Fostering Integrated STEM and Entrepreneurial Mindsets Through Design Thinking

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Aaron J. Sickel

To create, one must first question everything.

Eileen Gray (Architect and Designer)

Abstract

Design thinking refers to cognitive processes and design abilities that help designers develop solutions for human-centered problems. This chapter describes how design thinking can serve as an instructional driver to foster learners' integrated STEM learning outcomes and entrepreneurial mindsets. The author first defines the three constructs of design thinking, integrated STEM, and entrepreneurial mindsets. Next, he describes a design thinking project he facilitated for pre-service teachers enrolled in an elementary mathematics methods course as part of their university-based teacher education program. He unpacks how specific STEM learning goals and entrepreneurial mindsets were fostered and targeted during the project, with examples of pre-service teachers' learning from their design thinking journal entries. Drawing on research and his experience with design thinking education in the U.S. state of Hawai'i, the chapter concludes with the author's discussion of both challenges and opportunities for design thinking to play a prominent role across educational systems.

A. J. Sickel (✉)
College of Education, University of Hawai'i-Mānoa, 223 Everly Hall, 1776 University Ave, Honolulu, HI 96822, USA
e-mail: sickel@hawaii.edu

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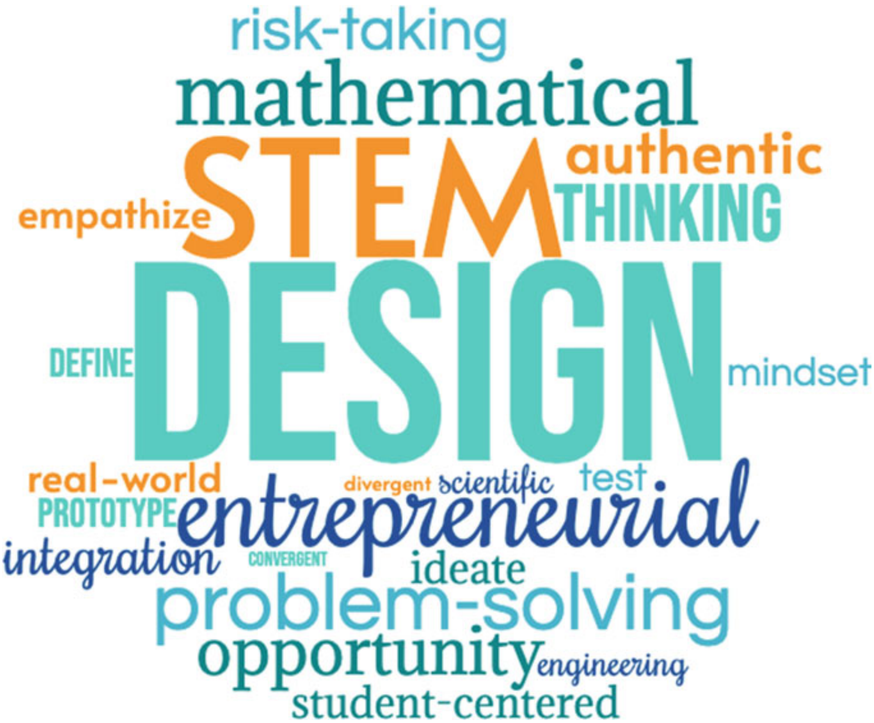
Graphical Abstract



Keywords

STEM · Entrepreneurial mindsets · Design thinking · Mathematics

1 Introduction

In the summer of 2017, I had just moved to Honolulu, Hawai‘i, to take a new position with the Hawai‘i State Department of Education’s (DOE) Office of Curriculum and Instructional Design after spending nine years in the field of university teacher education. By taking the position of STEM educational specialist, I was exploring an opportunity to work more closely with school systems in the field of STEM education. One of the first conversations with my new administrator included the topic of design thinking; specifically, the state office wanted me to work with local organizations to begin offering design thinking workshops for teachers as part of a broader focus on supporting inquiry and innovation in Hawai‘i’s public schools. At the time of the original conversation, I had read about design thinking and held only a cursory understanding of it from my prior work as a teacher educator. Yet, I was intrigued. One goal I had in this new position was to develop an openness to new ways of thinking about STEM—how students might become more engaged with learning the STEM subjects and how a range of pedagogical tools might help teachers deepen the learning experiences they create.

Over the two-year span I worked for the Hawai‘i DOE, design thinking became a priority within my portfolio of initiatives. I worked with local educational organizations who specialized in design thinking processes to offer professional development courses for teachers across the state. To upskill myself, I participated with the teachers in those professional development courses as a learner while they were led by design thinking educators. In the second year, I formed a design thinking collaborative so that educators across Hawai‘i who were using design thinking could work together to curate resources that would eventually be publicly shared with schools across the DOE. These resources offered specific ideas for lessons and units as well as strategies for scaling up the potential use and implementation of design thinking within individual schools and complex areas (a regional assemblage of schools, similar to school districts in U.S. mainland states). Design thinking had a considerable impact on my own way of thinking and my work as a STEM educator. I believe there is great potential for it to contribute to new ways of thinking about STEM education, and more specifically to the goals of this book, the fostering of learners’ entrepreneurial mindsets through STEM learning experiences.

Following this introduction (Section “Introduction”), the chapter is organized into four ensuing sections. In Section “Defining the Constructs”, I begin with a description of my views of design thinking, integrated STEM, and entrepreneurial mindsets based on literature and my work in Hawai‘i. In Section “The Paper Towel Project and Its Results”, I provide a descriptive example of how I integrated a design thinking project with the aim of fostering integrated STEM learning goals and entrepreneurial mindsets for pre-service teachers in an elementary mathematics methods course as part of an undergraduate teacher education program. In Section “Challenges and Opportunities for Design Thinking”, I discuss challenges and opportunities we have in the fields of integrated STEM education and entrepreneurial mindsets to make meaningful use of design thinking in the future. I conclude the chapter with Section “Conclusion” by summarizing the important concepts of the chapter.

2 Defining the Constructs

2.1 Design Thinking

Design thinking has become an increasingly popular construct in the field of business and commerce [1, 2]. Although it has no universal definition, Kimbell [3] explains that design thinking is described primarily from three different perspectives: (1) A general theory of design, (2) a cognitive style, and (3) an organizational resource.

Regarding the first perspective (design theory), design as a field is difficult to describe because "design has no special subject matter of its own apart from what a designer conceives it to be…design thinking may be applied to any area of human experience" [4, p. 16]. Whether it involves civil engineers designing a dam, a business manager designing a marketing plan, an artist designing a sculpture, or a teacher designing a lesson, design can play a role in the authentic work of any career and in the management of our everyday lives. What defines design thinking as a field is the negotiation of wicked or ill-defined problems. This kind of problem is open-ended, complex and has many possible solutions [5].

Regarding the second perspective (cognitive style), design thinking has evolved from a focus on specific descriptions of technological advances to also include a deeper look at the cognitive processes employed consistently by designers [6]. While not always linear in nature, design thinking is often associated with the nature of designers' active and creative thinking as they negotiate problems. In Razzouk and Shute's review of research on design thinking, they define it as "an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign" [7, p. 330]. The five-phase process presented in Fig. 1 was developed by the Hasso Plattner Institute for Design [8] (colloquially called the d.school) and has been used extensively by a variety of organizations as well as elementary, middle school, secondary, and post-secondary learning contexts.

Regarding the third perspective (organizational resource), brothers David M. and Tom Kelley further popularized the term, design thinking, with the launch of IDEO in 1978, a global design and innovation company aimed at helping businesses design products and services [9]. They began thinking about the elements, mindsets, and abilities that allow designers to be successful and were the most learnable by organizations wishing to tackle ill-defined problems. These elements, mindsets, and abilities include both cognitive constructs (moving between concrete and

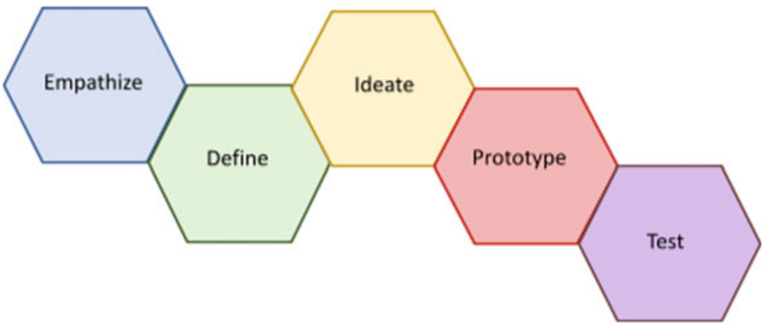


Fig. 1 Design thinking process developed at the d.school (reprinted with permission of [8])

abstract) and affective constructs (navigating ambiguity with an optimistic orientation). They discuss the importance of combining feelings, intuition, and inspiration along with rational and analytical mindsets to develop solutions that are both meaningful and functional [9].

2.2 Integrated STEM

It is important to articulate my views of integrated STEM teaching and learning. Below, I discuss my view of integrated STEM in alignment with essential features developed by a Hawai‘i DOE STEM Work Group, followed by reconsiderations of engineering design processes (EDPs) that often serve as the foundation for integrating STEM learning [10].

2.2.1 FAIR Features

As the STEM specialist for the Hawai‘i DOE, I came to understand there were many exciting examples of schools developing STEM programs or emphasizing STEM learning. At that time, the state had generally defined STEM education as encompassing three perspectives and goals [11]:

- Developing students’ learning and interest in the subjects of science, technology, engineering, and mathematics (silo view)
- Exposing students to integrated STEM learning experiences (integration view)
- Developing students’ “STEM skills”, e.g., problem-solving and creative thinking, which are helpful for both STEM and non-STEM careers (skills view).

In 2017–2018, I convened a work group of STEM teacher leaders with the task of further articulating goals for STEM education to public schools across the state. After examining the three existing goals, we were particularly interested in the notion of integrated STEM, which, on the one hand, has shown to produce positive student learning outcomes [12], yet on the other hand, has been difficult for teachers to operationalize [13]. We felt that further articulating this goal and view of STEM would help support the other two goals. After considering STEM literature and their own experiences as STEM educators, we asked the question, “What are the most fundamental or essential features of a high-quality STEM learning experience, regardless of grade level or guiding curriculum materials?” We felt that answering this question could provide clarity and coherence for future state-level STEM initiatives.

The resulting features were titled the FAIR Features of Integrated STEM, including: Student-Centered Instructional **Framework**, Authentic **Assessment**, Purposeful **Integration**, and **Real-World** Connections. Below, I describe each feature (the full explanation of each feature can be found in a document linked to the Hawaii DOE’s Learning Design website [11]).

Student-Centered Framework

To help teachers think about structuring STEM learning experiences, we articulated integrated STEM as being driven by an instructional framework that is student driven. We encouraged multiple frameworks depending on the specific experience being designed, which might include instructional approaches/sequences such as project-based learning [14] and/or design processes such as engineering design or design thinking.

Authentic Assessment

We encouraged teachers to conclude integrated STEM learning experiences with an authentic assessment, which we defined as being authentic to the STEM disciplines (e.g., developing a scientific presentation in similar ways that scientists would) and/or the goals of the specific task (e.g., if learners are being asked to develop a solution to a problem, they actually carry out that solution). We clarified that culminating assessments should be of varying types (e.g., physical models, written explanations, computer applications, etc.), and should assess skills and knowledge of particular STEM disciplines. While formative assessment is encouraged during integrated STEM experiences, we focused this feature on the critical role of authentic, culminating assessments.

Purposeful Integration

We viewed integrated STEM as involving the purposeful integration of at least two STEM subjects [15] and potentially non-STEM subjects [10]. Regarding standards, we felt a balance was needed between the state's adoption of standards-based learning and the open-ended nature of integrated learning. Specifically, there needed to be an anchoring standard of at least one STEM subject tied to the grade level according to the Next Generation Science Standards (NGSS) [16], Common Core Mathematics Standards [17], and/or International Society for Technology in Education (ISTE) Standards [18], but that the other subject connections may not be as explicitly tied to the targeted grade level, depending on the task. Essentially, we felt the problem, challenge, or task needed to authentically drive the learning as much as possible.

Real-World Connection

We encouraged teachers to help learners make explicit connections to the world around them throughout a STEM learning experience. This feature encourages a range of connections, from enacting or engineering solutions to addressing sustainability issues on the school campus to proposing solutions for teacher-presented scenarios, albeit scenarios related to a real-world problem.

2.2.2 Reconsidering Engineering Design Processes

It is helpful to compare design thinking practices with traditional views of engineering design processes in terms of human aspects of design and the role of contextual constraints. While I concur with other STEM educators' position [10] that EDPs can serve as important integrators or driving processes of STEM integration, I also believe there are ways in which traditional views of engineering design can be complemented by design thinking processes. Some scholars have discussed similar features between the two [19]. For example, the NGSS describes three important components of engineering design: defining problems, designing solutions, and optimizing solutions [16]. One might see some degree of alignment between these components and the d.school design thinking process, with the Define phase (defining problems), Ideate phase (designing solutions), and the Prototype and Test phases (optimizing solutions) addressing all components. However, such an explanation misses a few key elements from the perspective of design thinking: (1) highlighting the role of empathy and affect in design processes; and (2) ideating creatively before considering constraints. These two elements are discussed in turn.

Empathy and Affect

The Empathize phase can serve as a powerful means of connecting learners to the world around them, as they are required to consider how a particular real-world phenomenon is related to human issues and concerns. Design thinking educators have observed greater investment from students by beginning a design experience with empathy. For example, Cook and Bush described a STEM challenge using design thinking as the driving process in which fourth-grade students designed a prosthetic lower arm and hand to help a kindergarten student work on a computer [20]. They discussed the critical role of empathy because it "set the stage for students to care about the problem and as a result, they were personally invested and wanted to do everything in their power to design a solution for the kindergartner" (p. 99).

The Empathize phase supports learners' development and application of affective mindsets and characteristics throughout the experience. Brown describes a design thinker's personality profile, and extends the description beyond engineering design skills (e.g., thinking as part of a team, thinking and communicating in several languages of design) to move further into the world of affect [21]. Design thinking traits speak more to willingness, attitudes of persistence, and open mindedness. Not just tolerating ambiguity but a willingness to ask questions and take on new approaches; not just thinking as part of a team, but also adopting the perspective of someone else; not just handling uncertainty but adopting an optimistic attitude that a solution can be designed. In the same way that science education advocates for science as a human endeavor [16], design thinking offers a helpful nudge in the same direction for engineering and integrated STEM education.

Ideating Creatively Before Considerations of Constraints

A second way that design thinking offers a new perspective on traditional notions of engineering design is that it allows for a reconsideration of the role and placement of constraints during design processes. Many EDPs used in elementary, middle school, and secondary education highlight the critical role of constraints early on in the process. For example, a useful engineering model presented by the Teach Engineering website begins with the *Ask* phase before continuing on with *Research*, *Imagine*, *Plan*, *Create*, *Test*, and *Improve* [22]. One example prompt listed for the *Ask* phase includes: *What are the limitations?* However, during the early stages of design thinking, one does not need to initially consider constraints. Rather, the goal is to be open to the needs of end-users, define the problem in unique ways, and ideate creative solutions. This is not to say that reality and real-world constraints should not come into play. However, the advantage of this approach is that the designer does not need to prematurely take ideas off of the table, and it is always possible that part of a wild idea will become useful later on in the process. Moreover, creativity may be unnecessarily obstructed if learners focus intensely on constraints at the beginning of design processes. In essence, innovative design needs many ideas, with full acknowledgement that many of them will be adjusted or abandoned. This allows the design thinking process to make use of both divergent and convergent thinking during integrated STEM learning experiences. It facilitates divergent thinking early on while problems are being defined and solutions ideated, and then convergent thinking as solutions are fine-tuned through prototyping and testing [9].

I believe the advantages of design thinking might be a welcomed contribution within the field of engineering education, which in turn supports more of its use within integrated STEM education. Dym et al. discuss several concerns about the traditional engineering curriculum at universities. They call for engineering curricula to incorporate more attention to design, given that engineering programs have overly focused on knowledge of technical systems without attention to "the intellectual content of design," which is "consistently underestimated" [23, p. 104]. Due to concerns from industry about beginning engineers' preparedness with design, there has already been a shift toward more incorporation of design capstone courses at the conclusion of programs and cornerstone design courses at the beginning [23, 24]. This shift could potentially support a fuller set of desirable mindsets for engineering students, including a willingness to divergently identify new opportunities for innovative designs and a propensity for failing forward with confidence, both of which are discussed as important entrepreneurial mindsets in the next section.

2.3 Entrepreneurial Mindsets

After discussing the ways in which design thinking supports previously established goals of integrated STEM, I turn my attention to the desired outcome of developing students' entrepreneurial mindsets. The Network for Teaching Entrepreneurship [25], an international non-profit organization focused on entrepreneurial training and education, has articulated eight domains of the entrepreneurial mindset: (1) critical thinking; (2) flexibility and adaptability; (3) communication and collaboration; (4) comfort with risk; (5) initiative and self-reliance; (6) future orientation; (7) opportunity recognition; and (8) creativity and innovation. At a glance, STEM educators would be hard-pressed to view any of these domains as particularly incompatible with the goals of integrated STEM and could go as far as to say they are inherently situated within the design of most integrated STEM learning experiences. Therefore, the question becomes, what might be some ways in which the construct of entrepreneurial mindsets adds a new dimension to the goals of integrated STEM? I believe there are two distinguishing domains of entrepreneurial mindsets, which have great potential to add value to the design of STEM learning experiences: (1) opportunity recognition; and (2) comfort with risk.

2.3.1 Opportunity Recognition

The field of entrepreneurship is largely defined by the critical role of opportunities [26]—specifically “the process of discovery, evaluation and exploitation of opportunities” [27, p. 218]. In their book, *The Entrepreneurial Mindset*, McGrath and MacMillan present characteristics of habitual entrepreneurs, three out of five including notions of seeking and pursuing opportunities while avoiding exhaustion [28]. They go on to discuss different ways that entrepreneurs “stock the opportunity register” (p. 5) by constructing new ideas through opportunity recognition approaches, which include:

- *Redesign*—modify existing products/services
- *Differentiate*—highlight aspects of your products/services that distinguish you from competitors
- *Re-segment*—focus on better serving a segment of the target population with a product/service
- *Reconfigure*—change the current basis for segmentation and/or attract people to your product/services in a radically different way.

They present several specific strategies to aid entrepreneurs with these approaches, for example, creating attribute maps that help distinguish customer attitudes toward particular attributes of a product and sketching out fictitious super-products that would solve all problems under scrutiny. Entrepreneurs pursue opportunities that combine innovative thinking with practicality. As described earlier, one desired outcome of integrated STEM education is for learners to produce authentic products (FAIR Features) for human-centered problems (Empathy). To do this well, it will be helpful for learners to develop a mindset of opportunity recognition so that they identify key opportunities to innovate in ways that are helpful for their intended audience, user, client, or customer.

2.3.2 Risk-Taking

Due to the need to find new opportunities, entrepreneurship is not typically rooted in processes of optimization [27], a characteristic that distinguishes it from EDPs typically designed for elementary, middle school, and secondary education [16]. In part, this is based on an entrepreneur’s need to act upon opportunities in tight timelines. A study by Busenitz and Barney revealed that entrepreneurs were more likely to exhibit biases toward “overconfidence (overestimating the probability of being right) and representativeness (the tendency to overgeneralize from a few characteristics or observations)” [29, p. 10]. In essence, entrepreneurs engage in risk-taking that privileges taking chances with new opportunities without becoming bogged down with counterfactual thinking, regret, or inaction [27]. Engaging in STEM learning experiences from a design thinking perspective inherently requires a willingness to try an idea and then adjust or abandon that idea as needed. A risk-taking mindset is essential for this aim.

3 The Paper Towel Project and Its Results

After defining the constructs of design thinking, integrated STEM, and entrepreneurial mindsets, I now describe an example of a design thinking project that attempts to foster integrated STEM outcomes and entrepreneurial mindsets.

3.1 Context

During my time as STEM specialist for the Hawai‘i DOE, I began experimenting with explicit integration of design thinking into STEM units. The following project has been incorporated into professional development initiatives for in-service teachers and mathematics methods courses for elementary pre-service teachers. The purpose of this project is to help develop teachers' understandings of integrated STEM, design thinking and entrepreneurial mindsets by engaging in an experience as learners that attempts to integrate all three constructs.

To describe the paper towel project, I will first explain the sequence of activities that occurs when I facilitate the project in the order of the five design thinking phases from the d.school [8]: Empathize, Define, Ideate, Prototype, and Test. The description below is based on the most recent project facilitation in a mathematics methods course for elementary pre-service teachers in a university-based undergraduate teacher education program offered in 2021. Descriptions of discussions that ensued during the project are based on my planning documents as instructor of the course. The course consisted of seventeen pre-service teachers, thirteen of whom provided consent for their course assignments to be shared in published outlets. The description below includes specific examples of journal excerpts from three groups of pre-service teachers. After describing the five design thinking phases, I will then unpack how integrated STEM and entrepreneurial mindsets were fostered throughout the project. I will conclude this section with a discussion of items from a pre- and post-course survey completed by the thirteen consenting participants.

3.2 Design Thinking Phases

Given that the pre-service teachers were adults who would benefit from experiencing the challenge and uncertainty associated with these constructs, it was explained that the project would ask them to engage with content and practices above the elementary level. The learning experience began with a question about a common household product—paper towels. Pre-service teachers were provided the following scenario.

Your consulting business has been hired by a non-profit company, Consumer Reports™, to provide advice to everyday consumers about what paper towel brands represent the best value. You will help Consumer Reports™ consider new ways of testing paper towels that could help lead to insights into user experience and make the most helpful recommendations. Your project will have the following parameters:

- *You will engage in the Design Thinking Process to develop your recommendations*
- *Your project will need to include some form of paper towel testing*
- *You will need to give consideration to the price of paper towels and the concept of value.*

Pre-service teachers then learned more about Consumer Reports™ and their mission to help consumers become informed about a wide range of products. They watched videos demonstrating how Consumer Reports™ employees develop and perform tests on those products to compare them based on performance (e.g., placing a specific amount of food on a dinner plate before running it through different brands of dishwashing machines). Pre-service teachers completed a journal aligned to the design thinking process as they engaged in the activities.

3.2.1 Empathize

In order to engage in more purposeful testing and to provide helpful recommendations, it is important to think about the end-user. For this phase, pre-service teachers interviewed a friend or family member and each other to develop different examples of user experience. The goal was not to collect a large amount of data to systematically look for the most common responses, but rather to look at a range of different experiences and seek out unexpected insights. I have found that it is important to discuss the concept of *value* with the whole class during this first phase, and how that concept may have different meanings for different individuals. For example, while one person may interpret value to be based primarily on the notion of best quality for the cost, others may interpret value to include notions of brand loyalty or environmental consciousness. It is helpful for pre-service teachers to have an open mind about the concept of value before proceeding with the interviews. Table 1 presents the characteristics of interview prompts important for the Empathize phase of design thinking, along with examples of groups' written prompts aligned to those characteristics.

3.2.2 Define

After gaining information from paper towel users, pre-service teachers engaged in a process of defining a problem they wanted to solve. In groups, they looked across

Table 1 Interview prompt characteristics and examples

Prompt characteristics	Example prompts discussed as a class	Fall 2021 pre-service teacher groups' prompts
Elicit specific experiences	You mentioned you use the paper towel to clean dirt off of your counter. Can you show me how?	How often do you use paper towels? Do you prefer using paper towels over other types of cleaning product (reusable cloths, etc.)? *(Group 1 Journal)*
Get at the *Why*	Why do you consider ____ characteristic when purchasing paper towels?	Why do you usually buy that brand? *(Group 2 Journal)*
Elicit feelings and emotions	How does it make you feel when a paper towel does not work in the way you want?	What would you use as a substitute for paper towels? *(Group 2 Journal)*
Engage users in unexpected perspectives	Think about your favorite activity or hobby. How might a paper towel be helpful or play a part in that activity?	What would your ideal paper towel company be like? Your ideal paper towel? *(Group 3 Journal)*

their interview responses and began developing a specific point of view. They typed individual excerpts of interview responses onto sticky notes using the google application, Jamboard™. They grouped their notes together, synthesizing information about their users and the specific needs they have, with the goal of constructing insights about their paper towel experiences. One design thinking strategy I encouraged pre-service teachers to incorporate was to focus on extreme users (e.g., those who use paper towels constantly or rarely). Additionally, pre-service teachers were encouraged to be aware of potential insights regarding users' preferences with particular brands or expectations of paper towel companies. Table 2 provides examples from three groups' journals of how identified needs can lead to insights for different types of users.

There are many helpful insights that arose from the Define phase, which we discussed as a whole class. For example, pre-service teachers developed insights that are common across extreme users (e.g., the notion that absorption and durability are the most important characteristics). Additionally, there were insights that can be viewed as complementary. Group 1 discussed how the constant user likes to use a paper towel more than once within a certain timeframe, and preferred to reuse paper towels more so than cloth rags. While this finding is not a direct insight from Group 2's rare user, if that person was able to use a single paper towel for cleaning more than one surface, this would likely be seen as beneficial. Affordable cost was highly valued by both the extreme and rare user in Table 2. However, we discussed the opportunity for companies to persuade their users that increased total price might be cheaper over time if customers get more money out of each towel used during cleaning due to durability or reusability.

Table 2 *Points of view* for users of paper towels

Users interviewed by pre-service Teacher groups	Needs	Insights
Constant user *(Group 1 Journal)*	• Weekly/daily cleaning • Drying hands • As a replacement for a plate • Does not care about the brand, only wants the cheapest single roll on the shelf	• Most important characteristics is that it is cheap and a single roll • Does not care about effects on environment • Uses it very often to dry/clean hands • Does not like the idea of having to wash a rag after using it once to clean. It's a waste of water
Rare user *(Group 2 Journal)*	• To wipe hands dry • Clean tables • Put snacks on top	• Cost is a factor, only buys when paper towels are on sale • Values durability
User interested in specific companies *(Group 3 Journal)*	• Cleaning and spills • Wiping hands post-washing • Eating	• Absorption and durability are important • Consumer would like information about companies to be more accessible

The Define phase concludes with the learners constructing *How Might We* questions that focus on insights from the *Point of View* activity. This allows the learners to narrow the focus on one or two problems with purpose rather than an open slate of potential problems. Two examples are presented below.

- How might we develop tests comparing the performance of different paper towel brands that are authentic to specific users' needs?
- How might we make a recommendation about the mathematical value of different paper towel brands?

3.2.3 Ideate

After defining a problem, the next phase was focused on brainstorming a wide range of possible solutions based on users' insights from the Define phase. Prior to brainstorming, pre-service teachers were reminded to follow the guidelines of ideation from the perspective of design thinking:

- Quantity over quality—record as many ideas as possible
- Encourage wild ideas
- Build off of each other's ideas.

They brainstormed ideas to test and compare the performance of different brands of paper towels individually, in groups, and then as a whole class. Several of the users expressed interest in durability, and therefore all three groups designed a

Strength Test to identify the weight that a towel from each Brand could withstand before breaking. In addition to this common *Strength Test*, the groups discussed more divergent views of tests that might help them assess a towel's other authentic functions, i.e. cleaning surfaces and absorbing liquids. The following list presents examples of tests considered as a class:

- *Shammy Test*: How quickly does the paper towel dry before it can be used again?
- *Dust Test:* How many counters or shelves can the same paper towel be used to clean before it's saturated?
- *Scrub Test*: How many hard scrubs can one get out of the paper towel on scratchy surfaces before it tears?
- *Spill test*: How many paper towels does it take to wipe up a common spill of liquid?
- *Mildew Test*: How long can a wet paper towel sit around before it smells or develops mildew?

3.2.4 Prototype

The purpose of the Prototype phase was for pre-service teachers to commit to at least two different testing ideas and try them out quickly and safely, so they could make any necessary adjustments or change course without spending a substantial amount of time in a formal Test phase. Groups were encouraged to perform just one trial of each test and then discuss what worked or what might need to be changed. For example, Group 3 prototyped a *Spill Test*. Their initial procedure involved spilling ½ cup of water on a surface and recording the number of towels needed to absorb water from the spill area. According to their report, the test seemed to be helpful but they also found some elements of the procedure that needed clarity. They provided the following notes:

- *Tests give good information*
- *To implement consistently we need to wipe the spill and not remove the dripping towels from the spill area until spill is dry (affects number of towels used)*
- *Use less water; ¼ measuring cup*

(Group 3 Journal).

Figure 2 provides images submitted by Group 3 to show how the test changed to laying paper towels and leaving them in the spill area after the first iteration. They made this change for two reasons: (1) to avoid transferring water away from the spill area inconsistently, and (2) to more authentically engage in a clean-up process.

3.2.5 Test

After the groups' paper towel tests were prototyped and adjusted, they engaged in the final Test Phase. Pre-service teachers were directed to perform their paper towel tests with different brands using clear, consistent procedures, considering what is

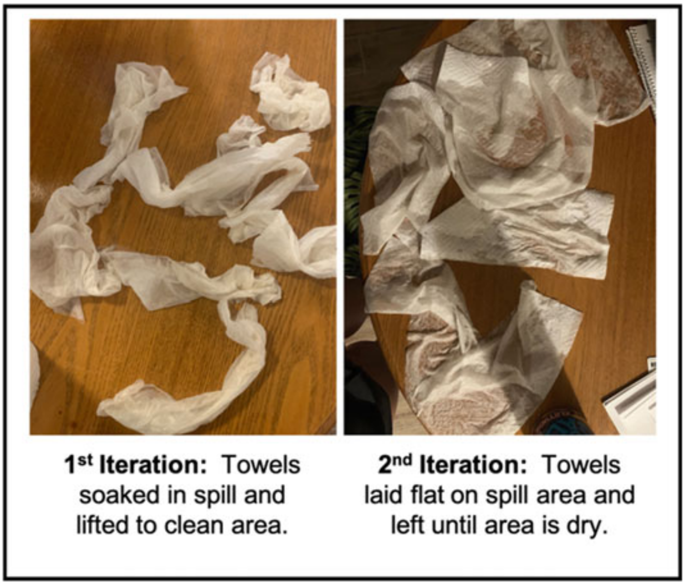


Fig. 2 Group 3's images of the spill test for two iterations of the prototype

being manipulated (independent variable), measured (dependent variable), and what variables are serving as the controls. They were directed to consider the question of mathematical value, recording information related to cost, number of rolls, and number of sheets per roll.

Pre-service teachers analyzed their data from the Test phase and developed recommendations both for their testing procedures but also regarding which paper towel brand is the best value considering performance and cost. This led to an explicit focus on mathematical reasoning. They realized that to make claims of comparison, units needed to be precise, manipulated, and used consistently in the analysis. They were encouraged to frame a mathematical question to answer. For example, Group 3 sought to answer the question, *What is the user's cost per spill of ¼ cup of water?* Table 3 presents the mathematical calculations used by Group 3 to determine the customer's cost per spill of water. This table provides their calculations for one brand of paper towels.

Group 3 completed the same steps of analysis for another brand that performed the *Spill Test*. Table 4 shows a comparison of calculations comparing two different brands.

Group 3 found that the mathematical calculations provide nuanced insights into the performance of the two brands. For example, based only on the cost of one roll and the performance of the brands, one might conclude that Brand B is the best value. One roll of Brand B cost $1.49 with an average performance of 8 sheets per spill, whereas one roll of Brand A cost $1.92 with an average performance of 8.5 sheets per spill. With Brand A being more expensive per roll and requiring half of one sheet more than Brand B to clean up each spill, the conclusion could be in favor

Table 3 Group 3's calculations for one brand of paper towels (Group 3 Journal)

Step	Equation	Calculations for Brand A
1. Establish cost per sheet	[Package cost/(#Rolls × #Sheets per roll)] = **Cost per sheet**	Cost per sheet = [$30.72/(16 × 250)] = **$0.0077 per sheet**
2. Determine number of spills cleaned per roll	Sheets per roll/Average #sheets required to clean spill = **#Spills per roll**	250/8.5 = **29.4 spills per roll**
3. Determine cost per spill	Cost per sheet × Average #sheets required to clean spill = **Cost per spill**	$0.0077 × 8.5 = **$0.0655 per spill**

Table 4 Spill test calculations comparing two brands of paper towels (Group 3 Journal)

Calculations	Brand A 8.5 sheets per spill (Recommended)	Brand B 8 sheets per spill
Cost per roll	$1.92	$1.49
Cost per sheet	$0.0077	$0.0155
Spills cleaned per roll	29.4	12
Cost per spill	$0.0655	$0.124

of Brand B. However, with further numerical analysis, Group 3 found that the cost per sheet was actually lower for Brand A because the roll had so many more sheets than Brand B (250 vs. 96 sheets per roll). This explains why one roll of Brand A can clean up more than twice as many spills than Brand B, with the cost per spill being almost half (6.5 cents vs. 12.4 cents). Therefore, Group 3 determined the cost value to be in favor of Brand A, and recommended it from the perspective of cost analysis.

In addition to analysis of economic value, pre-service teachers researched information on people's practices and preferences with paper towels as well as companies' approaches to ethical issues. They drew on this information to present their final recommendations to the class and the users they interviewed during the Empathize phase. A whole-class discussion ensued, focusing on questions about the mathematics and science they grappled with during the project, as well as the following questions that remained uncertain:

- How might a paper towel be designed differently for particular goals?
- How could a redesign lead to different marketing strategies, appealing to different types of users?
- Is there a way to completely change the paper towel market?

This discussion was rich with endless complexities for a seemingly simple product. For example, a topic explored in depth was the detrimental environmental impacts of paper towels. Pre-service teachers found examples of paper towels made of biodegradable, non-GMO grasses such as bamboo and sugarcane as well as reusable, compostable towels made of cellulose and cotton that are also highly absorbent, thereby also meeting the need of several of the constant users [30]. This presents an opportunity to market the product simultaneously to the environmentally conscious user, the constant user who wants ease of use, and the rare user who can spend less money by purchasing efficient, reusable towels.

Group 1 found that paper towels could present some health hazards for people. They reported the following notes from their research:

- *To create paper towels, they go through a chemical (chlorine) bleaching process*
- *This process may leave harmful, potentially toxic, dioxins in the paper towels*
- *Dioxins have been found to be carcinogenic to humans and animals*

(Group 1 Journal).

Group 1 reported that one of their users might change their daily practices with paper towels based on the test data and research information presented to the user, including information about the potential to be more environmentally conscious by using reusable antimicrobial towels:

Based on the absorption test and durability tests, she [user] might reconsider using a different brand when cleaning because she sees that cheap isn't always the best. For now, she will continue to use paper towels one time because of the germs. She will no longer be using them to dry her face due to the fact that paper towels may contain chemicals that are carcinogenic. She is wary about the antimicrobial towels but may consider them for in the bathroom or if she uses them for one specific purpose in the kitchen. (Group 1 Journal).

Based on a user's interest in the companies that manufacture the paper towels, Group 3 researched the ethical practices of their selected paper towel brands. They reported that one user was "glad to know that [the recommended brand] is managed by a more ethical company [than other brands]" and wished that "information like company ties, values, and Human Rights information policies were more accessible to consumers" (Group 3 Journal).

Ultimately, pre-service teachers reflected on their experience as design thinkers, realizing that they integrated a wide range of knowledge and skills during the project, and arrived at insightful solutions.

3.3 Facilitating Integrated STEM

Below, I discuss how this design thinking project supported the FAIR Features of STEM and empathy while avoiding a premature consideration of constraints.

3.3.1 Design Thinking Supported the FAIR Features and Developing Empathy

The design thinking sequence met the criterion of a Student-Centered Instructional **Framework**; it provided an overarching structure but allowed pre-service teachers to engage in exploratory experiences and make their own decisions about what questions to ask, testing ideas to prototype, information to research, and how to pursue their final recommendations.

The final presentation of the paper towel project served as an Authentic **Assessment** in that learners were required to develop tests authentic to how a real company engages in the same practice.

There were many opportunities to engage the pre-service teachers in Purposeful **Integration**. The anchoring common core mathematics standard asked pre-service teachers to "use units as a way to understand problems and to guide the solution of multi-step problems" [17, para 1]. The mathematical analysis to assess a paper towel brand's value required multi-step thinking, leading to a tabular mathematical model (See Tables 3 and 4) with a precise selection of units. This project had the added benefit of helping pre-service teachers view the mathematics component as creative and necessary to arrive at a final solution. The project also required learners to engage in the scientific practices of planning and carrying out investigations [16], as they had to develop fair tests, and engineering practices of defining problems and solutions. Last, pre-service teachers engaged in internet research and met ISTE standard 3.a. by employing "effective research strategies to locate information and other resources for their intellectual or creative pursuits" [18, para 4].

Linking the paper towel performance to cost provided an opportunity for an explicit **Real-World** Connection, because the pre-service teachers are all consumers who purchase paper towels. This Real-World Connection supported the broader goal of integrating **empathy and affect** into the STEM learning experience. The pre-service teachers become invested in developing a final recommendation that would inform their users from the Empathize phase, who were their own friends and family. The groups' research on the potential hazards of paper towels and companies' ethical practices provided information that was helpful to their users, which supported pre-service teachers with considering the information needs of a wide range of customers.

3.3.2 Design Thinking Supported Divergent Thinking by Avoiding a Premature Focus on Constraints

It is intuitive for pre-service teachers to consider tests focused on durability and absorption based on their own experience of using paper towels. However, the design thinking sequence pushed pre-service teachers to ideate a range of test ideas that initially seemed unusual or impractical due to the focus on users' needs. This led to creative test ideas often excluded from earlier iterations of the unit grounded solely on scientific experimentation, for example the *Shammy Test* and *Mildew Test*, which focused on users' needs related to reusability. Group 3 decided to engage in a *Spill Test* in a way that mirrors how a user might clean up a spill with a desire for authentic results. Constraints were eventually examined during the Prototype phase, but by avoiding a discussion of constraints early in the process, pre-service teachers were free to ideate as many test ideas as they could. This ideation step helped facilitate my broader goal of supporting divergent and creative thinking during integrated STEM learning experiences.

3.4 Facilitating Entrepreneurial Mindsets Through Design Thinking

The design thinking sequence supported the entrepreneurial mindsets of opportunity recognition and risk-taking, as discussed in turn.

3.4.1 Problem-Framing Supported Opportunity Recognition

Design thinking engages learners in perspective-taking and problem-framing [9]. The Define phase of the d.school's design thinking process is a critical component that requires more time than what learners might originally anticipate. In the paper towel project, pre-service teachers invest time in thinking about the problem flexibly. They asked questions like, "Does a typical strength test of placing pennies on a towel until it breaks solve anyone's problem?" Without dedicated time to think about problems in relation to insights from user experience, a proposed solution may be innovative in design but not of much use to end-users. The problem-framing component inherently imbedded into design thinking processes allows for learners to brainstorm and discuss new opportunities. This occurred during the paper towel project during the Define and Ideate phases when pre-service teachers looked for opportunities to redesign a typical paper towel test to be more authentic to their users' needs, and after the Test phase, where the conversation naturally veered toward ongoing opportunities to re-segment paper towel products for users who care about health, environmental and ethical issues.

3.4.2 Prototyping Supported Risk Taking

Design thinking has great potential to help learners become more comfortable with taking risks with its focus on recognizing new and potentially surprising opportunities from the Empathize and Define phases. Risk taking is particularly supported by the Prototype phase. Engaging in iterative prototyping can increase learners' creative confidence in trying new ideas [31] with less pressure for any one idea to immediately succeed. This failing forward perspective makes it less likely for a learner to invest too much time and resources in a solution idea that does not work, a natural challenge when working with ill-structured problems. A typical scientific experiment would require a methodical and careful set of procedures to ensure fair testing (considering independent and dependent variables) and safety. This type of testing is employed in the final Test phase. However, in the design thinking process, pre-service teachers were first encouraged to do a shorter, simplified version of their ideas (as prototypes). The pre-service teachers developed an idea with paper towels in hand, and then, had dedicated time to make any adjustments without feeling rushed. During our class discussions, several pre-service teachers noted that the Prototype phase was helpful with maintaining a low-stakes atmosphere while also allowing for improved procedures during the final Test Phase.

3.5 Pre-service Teachers' Self-reported Course Outcomes

Design thinking projects that foster integrated STEM and entrepreneurial mindsets may need to be integrated into courses or timeframes that are traditionally dedicated for individual STEM subjects within elementary, secondary, middle school, and postsecondary learning contexts. The paper towel project was an extensive unit lasting multiple weeks within a one-semester mathematics methods course for elementary pre-service teachers. The paper towel project was designed to be in support of broader course goals; specifically, developing pre-service teachers' confidence as learners and teachers of elementary mathematics. The project provided a context for pre-service teachers to engage in a student-centered, mathematics-centric STEM unit as learners while also observing and discussing how I designed and facilitated the experience as their teacher. Thirteen pre-service teachers from the course responded to survey items aligned to the desired course outcomes pre- and post-course. The results are presented in Table 5.

Across the three survey items, the majority of pre-service teachers reported a positive change on each of the three items (e.g. Disagree to Agree). All pre-service teachers who recorded no change for any of the items provided the same responses of neutral, agree, or strongly agree on both the pre- and post-course survey. Additionally, there were no pre-service teachers who reported a negative change from the pre- to post-survey for any of the items (e.g. Agree to Disagree). While I cannot make claims about how the design thinking project is specifically associated with particular changes on the survey items (in relation to other course components), it is encouraging to note that the course embedded a significant, time-consuming design thinking project and also yielded positive outcomes related to preparing pre-service teachers to be elementary mathematics educators.

Table 5 Pre-service teachers' change in responses to the mathematics course Likert-type survey items (5-point scale including strongly disagree, disagree, neutral, agree, and strongly agree)

Survey items	Same response of neutral, agree, or strongly agree from pre to post	Positive change in response from pre to post (e.g. Disagree to agree)
I feel confident as a learner of mathematics	4	9
I feel confident as a teacher of mathematics	2	11
I know how to plan a student-centered mathematics lesson	4	9

4 Challenges and Opportunities for Design Thinking

While design thinking offers opportunities to foster entrepreneurial mindsets during integrated STEM learning experiences, it is pertinent to discuss existing challenges for future implementation across elementary, middle school, secondary, and post-secondary learning contexts. For each challenge listed below, I offer opportunities to move forward.

4.1 Avoiding Rote Design Processes

As discussed previously, both designers and entrepreneurs engage in creative and divergent thinking, which is not always suited to a step-by-step process that must be followed with fidelity. It is interesting to note that the d.school is in the process of moving away from a heavy reliance on the five-phase sequence described in this chapter and moving toward a greater focus on core design abilities. These design abilities, e.g., moving between concrete and abstract, experimenting rapidly, and building and crafting intentionally [32], can be employed flexibly and support designers who wish to tackle ill-structured problems with a wide range of purposes (be it solving problems related to customers' needs and/or global issues related to sustainability and the environment). To this aim, there is an opportunity for design thinking educators to share examples with the wider STEM education community of how design thinking processes naturally include flexibility as they unfold. For example, prototyping and testing may lead learners back to the Ideate phase to brainstorm new solutions or even the Define Phase if they realize the problem might need to be reconsidered. A useful example of flexibility can be found in a study by McCurdy et al. [33]. They studied nineteen 7th grade students as they developed their own problem-based design thinking tasks and found that students engaged in more than one type of solution pathway, concluding: "there were no apparent dead ends or complete roadblocks as long as students were considering the overarching authentic problem" (p. 45). Educators may feel more comfortable with flexible pathways if they engage in design thinking experiences as learners, through formal professional development programs or from other educators who have implemented design thinking in their classrooms. The more educators see articulations of this phenomenon in practice, the more opportunities exist for them to develop a value for flexible paths and a willingness to support adaptive implementation with their learners.

4.2 Time

Similar to any student-centered learning experience, time is needed to allow for an entire design thinking process to be completed. In my own experience of working with teachers in Hawai'i professional development workshops, teachers often find time to integrate the first four phases of the d.school process by concluding with a low-resolution prototype and some feedback but without an authentic cycle of testing and redesign due to time constraints. A challenge of student-centered projects is teachers' concerns about whether they have time to devote to a lengthy learning experience within the curriculum, both from the perspective of implementation and assessment. There are opportunities for researchers to explore the factors that increase teachers' willingness to engage students in a full design thinking process within the realities of school structures. For example, educators might be best served to initially find low-risk spaces to try out a design thinking experience. This might include an end-of-the year project, during science fairs, as part of extracurricular activities like school clubs, or within other timeframes that allow for flexible learning (study hall, genius hour, or library time). The science education community has learned that it is important for teachers' beginning experiences with inquiry-based teaching to be positive and low-risk [34, 35]. I suspect that engaging in a positive, full experience with implementing design thinking in the classroom has potential to increase teachers' confidence and willingness to pursue additional learning experiences driven by design thinking processes. This proposition, however, needs further investigation.

4.3 STEM and Entrepreneurial Mindset Outcomes

Most formal learning contexts, particularly elementary, middle, and secondary schools, are responsible for aligning lessons, units and projects to state or national learning standards divided by specific subject areas. Regardless of the pedagogical approach, integrated STEM educators have called for a focus on aligning STEM learning outcomes to both conceptual and skill-based learning standards across the STEM disciplines [10]. There are a few helpful examples in the STEM educational literature that highlight the implementation of design thinking with explicit alignment to STEM learning outcomes. Cook and Bush describe how a teacher integrated design thinking into an existing unit that also focused on students' learning about structure and function [20]. Simeon et al. found that secondary-level students in Nigeria developed conceptual understandings of Newtonian physics concepts after completing STEM learning modules that incorporated elements of design thinking [36]. I offered another example of university students learning mathematics content and developing science and engineering practices within this chapter. Yet, the research and practical examples for STEM learning within design thinking experiences are limited. Across both practitioner and research journals, there are endless opportunities to articulate more examples of supporting STEM learning with design thinking as the driver and to investigate the factors that shape successful learning experience designs. Moreover, there are opportunities to further establish design thinking practices and entrepreneurial mindsets as important STEM outcomes in and of themselves. Just as Marks and Chase found that elementary students gained knowledge of iterative prototyping (as an intended learning outcome) after a design thinking intervention, it will be important to examine the potential benefits of developing outcomes associated with creative confidence, problem-framing and opportunity recognition [37].

4.4 Scaling Across Systems

Most studies and illustrations of design thinking in the STEM, engineering, and design literature highlight examples of individual educators or small collaborative teams engaged in the process of creating new learning experiences that utilize design thinking. Similarly, my experiences as a STEM educator in Hawai‘i have revealed that design thinking is being both explored and employed in isolated pockets across the state. Some schools have fully embraced the process, such as Waipahu High School, which has dedicated space for design thinking initiatives within their career academies [38]. Some schools have teachers who have designed and implemented design thinking learning experiences within their own courses, and I suspect there are other schools with less access to design thinking professional development. A key question that arose during my work on the DOE Design Thinking Collaborative was, how can it scale across a school or complex area/district? Table 6 lists common perceived barriers I have encountered for any educational institution or system about scaling design thinking efforts, as well as strategies that have held the most promise with gaining traction. The strategies focus on negotiating the realities of school systems, encouraging a *start anywhere you can* approach, and relying on positive experiences and invitations rather than top-down policies and mandates.

Table 6 Perceived barriers and strategies to support forward movement of design thinking initiatives in educational systems

Perceived barriers	Potential strategies to move forward in educational systems
Lack of leadership support	Align design thinking proposals to existing initiatives, priorities, or already identified challenges related to student learning
Lack of collaboration	Consider starting collaborative efforts to develop design thinking projects with a wide range of stakeholders e.g., students, teachers (your school or another school), parents, local organizations and/or community members
Incompatibility of educators’ mindsets with design thinking	Invite teachers to try a design thinking mini-activity as learners or with their students in a low-risk environment to build confidence and reflect on the experience
The ‘One more thing on my plate’ perspective	Provide examples of how design thinking can be incorporated into multiple grade levels and subject areas

5 Conclusion

In this chapter, I have attempted to describe how design thinking can drive a STEM learning experience, and the benefits this construct offers to the goal of fostering entrepreneurial mindsets through STEM education. Design thinking engages learners in the human aspects of design and adds value to STEM learning experiences by complementing traditional views of engineering design and inherently supporting entrepreneurial mindsets such as opportunity recognition and risk taking through problem-framing and rapid prototyping. It is important to note that I do not argue for design thinking to be the sole driving or integrating process of STEM learning experiences. Far from it, there are multiple research-supported instructional approaches that educators can use depending on their teaching goals and the nature of the STEM task. However, design thinking has untapped potential in a wide range of learning contexts. The literature on design thinking specific to STEM education and entrepreneurial mindsets is developing but still in its infancy. More research in this area has great potential to shed light on helpful strategies to confront challenges I proposed, while also revealing new opportunities to enhance STEM and entrepreneurial mindset outcomes not yet conceived. It is my hope that this chapter serves as one stepping stone toward a fuller understanding of the potential pedagogical value and instructional applications of design thinking to STEM learning experiences that foster entrepreneurial mindsets.

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Aaron Sickel completed both his undergraduate degree (2004) and master's degree (2008) in science education from Northwest Missouri State University in the U.S. He earned his Ph.D. in curriculum and instruction from the University of Missouri in 2012. Aaron has worked as a university teacher educator in Ohio (U.S.), Sydney (Australia), and Hawai'i (U.S.). He also served as the statewide STEM educational specialist for the Hawai'i State Department of Education. Research interests include science, mathematics, and integrated STEM education, beginning teacher development, teacher education curricula, and constructivist-oriented instructional models.