○

	Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
15. Students' achievement in science is directly related to their teacher's effectiveness in science teaching.	○	○	○	○	○
16. If parents comment that their child is showing more interest in science at school, it is probably due to the performance of the child's teacher.	○	○	○	○	○
17. I find it difficult to explain to students why science experiments work.	○	○	○	○	○
18. I am typically able to answer students' science questions.	○	○	○	○	○
19. I wonder if I have the necessary skills to teach science.	○	○	○	○	○
20. Effectiveness in science teaching has little influence on the achievement of students with low motivation.	○	○	○	○	○
21. Given a choice, I would not invite the principal to evaluate my science teaching.	○	○	○	○	○

	Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
22. When a student has difficulty understanding a science concept, I am usually at a loss as to how to help the student understand it better.	○	○	○	○	○
23. When teaching science, I usually welcome student questions.	○	○	○	○	○
24. I don't know what to do to turn students on to science.	○	○	○	○	○
25. Even teachers with good science teaching abilities cannot help some kids learn science.	○	○	○	○	○

Technology Teaching Efficacy and Beliefs

Directions: Please respond to these questions regarding your feelings about your <u>own</u> teaching.

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1. I am continually improving my technology teaching practice.	○	○	○	○	○
2. I know the steps necessary to teach technology effectively.	○	○	○	○	○
3. I am confident that I can explain to students why technology experiments work.	○	○	○	○	○
4. I am confident that I can teach technology effectively.	○	○	○	○	○
	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
5. I wonder if I have the necessary skills to teach technology.	○	○	○	○	○
6. I understand technology concepts well enough to be effective in teaching technology.	○	○	○	○	○
7. Given a choice, I would invite a colleague to evaluate my technology teaching.	○	○	○	○	○
8. I am confident that I can answer students' technology questions.	○	○	○	○	○
	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
9. When a student has difficulty understanding a technology concept, I am confident that I know how to help the student understand it better.	○	○	○	○	○
10. When teaching technology, I am confident enough to welcome student questions.	○	○	○	○	○
11. I know what to do to increase student interest in technology.	○	○	○	○	○

Technology Teaching Outcome Expectancy

Directions: The following questions ask about your feelings about teaching in general. Please respond accordingly.

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1. When a student does better than usual in technology, it is often because the teacher exerted a little extra effort.	○	○	○	○	○
2. The inadequacy of a student's technology background can be overcome by good teaching.	○	○	○	○	○
3. When a student's learning in technology is greater than expected, it is most often due to their teacher having found a more effective teaching approach.	○	○	○	○	○
4. The teacher is generally responsible for students' learning in technology.	○	○	○	○	○
5. If students' learning in technology is less than expected, it is most likely due to ineffective technology teaching.	○	○	○	○	○

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
6. Students' learning in technology is directly related to their teacher's effectiveness in technology teaching.	○	○	○	○	○
7. When a low achieving child progresses more than expected in technology, it is usually due to extra attention given by the teacher.	○	○	○	○	○
8. If parents comment that their child is showing more interest in technology at school, it is probably due to the performance of the child's teacher.	○	○	○	○	○
9. Minimal student learning in technology can generally be attributed to their teachers.	○	○	○	○	○

Student Technology Use

Directions: Please answer the following questions about how often students use technology in settings where you instruct students. If the question is not applicable to your situation, please select “Not Applicable.”

During technology instructional meetings (e.g. class periods, after school activities,
days of summer camp, etc.), how often do your students...

	Never	Occasionally	About half the time	Usually	Every time	⃠ Not Applicable
1. Use a variety of technologies,e.g. productivity, data visualization, research, and communication tools.	○	○	○	○	○	○
2. Use technology to communicate and collaborate with others, beyond the classroom.	○	○	○	○	○	○
3. Use technology to access online resources and information as a part of activities.	○	○	○	○	○	○
4. Use the same kinds of tools that professional researchers use, e.g. simulations, databases, satellite imagery.	○	○	○	○	○	○

	Never	Occasionally	About half the time	Usually	Every time	⃠ Not Applicable
5. Work on technology-enhanced projects that approach real world applications of technology.	○	○	○	○	○	○
6. Use technology to help solve problems.	○	○	○	○	○	○
7. Use technology to support higher-order thinking, e.g. analysis, synthesis and evaluation of ideas and information.	○	○	○	○	○	○
8. Use technology to create new ideas and representations of information.	○	○	○	○	○	○

Technology Instruction

Directions: Please answer the following questions about how often students engage in the following tasks during your instructional time.

During technology instructional meetings (e.g. class periods, after school activities,
days of summer camp, etc.), how often do your students...

	Never	Occasionally	About half the time	Usually	Every time
1. Develop problem-solving skills through investigations (e.g. scientific, design or theoretical investigations).	○	○	○	○	○
2. Work in small groups.	○	○	○	○	○
3. Make predictions that can be tested.	○	○	○	○	○
4. Make careful observations or measurements.	○	○	○	○	○
5. Use tools to gather data (e.g. calculators, computers, computer programs, scales, rulers,	○	○	○	○	○

	Never	Occasionally	About half the time	Usually	Every time
6. Recognize patterns in data.	○	○	○	○	○
7. Create reasonable explanations of results of an experiment or investigation.	○	○	○	○	○
8. Choose the most appropriate methods to express results (e.g.drawings, models, charts, graphs, technical language, etc.).	○	○	○	○	○

	Never	Occasionally	About half the time	Usually	Every time
9. Complete activities with a real-world context.	○	○	○	○	○
10. Engage in content-driven dialogue.	○	○	○	○	○
	Never	Occasionally	About half the time	Usually	Every time
11. Reason abstractly.	○	○	○	○	○
12. Reason quantitatively.	○	○	○	○	○
13. Critique the reasoning of others.	○	○	○	○	○
14. Learn about careers related to the instructional content.	○	○	○	○	○

21st Century Learning Attitudes

Directions: Please respond to the following questions regarding your feelings about learning ***in general***.

"I think it is important that students have learning opportunities to..."

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1. Lead others to accomplish a goal.	○	○	○	○	○
2. Encourage others to do their best.	○	○	○	○	○
3. Produce high quality work.	○	○	○	○	○
4. Respect the differences of their peers.	○	○	○	○	○
	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
5. Help their peers.	○	○	○	○	○

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
6. Include others' perspectives when making decisions.	○	○	○	○	○
7. Make changes when things do not go as planned.	○	○	○	○	○
8. Set their own learning goals.	○	○	○	○	○
	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
9. Manage their time wisely when working on their own.	○	○	○	○	○
10. Choose which assignment out of many needs to be done first.	○	○	○	○	○
11. Work well with students from different backgrounds.	○	○	○	○	○

Teacher Leadership Attitudes

Directions: Please respond to the following questions regarding your feelings about teacher leadership ***in general.***

"I think it is important that teachers ..."

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1. Take responsibility for all students' learning.	○	○	○	○	○
2. Communicate vision to students.	○	○	○	○	○
3. Use a variety of assessment data throughout the year to evaluate progress.	○	○	○	○	○
4. Use a variety of data to organize, plan and set goals.	○	○	○	○	○
5. Establish a safe and orderly environment.	○	○	○	○	○
6. Empower students.	○	○	○	○	○

STEM Career Awareness

Directions: Please respond to the following questions based upon how much you
disagree or agree with the statements.

"I know ..."

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1. About current STEM careers.	○	○	○	○	○
2. Where to go to learn more about STEM careers.	○	○	○	○	○
3. Where to find resources for teaching students about STEM careers.	○	○	○	○	○
4. Where to direct students or parents to find information about STEM careers.	○	○	○	○	○

Teaching Design, Engineering, & Technology Survey

	1 (Not At All)	2	3	4	5 (Very Much)
1. How familiar are you with Design/Engineering/Technology as typically demonstrated in the examples given in the overview?	○	○	○	○	○
2. Have you had any specific courses in Design/Engineering/Technology outside of your preservice curriculum?	○	○	○	○	○
3. Did your preservice curriculum include any aspects of Design/Engineering/Technology?	○	○	○	○	○
4. Was your pre-service curriculum effective in supporting your ability to teach Design/Engineering/Technology at the beginning of your career?	○	○	○	○	○
5. How confident do you feel about integrating more Design/Engineering/Technology into your curriculum?	○	○	○	○	○

	1 (Not At All)	2	3	4	5 (Very Much)
6. How important should pre-service education be for teaching Design/Engineering/Technology?	○	○	○	○	○
7. Do you use Design/Engineering/Technology activities in the classroom?	○	○	○	○	○
8. Does your school support Design/Engineering/Technology activities?	○	○	○	○	○
9. Do you believe Design/Engineering/Technology should be integrated into the K-12 curriculum?	○	○	○	○	○

	1 (Not At All)	2	3	4	5 (Very Much)
1. How familiar are you with Design/Engineering/Technology as typically demonstrated in the examples given in the overview?	○	○	○	○	○
2. Have you had any specific courses in Design/Engineering/Technology outside of your preservice curriculum?	○	○	○	○	○
3. Did your preservice curriculum include any aspects of Design/Engineering/Technology?	○	○	○	○	○
4. Was your pre-service curriculum effective in supporting your ability to teach Design/Engineering/Technology at the beginning of your career?	○	○	○	○	○
5. How confident do you feel about integrating more Design/Engineering/Technology into your curriculum?	○	○	○	○	○

To what extent do you agree that a typical engineer....

	1 (Strongly Disagree)	2	3	4	5 (Strongly Agree)
10. Works well with people.	○	○	○	○	○
11. Has good verbal skills.	○	○	○	○	○
12. Has good math skills.	○	○	○	○	○
13. Has good writing skills.	○	○	○	○	○
14. Earns good money.	○	○	○	○	○
15. Likes to fix things.	○	○	○	○	○
16. Does well in science.	○	○	○	○	○

To what extent do you agree that a typical engineer....

	1 (Strongly Disagree)	2	3	4	5 (Strongly Agree)
10. Works well with people.	○	○	○	○	○
11. Has good verbal skills.	○	○	○	○	○
12. Has good math skills.	○	○	○	○	○
13. Has good writing skills.	○	○	○	○	○
14. Earns good money.	○	○	○	○	○
15. Likes to fix things.	○	○	○	○	○
16. Does well in science.	○	○	○	○	○

To what extent do you agree with the following statements...?

	1 (Strongly Disagree)	2	3	4	5 (Strongly Agree)
17. Most people feel that female students can do well in Design/Engineering/Technology.	○	○	○	○	○
18. Most people feel that minority students (African American, Hispanic / Latino, and American Indian) can do well in Design/Engineering/Technology.	○	○	○	○	○

As you teach a science curriculum, it is important to include...

	1 (Not at all Important)	2	3	4	5 (Very Important)
19. Planning a project.	○	○	○	○	○
20. Using engineering to develop new technologies.	○	○	○	○	○

I am interested in learning more about Design/Engineering/Technology through...

	1 (Not at all Interested)	2	3	4	5 (Very Interested)
21. In-service.	○	○	○	○	○
22. Workshops.	○	○	○	○	○
23. Peer training.	○	○	○	○	○
24. College courses.	○	○	○	○	○

I would like to be able to teach my students to understand the...

	1 (Strongly Disagree)	2	3	4	5 (Strongly Agree)
25. Design process.	○	○	○	○	○
26. Use and impact of Design/Engineering/Technology.	○	○	○	○	○
27. Science underlying Design/Engineering/Technology.	○	○	○	○	○
28. Types of problems to which Design/Engineering/Technology should be applied.	○	○	○	○	○
29. Process of communicating technical information.	○	○	○	○	○

My motivation for teaching science is...

	1 (Strongly Disagree)	2	3	4	5 (Strongly Agree
30. To prepare young people for the world of work.	○	○	○	○	○
31. To promote an enjoyment of learning.	○	○	○	○	○
32. To develop an understanding of the natural and technical world.	○	○	○	○	○
33. To develop scientists, engineers, and technologists for industry.	○	○	○	○	○
34. To promote an understanding of how Design/Engineering/Technology affects society.	○	○	○	○	○

How strong is each of the following a BARRIER in integrating Design/Engineering/Technology in your classroom?

	1 (Not Strong At All)	2	3	4	5 (Very Strong)
35. Lack of time for teachers to learn about Design/Engineering/Technology.	○	○	○	○	○
36. Lack of teacher knowledge.	○	○	○	○	○
37. Lack of training.	○	○	○	○	○
38. Lack of administration support.	○	○	○	○	○

How strongly do you agree that ...

	1 (Strongly Disagree)	2	3	4	5 (Strongly Agree)
39. Design/Engineering/Technology has positive consequences for society.	○	○	○	○	○

How much do you know about the ...

	1 (Very Little)	2	3	4	5 (Very Much)
40. National science standards related to Design/Engineering/Technology?	○	○	○	○	○

Please answer the following questions by clicking on the most appropriate answer

	1 (Not At All)	2	3	4	5 (Very Much)
41. How enthusiastic do you feel about including Design/Engineering/Technology activities in your teaching of mathematics?	○	○	○	○	○
42. How enthusiastic do you feel about including Design/Engineering/Technology activities in your teaching of science?	○	○	○	○	○
43. How prepared do you feel to include Design/Engineering/Technology activities in your teaching of mathematics?	○	○	○	○	○
44. How prepared do you feel to include Design/Engineering/Technology activities in your teaching of science?	○	○	○	○	○

45. How important is it for you that Design/Engineering/Technology activities are aligned to mathematics state and national standards?	○	○	○	○	○
46. How important is it for you that Design/Engineering/Technology activities are aligned to science state and national standards?	○	○	○	○	○

To what extent do you agree that for minority students (African American, Hispanic/Latino, and American Indian).....

	1 (Strongly Disagree)	2	3	4	5. (Strongly Agree)
47. Design/Engineering/Technology activities increase their interest in pursuing a career in engineering?	○	○	○	○	○
48. The Design/Engineering/Technology activities increase their performance in science?	○	○	○	○	○
49. The Design/Engineering/Technology activities increase their performance in mathematics?	○	○	○	○	○
50. The Design/Engineering/Technology activities increase their technological literacy?	○	○	○	○	○

To what extent do you agree that for female students...

	1 (Strongly Disagree)	2	3	4	5. (Strongly Agree
51. Design/Engineering/Technology activities increase their interest in pursuing a career in engineering?	○	○	○	○	○
52. The Design/Engineering/Technology activities increase their performance in science?	○	○	○	○	○

53. The Design/Engineering/Technology activities increase their performance in mathematics?	○	○	○	○	○
54. The Design/Engineering/Technology activities increase their technological literacy?	○	○	○	○	○

To what extent do you agree that for male students...

	1 (Strongly Disagree)	2	3	4	5. (Strongly Agree)
55. Design/Engineering/Technology activities increase their interest in pursuing a career in engineering?	○	○	○	○	○
56. The Design/Engineering/Technology activities increase their performance in science?	○	○	○	○	○
57. The Design/Engineering/Technology activities increase their performance in mathematics?	○	○	○	○	○
58. The Design/Engineering/Technology activities increase their technological literacy?	○	○	○	○	○

APPENDIX G. PERMISSION FROM THE JOURNAL FOR STEM EDUCATIONAL RESEARCH FOR PUBLICATION

RE: Permission Request

Journalpermissions <journalpermissions@springernature.com>
Wed 10/27/2021 8:28 AM
To: Jung Han <han336@purdue.edu>
Cc: Kelley, Todd R <trkelley@purdue.edu>

Dear Jung,

Thank you for your recent email. Springer Nature journal authors may reuse their article's Version of Record, in whole or in part, in their own thesis without any additional permission required, provided the original publication is properly cited and includes the following acknowledgement '"Reproduced with permission from Springer Nature". This includes the right to make a copy of your thesis available in your academic institution's repository, or other repository required by your awarding institution. For more information please visit see our FAQs here..

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Best wishes,
Bod

Bod Adegboyega
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Springer Nature
4 Crinan Street, London N1 9XW, UK
T +44 (0) 442034263235
Bod.adegboyega.1@springernature.com

From: Jung Han <han336@purdue.edu>
Sent: 11 October 2021 05:48
To: Journalpermissions <journalpermissions@springernature.com>
Cc: Kelley, Todd R <trkelley@purdue.edu>
Subject: Permission Request

[External - Use Caution]

To whom it may concern,

My name is Jung Han, a Ph.D. Candidate at Purdue University. As my dissertation is article-based, I would like to ask your permission to use my recent article published in your journal. May I ask your permission for me to publish my article titled "Factors Influencing Student STEM Learning: Self-

Efficacy and Outcome Expectancy, 21st Century Skills, and Career Awareness" as one of the three articles in my dissertation? Thank you so much.

Han, J., Kelley, T., & Knowles, J. G. (2021). Factors Influencing Student STEM Learning: Self-Efficacy and Outcome Expectancy, 21 st Century Skills, and Career Awareness. *Journal for STEM Education Research*, 1-21. https://doi-org.ezproxy.lib.purdue.edu/10.1007/s41979-021-00053-3

Sincerely,
Jung Han

Ph.D. Candidate, Graduate Assistant
han336@purdue.edu
STEM Education Leadership
Engineering/Technology Teacher Education
Department of Technology Leadership and Innovation
Purdue Polytechnic Institute

APPENDIX H. COMMUNICATION WITH JOURNAL OF ENGINEERING DESIGN FOR PUBLICATION

Questions and Requests: Journal of Engineering Design

From: jed_admin@sky.com <jed_admin@sky.com>
Sent: Wednesday, December 8, 2021 5:39 AM
To: Kelley, Todd R <trkelley@purdue.edu>
Subject: RE: Questions and Requests: Journal of Engineering Design

The journal's publishing contact has got back to me.

Basically, permission will depend on what author publishing agreement the authors will sign.

If Ms Han signs copyright over to T&F/the journal, she would need permission to reproduce it in the dissertation. The Permissions team permissionrequest@tandf.co.uk should be able to help direct what permissions Ms Han needs here. Here is the guide for her to request permissions.

If she is going to publish the article in open access then she does not need any permissions from T&F as she would be the copyright holder of the content.

I hope this helps.

Regards
Alex Duffy

Questions and Requests: Journal of Engineering Design

From: Kelley, Todd R <trkelley@purdue.edu>
Sent: 02 December 2021 18:24
To: Jed Admin <jed_admin@sky.com>; Jung Han <han336@purdue.edu>
Subject: RE: Questions and Requests: Journal of Engineering Design

Hello Mr. Duff,
I would appreciate it if you can find out from the publisher regarding republishing of the dissertation study. This is a new approach to a Ph.D. at Purdue but the grad school requires documentation of permissions to republish the dissertation. I would not want Ms. Han to not be able to graduate because we are waiting on this information. I would appreciate it if you could make some phone calls and find out this decision. Ms. Han only has a few days until she needs to deposit her document.
We certainly understand regarding the resubmission of the manuscript. We understand that it is already under review again, that's fine and we can incorporate these changes when she resubmits the manuscript in round #3.
Thanks,
Dr. Kelley
Purdue University

APPENDIX I. APPROVAL FOR USING STUDENT PROTOTYPE PICTURES

JH

Jung Han
Wed 9/29/2021 2:59 PM
To: [redacted] <[redacted]>
Cc: Kelley, Todd R

Hi [redacted]

I hope this email finds you well. We are currently working on journal publishing and wondering if we could use the photos of the lure prototypes that your students produced? Thank you so much again for your support and all your hard work during the TRAILS project.

Sincerely,
Jung Han

Ph.D. Candidate, Graduate Assistant
han336@purdue.edu
TRAILS
STEM Education Leadership
Engineering/Technology Teacher Education
Department of Technology Leadership and Innovation
Purdue Polytechnic Institute

CA

[redacted] <[redacted]>
Wed 9/29/2021 3:05 PM
To: Jung Han

You are welcome to use any pictures of our student work.

JJ

[redacted] <[redacted]>
Wed 9/29/2021 3:08 PM
To: Jung Han

yes, please do.

[redacted]

APPENDIX J. CONFIRMATIONS FOR INTERESTS IN STUDY PARTICIPATION

On Wed, Aug 7, 2019 at 10:12 PM Jung Han <han336@purdue.edu> wrote:

Hello TRAILS teachers,

It was great working with you for the past years.
I am planning to start my dissertation work and would like to develop a research from TRAILS data. One area of focus will be investigating STEM lesson implementation when the TRAILS project has ended and there is no longer funding.

**What I will be collecting:

1. **21st Century Survey** (30 questions)
    - Pretest – Due Oct 1st, 2019
    - Posttest – Due Dec 1st, 2019
1. **Dbait Knowledge Test** (24 questions) – If you teach D-bait this fall. (If you teach a custom lesson, D-bait tests are not needed)
    - Pretest - Due Oct 1st, 2019
    - Posttest - Due Dec 1st, 2019

**If you are volunteering to help me with this work, please respond to this email with the information;

1. Are you teaching a TRAILS lesson this year? **Which TRAILS lesson will you be teaching?**
2. **If you are not teaching a TRAILS lesson**, can you implement the **21st Century Skills Survey (pretest only)?**
3. How many **IRB forms** do you need?

I hope you all for a wonderful start to the fall semester.

Thanks,
Jung

Ph.D. Student, Graduate Assistant
han336@purdue.edu
Engineering/Technology Teacher Education
TRAILS
345 Young Hall
Department of Technology Leadership and Innovation

From: [redacted] <[redacted]>
Sent: Thursday, August 8, 2019 4:53:36 PM
To: Jung Han <han336@purdue.edu>
Cc: [redacted]
Subject: Re: Dissertation Participants Recruiting

Hey Jung,
[redacted], and I will be teaching TRAILS lessons again this year but we are changing up our implementation days. Below are the answers to your questions.

1. Are you teaching a TRAILS lesson this year? **Which TRAILS lesson will you be teaching?**
[redacted] and I plan to teach Bumblebot in the fall
[redacted] and I plan to teach DBait in the spring
2. **If you are not teaching a TRAILS lesson**, can you implement the **21st Century Skills Survey (pretest only)?**
Amanda and I could administer 21st Century Skills survey and DBait Pre-Test before the due dates you have requested but would not be able to give you post-test data on DBait until late spring.
3. How many **IRB forms** do you need?
Amanda and I will need around 50
Please let us know if you have any questions and good luck!
[redacted]

From: [redacted] <[redacted]>
Sent: Friday, August 9, 2019 11:20:21 AM
To: Jung Han <han336@purdue.edu>
Subject: Re: Dissertation Participants Recruiting

I assume these are tests taken by students (not just me). Our DBait lesson is in the fall & our custom lesson is in the spring. I would be able to do this for you. We have not finished registration yet. Right now my schedule says 17 students. If you send me 25, that should be more than enough. You could also send me a digital copy of the IRB forms and I can make copies.

-[redacted]