Framing Failure: Leveraging Uncertainty to Launch Creativity in STEM Education

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***Abstract*—The sentiment that creativity is the most important skill needed to solve the problems that we face is repeated by different business and industry leaders around the world). Since January 2020, the call for creativity has been amplified in response to the problems and obstacles caused by COVID19. Yet, creativity remains the most neglected 21st century skill addressed in STEM education. This paper develops the strong conceptual connections between creativity and failure within STEM (science, technology, engineering and mathematics) to propose the Intersection of Failure and Creativity Framework (IFCF). The IFCF represents an improved way to engage students in integrated STEM activities that call for the development of solutions to real world problems by engaging in engineering design. The IFCF will better prepare teachers and students to address the changes and uncertainty of a rapidly-evolving world and address the calls of businesses for a workforce capable of innovation.**

***Index Terms*—STEM education, 21st century learning skills, creativity, failure, Innovation, interdisciplinary and integrated approaches**

I. Introduction

There is a creativity crisis in the United States and around the world [1]-[3]. Businesses report that the younger workforce have appropriate mathematics and science skills, however they lack creativity, which is necessary for innovation in many fields, including STEM (Science, Technology, Engineering, Mathematics). Nussbaum and colleagues argue that the "new core competence is creativity" which businesses believe will make them viable in the global economy (p. 62) [4]. Creativity is necessary to solve problems that we may face as a global society. These problems range from product and process development to global grand challenges, such as climate change, cyber security, and most recently Covid-19 [5]-[7].

The STEM fields are constantly evolving to address the grand challenges of the 21st century in areas such as energy, health, education, the environment, national security, and global development [8], [9]. In the area of health, the need for the rapid development of products and processes to address Covid-19 illustrates the creativity needed to solve complex and pressing challenges. A range of different Covid-19 indicator tests were rapidly developed and designed to meet the global need to stop the spread of the virus and help countries to move out of lockdown and keep their economies moving. The push to rapidly generate safe vaccines, is illustrative of the need for new approaches and creativity; some of the Covid-19 vaccines are the first of their kind, using mRNA instead of using a weakened version of the virus to trigger an immune response. Without creativity leading to innovation surrounding the grand challenge of Covid-19, STEM professionals may not have met the needs of our society so quickly. Educators need to focus on creativity in K-12 STEM to prepare students for the ever changing needs of a global society and economy [6], [10], [11].

More broadly, STEM education argues for the development of 21st century skills to prepare our students for the unique needs of a global society and economy [6], [10], [11]. 21st Century Skills include critical thinking, communication, collaboration, and creativity, and while these skills are applicable across all disciplines [12], [13], they are central to current reforms in science education calling for the use of integrated STEM approaches to the teaching and learning of science [14], [15]. The argument being that students should not be positioned simply as consumers of information, but knowledge creators through application of 21st Century Skills. Much research has explored critical thinking, collaboration, and communication within STEM education, however creativity remains under-researched [15], [16]. Thus, this paper explores definitions of creativity and the role of creativity in K-12 integrated STEM education. We present a review of the literature on creativity and argue for explicit attention to failure and the development of creative outcomes for students engaged in the engineering design process, which is central to K-12 integrated STEM experiences. This review leads to the presentation of a framework that explains the intersection between creativity and failure in integrated STEM experiences to guide implementation and research related to the development of the future STEM workforce.

Our overarching purpose is to answer the question: How might we frame failure as the launch for creativity within integrated STEM? First, we briefly define integrated STEM as a pedagogical approach to K-12 science teaching to provide context for the use of our proposed framework. Next, to help guide the exploration of creativity in integrated STEM spaces, we first discuss definitions of creativity and examine how creativity is

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framed in engineering and engineering practices utilized in integrated STEM settings. We specifically explore creativity through the lens of grand challenges such as Covid-19. Next, we explore the role of failure in engineering design and how it promotes creativity. The paper culminates by illustrating how the proposed framework can improve K-12 integrated STEM learning by walking readers through a modified STEM curriculum that emphasizes creativity.

II. Background Literature

A. *Integrated STEM*

Within the United States, K-12 STEM education has shifted to a focus on interdisciplinary or integrated instruction rather than disciplinary approaches to teaching of science, technology, engineering, and mathematics [17], [18]. Central to integrated STEM is the use of real-world contexts to both contextualize learning and motivate student engagement [14], [19], [20]. Students are expected to engage in STEM practices and apply 21st century skills [13], [21] to develop solutions to these real world problems. For example, Kelley and Knowles define integrated STEM 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) [19]. Given the prominence of engineering within the NGSS, many researchers specifically incorporate engineering contexts and represent real world problems for integrated STEM instruction as engineering design problems as the context for learning [14], [22]-[24]. Thus, we focus on engineering as the context within integrated STEM instruction for students to engage in creativity practices.

B. *Engineering Design*

Design is the central activity of engineering [25] and includes the processes of defining problems, generating and evaluating solutions, testing and optimizing solutions, and communicating solutions [26]. K-12 students are expected to engage in the engineering design process which is defined in the *Frameworks for K-12 Science Education* [17] as:

- A systematic process for solving engineering problems, is based on scientific knowledge and models of the material world. Each proposed solution results from a process of balancing competing criteria of desired functions, technological feasibility, cost, safety, esthetics, and compliance with legal requirements. There is usually no single best solution but rather a range of solutions. Which one is the optimal choice depends on the criteria used for making evaluations (p.52).

The *Framework for Quality K-12 Engineering Education* [21] provides a more specific set of key indicators for quality K-12 engineering. In addition to engaging in the engineering design process, students should develop an understanding of engineering (e.g., careers, specific tools), and engage in the professional skills of engineering (e.g., ethics, social impacts of engineering, teamwork, and communication). Most important to the development of a creativity framework for integrated STEM is that students engage in engineering thinking [22], which includes reflective decision-making and argumentation [27], [28].

C. *Defining Creativity*

There is no single, concrete definition of creativity in STEM or STEM education. Therefore, to define creativity in STEM we draw on the multitude of creativity definitions outside and within the limited research surrounding creativity in engineering.

There is a long standing history that surrounds conceptions of creativity. These conceptions have strong cultural connotations to art and artistic talents [29], [30], as research has historically focused on artistic creativity as an intuitive and rare trait. This is often called big- C creativity, known as creative genius, “that transforms the boundaries of an entire discipline or domain” (p.2) [31]. Art bias is a common conception of creativity, however this is a very limited view of creativity [30]-[33]. Creativity is often associated with what Runco states is "the misunderstanding of creativity that equates it with artistic talent, [with the result that] only individuals with artistic talent are labeled creative" (p. 401) [30].

Many definitions of creativity exist in the literature, with most including originality or novelty of a product and its value to society through effectiveness or usefulness [1], [34], [35]. For example, Zabelina defines creativity as “the ability to produce work that is both novel and meaningful or useful. As opposed to products that are trivial or bizarre” (p. 161) [36]. Smith and Henriksen provide a more explicit definition of creativity, explaining that creativity is “developing ideas and/or objects that are new novel (original) or interesting, effective (or useful), and have a certain aesthetic sensibility as a whole” (p. 7) [37]. Punie and colleagues more succinctly describes creativity as "a product or process that shows a balance of originality and value” (p. iii) [35]. However, Runco and Jaeger argue that it is specifically the process leading to product development that is creative [38], thus they purposefully omit the product as a main outcome of creativity to avoid “the assumption that all creativity (or all innovation, for that matter) is manifested in a tangible product.” (p. 400) [30].

D. *Creativity in Engineering*

Within engineering, the major practice is the development of design solutions through engagement in an iterative engineering design process [17]. Engineering design is an iterative process of “testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution” (p. 210) [18]. Common elements of an iterative engineering design process are problem identification and scoping, ideation, design, testing, and redesign [25]. In engineering problems are often “ill defined” or “ill structured” (p. 2) [39]. Therefore, engineers and engineering students must examine the problem from various perspectives to understand the criteria and constraints that would make a solution successful. This is known as problem exposure and scoping. Problem scoping is an essential aspect of the EDP and allows engineers and engineering students to determine “the nature and boundaries of a problem” (p. 43) [40]. It is within the problem scoping and forward gazing toward a solution where creativity training may assist engineers and students to more creative solutions.

Specific to engineering, Charyton and Merrill specifically define functional creativity as “products designed by engineers typically serve a functional and useful purpose” (p. 146) [41]. The term product is used broadly here, engineering products include not only physical products, but also systems and processes [42] making Charyton and Merril’s the most relevant for integrated STEM [41]. It is also the case that in K-12 STEM, the focus of student learning is on engaging students in science and engineering practices, rather than the end product of the design process [18].

Thus, creativity within K-12 integrated STEM is defined here as developing ideas, processes, and/or products that are novel (original) and functional (effective or useful). While aesthetic sensibility or elegance in an idea, process, or product can be relevant and important, it is not always a criterion [1], [34], [35], [37], [38], [41].

E. The Role of Failure

A central feature of the engineering design process is the role of failure. As engineers engage in the iterative design process, it is inevitable that early prototypes of a product will not meet the requirements of novelty and functionality. Indeed, failure is expected, and it is through creativity that these failures lead to stronger designs and innovation [43]. However, within the current research, failure and creativity have not been formally linked.

The 2009 NRC report on engineering and engineering habits of mind specifically includes the value that engineers place in learning from failure. The report concludes that “investigating failure” as part of their “analysis” definition of the engineering habits of mind is lacking in most engineering curriculums (p. 83) [44]. This lack of attention to failure in curriculum is problematic, as failure creates the opportunity to engage in reflective decision-making and argumentation [27], [28]. Failure needs to be central in student learning in K-12 engineering and integrated STEM lessons. For example, Moore and colleagues in their *Framework for Quality K-12 Engineering Education* argue, “Engineering requires students to be independent, reflective, and metacognitive thinkers who understand that prior experience and learning from failure can ultimately lead to better solutions” (p. 5) [22].

Koschmann *et al*. (1998) describe the role of failure as “a means of revealing the nature of the world around us” (p. 25) and “a disruption in the normal functioning of things forcing the individual to adopt a more reflective or deliberative stance toward ongoing activity” (p. 26). With this understanding, engineers and students are positioned as reflective participants in the occurrence of failure. Dewey, as cited by Koschmann and colleagues [45] describes the tendency of scientists, artists and learners to place themselves in situations where failures occur so they can acquire more knowledge and understanding by solving the breakdown. In this perspective, failure is a process to be analyzed starting with the failure itself. The failure has already happened, thus, the events leading up to the failure are the key to figuring out the disruption. For example, in the Chernobyl disaster of 1986, following the immediate action to deal with safety and rescue, the next step was to figure out *why* the failure occurred, in order to prevent it from happening again. Indeed, scientists and engineers continue to study the failure at Chernobyl. As Beresford and colleagues explain, by continuing to study the failure at the Chernobyl nuclear plant, scientists and engineers are learning how to prevent radiological accidents [46].

We define this reflection process as **backward gazing**. Backward gazing is the most prominent form of reflection surrounding failure in our culture and in engineering. We often become fixated in backward gazing reflection and analysis of failure with the hope to prevent such a failure from occurring again. However, it is also critical to consider the knowledge and understanding developed as a result of dealing with the aftermath of a failure event; it is this new understanding that provides the momentum and creativity to propose new solutions (**forward gazing**). Within redesign, engineers engage in diagnostic troubleshooting [47], focusing their attention on “problematic areas of a design solution during performance tests” (p. 360) [28] to re-examine the problem from their understanding of a failure event and creatively propose new solutions pathways.

Within the example of the Covid-19 pandemic, the immediate scientific focus was on stopping the ongoing contagion and the development of therapeutics and vaccines. This **forward gazing** process is described in the *Independent Panel for Pandemic Preparedness and Response Report* [48]:

- When the scale of the pandemic and its impact became evident, as well as the failures in the chain of preparedness and response, communities and leaders around the world rallied in response, rethinking systems, providing mutual support and solidarity, and sparing no effort in devising the care, treatments, and prevention needed to confront severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (p. 5).

The **backward gazing** process of understanding the origins of the Covid-19 virus is only now drawing more attention. The *Independent Panel for Pandemic Preparedness and Response Report* [48] also addressed the question of “why” and the failures that occurred at the beginning of the Covid-19 pandemic. The report states that not only was "the world not prepared for the coronavirus disease (Covid-19) pandemic" (p. 5) but there were "lost opportunities to apply basic public health measures at the earliest opportunity" and that known "public health containment measures should have been implemented immediately in any country with a likely case" (p. 17). The debate about the source of Covid-19 and our lack of preparedness are backward gazing questions being explored by scientists.

Petroski discusses the importance of failure within the design process as "it is the anticipation and observation of failure, every new failure—no matter how seemingly benign—presents a further means towards a fuller understanding of how to achieve a fuller success" (p. 45) [49]. In other words, the iterative nature of the engineering design process is intrinsically linked to reflection on failure, which both draws on the creative potential of engineers and results in innovation through creativity. These interconnections between creativity and failure are the center of our proposed framework.

III. The Intersection of Failure and Creativity Framework

In the Intersection of Failure and Creativity Framework (IFCF) the recursive process of reflection, **backward** and **forward gazing**, revolves around failure and success**.** This process occurs when failure or minimal success reveals a new problem within the original problem or a new problem within the current solution (see Fig. 1).

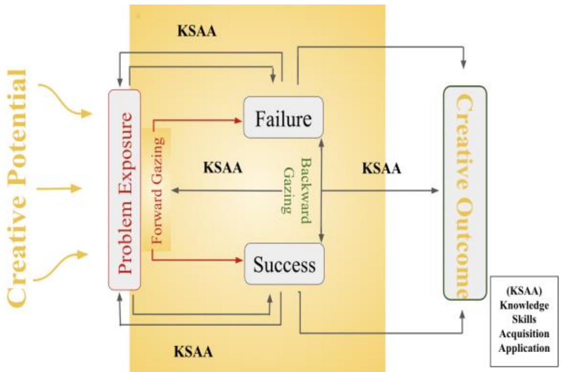

Figure 1. Intersection of failure and creativity framework

A. *Forward Gazing and Problem Exposure*

The process of forward gazing is looking and moving towards possible failure by embracing the risk-taking associated with the process. Here, the individual must embrace that failure or various degrees of success are a possibility and allow their creative potential to drive the process forward. This process of risk-taking towards success and/or failure begins with **problem exposure**.

Engineering design begins with the identification of an engineering problem and engagement in the practice of problem scoping, the process of developing and understanding of the relevant criteria and constraints [50]. Basdur identifies problem scoping and problem finding as elemental within the process of creativity. It is not sufficient to merely "solve" a problem creatively, creativity must also be applied to the implementation of a solution and to the discovery of the problem in the first place" (p. 239) [51]. The potential for creativity should be activated at the outset of problem exposure, as seen in the IFCF. In addition to the application of creativity approaching a new problem, prior expertise and knowledge are activated during problem exposure.

B. *Knowledge & Skills -Acquisition and Application*

Amabile explains expertise in creativity as the "intellectual space used to explore and solve problems" (p. 79) [52]. In Amabile's definition, expertise is built within experiences and opportunities. Inherent to engineering is the application of STEM content knowledge, both to the design of potential solutions (forward gazing) and the analysis of the success/failure of these design prototypes (backward gazing). Relevant in forward gazing, is creative application of STEM content knowledge in putting forth possible design solutions. Whereas within backward gazing, STEM content knowledge is used in evaluating the causes for design failure and suggesting potential modifications. As experts, engineers have the capability to map prior knowledge and experiences from previous engineering challenges on to novel problems. However, a design failure can also create the need to develop and learn new STEM content to innovate and develop creative solutions. For example, the knowledge of mRNA used in some Covid-9 vaccines is an application of novel content to a problem, instead of applying the existing approach of using a live, albeit weakened, virus. The widely circulated mRNA Covid-19 vaccines, such as Pfizer BioNTech and Moderna vaccines were released to the public less than a year after Covid-19 became a pandemic. Yet, it took 30 years of forward gazing and backward gazing to solve the problem of making a vaccine that was not made from weakened virus cells and could be mass produced in a short amount of time. Over this 30-year time period the scientists and engineers had gained expertise, and thus knowledge and skills, with mRNA vaccines and were able to put their knowledge acquisition into application to help solve a novel problem, the Covid-19 virus.

C. *Creative Potential*

Creative potential is illustrated at the "start" of the IFCF to express that all individuals have the ability to be creative. A problematic occurrence surrounding creativity is a long-standing belief that creativity is an intuitive trait. Researchers use words defining creativity in STEM as "intuitive" and "authentic and naturally occurring" [53], [54]. This creates a common conception of creativity as an inherent trait, which is a false claim. Instead, the research surrounding creativity informs us that all people have what is called creative potential and that creativity is trainable [35], [38], [55]-[58]. Creativity is a skill with the ability to be developed and utilized.

IV. Application of the Intersection of Failure and Creativity Framework in the Classroom

In the previous section, we described the IFCF in the context of the work of professional engineers, highlighting the central role of creativity and failure in the iterative design process. In this section, we turn our attention to K-12 integrated STEM education. Integrated STEM education begins with a real-world problem that is intended to both contextualize and motivate student learning [22], [59], [60]. Often this real-world problem is represented as an engineering design problem. There are multiple models of the EDP that are utilized in K-12 classrooms, each illustrating that the EDP is an iterative process. Common across representations of the EDP are distinct phases, such as define, plan, build, test, redesign, and communicate [22], [61] (see Fig. 2). In the first phase, students are introduced to the design challenge, usually through a client letter which establishes the criteria and constraints of the problem space. Second, in the *Learn* phase, students engage in learning the necessary background STEM content, Next students enter the iterative design stage, first using their prior knowledge and experiences to propose a prototype design in the *Plan* phase, followed by the building and testing of the prototype in *Build/Try*. Finally, the students enter the *Decide* phase, where the prototype is formally evaluated against the client's needs and the associated criteria and constraints.

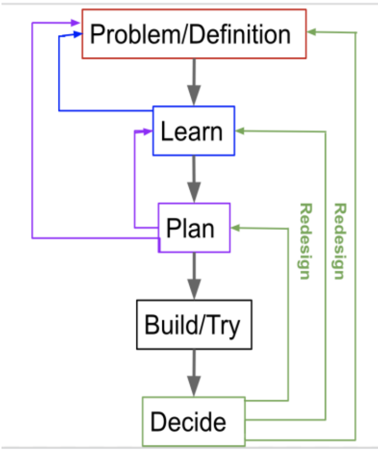

Figure 2. Generalized Engineering Design Process (EDP)

We illustrate the implementation of a typical K-12 STEM integrated unit using the Virginia Middle School Engineering Education Initiative's (VMSEEI) curriculum *Save the Penguins Engineering Teaching Kit*, which invites middle school students to develop possible solutions to protect penguins from impacts of climate change by engaging in the Engineering Design Process (EDP). While the engineering context is directly connected to the real-world problems of global warming and impacts that endangered penguin populations, the engineering design challenge is narrower in scope. Specifically, within the Save the Penguins curriculum students are focused on developing a habitat to protect equatorial penguins from increasing temperatures during their nesting season. Students are asked to develop a prototype to solve the problem of keeping a penguin (ice cube) from melting under a heat lamp (changing environment). Table I provides an overview of the lessons within the Save the Penguins curriculum.

The EDP starts with understanding the nature of the design challenge, and the criteria and constraints inherent to the problem. Teachers, unlike engineers, are engaging students in engineering practices with specific learning goals in mind. These goals include application of STEM practices, as well as specific content learning goals. Thus, teachers often narrow the scope of the design problem to ensure the learning and application of specific STEM content. The design problem in *Save The Penguins* (see Table I: Problem Definition) is narrow and provides explicit vocabulary of what is needed in a successful design solution. For example, the word *habitat* alludes to some sort of shelter, while *increasing temperature* explains the nature of the test that the habitat and penguin will undergo. The narrowing of the problem allows the teacher to focus on the specific science content objectives that students are expected to apply in developing a design solution, allowing teachers to assess students' understanding through their use of specific concepts (e.g., conduction, convection, and radiation) in explaining their design decisions. In addition, students are presented with a specific set of materials, which further narrows the problem-solving space. These curricular decisions severely limit the application of problem scoping and creativity in possible solutions.

TABLE I. STEPS OF THE ENGINEERING DESIGN PROCESS WITH SAVE THE PENGUINS

Problem Definition	Students are tasked to design a habitat to minimize melting of an ice-cube penguin placed in a solar cooker* for 20-minutes.
Learn	Students engage in a series of science demonstrations designed to teach the concepts of insulation, conduction, convection, and radiation. Students test the heat transfer properties of available **materials for building their penguin habitats.
Plan	Students brainstorm possible design solutions and develop a consensus prototype model.
Build/Try	Students build and test their protype habitat, collecting pre- and post- weights of the ice-cube penguin.
Decide	Students analyze class data from their tests and determine ways in which to improve their designs. If time allows, students rebuild and test their modified designs.

* Plastic storage container, painted black on the bottom with the sides lined with aluminum foil, with three high-wattage lights directed at the inside of the container.

**Aluminum foil, mylar, cotton balls, wooden craft sticks, bubble wrap, and different colored felt, cardstock, and foam.

As students move from *Learn* into *Plan* (see Fig. 2), some teachers ask student groups to come up with three possible solutions and then pick one for the *Build/Try* phase. The arrows leading from *Learn* and *Plan* back into *Problem Definition* represent how students are expected to think about possible solutions and come to a consensus single design to prototype. Specifically, students are expected to check that their designs adhere to the problem criteria and constraints and that they can explain their decisions using the concepts from the *Learn* phase. These arrows represent the formal process of Evidence Based Reasoning (EBR) [62], [63]. Specific to engineering, EBR addresses the call within the NGSS for students to use evidence and scientific and mathematical knowledge to develop explanations in science and justify design decisions in engineering, the STEM practice of *engaging in argument from evidence* [17], [18]. During the *Plan* phase, students are asked to justify their thinking about their initial design decisions using the STEM content learned during the *Learn* phase [62], [63]. While this process is parallel to forward gazing (see Fig. 1), there is no explicit attention paid to activating students' creative potential, indeed the problem has been narrowed down to the point where there is little room for creativity.

For example, Park and colleagues' investigation of a classroom implementation of the Save the Penguins curriculum reported that students "continuously used rescue blankets or aluminum foils in their prototypes" (p.8) [64]. They attribute this to the *Learn* phase of the EDP and how the concept of radiation was modelled during the science demonstrations by using a Mylar rescue blanket to block heat from a heat lamp. Although this shows application of science content (radiation) to a successful design, it limits creativity and possible innovation. In other words, the positioning of the *Learn* phase and the specific nature of the activities within *Learn*, too heavily influenced students' design thinking. The explicit focus of K-12 STEM curriculum developers is on content learning goals, with 21st Century Skills, such as creativity, at best as implicit goals. This is problematic given the stated goals of preparing a STEM workforce prepared to innovate.

Inevitably, the first prototypes of a penguin habitat results in a failure, or minimal success event. Thus, during the *Decide* phase, students are expected to use both evidence (from iterative testing) and reasoning (using the target scientific and mathematical content) to improve their prototype [65]. Teachers typically guide students in this analysis which most often leads to discussion and reinforcement of the target science content from the *Learn* phase. This is represented in Fig. 1 as arrows from *Decide* leading back to *Learn*. However, students are not being encouraged to learn new content to support new, creative approaches to design solutions, rather this step is reinforcing the learning of the science content. The arrow leading back from *Decide* to *Plan* represents the important process of redesign, a critical component within the iterative EDP [22], [42], [44], [59]. Unfortunately, "skipping the redesign part of the engineering challenge is one common strategy used by teachers to decrease the amount of time spent on engineering design challenges" (p. 148) [59]. However, redesign is crucial in normalizing failure and helping students move forward for more creative and innovative solutions. Park and colleagues indicated that students' prototypes had minimal change in their final design [64]. The changes that did occur included previous science content applied in a similar but more effective manner, for example adding an extra layer of insulation to their prototype. The ultimate goal of the Save the Penguins curriculum is learning science content related to heat transfer through engagement with an EDP. This goal can be accomplished by following the processes illustrated in either Fig. 1 or Fig. 2, however we argue that the IFCF (Fig. 1) provides an additional focus on the knowledge and skills necessary for innovation.

V. Using the IFCF to Improve K-12 Integrated STEM Teaching

The IFCF (Fig. 1) represents the same generalized EDP as shown in Fig. 2, however it prioritizes the roles of creativity and failure. As such, the IFCF has critical implications for the teaching of K-12 integrated STEM. In the following section we first describe strategies for activating creative potential and then show how these strategies and the IFCF approach can be used to modify and improve the Save the Penguins curriculum.

A. *Activating Creative Potential*

Creative potential in the individual can be explored through creativity training. For example, the ability to produce multiple solutions (divergent thinking) in the face of failure is the precedent to creative outcomes. Creative training is not providing anything that was not already existing within the individual; rather, it allows the utilization and reinforcement of what the individual already possesses. Pfeiffer and colleagues argue that students' creative potential and capability for creativity is "diminished if not nurtured and practiced" (p. 2) [66]. To nurture and build students' creative potential, we propose the introduction of creativity training into K-12 integrated STEM lessons.

B. *Problem Exposure*

Using the IFCF (Fig. 1), students enter the design process with *Problem Exposure*, which starts with an ill-defined or ill-structured problem statement. Students are given the opportunity to ask questions about the problem and move into forward gazing with minimal limitations to possible solutions. In a modified version of Save the Penguins students are given minimal information about equatorial penguins and asked to discuss all problems that may occur:

- In South Africa, where equatorial penguins live, it is getting warmer. Spring is coming sooner and penguins are getting too hot. When it's nesting season, the penguins are supposed to be guarding their egg, but they are getting so hot that they are taking more and more breaks to cool off in the water. What problems do you think this may cause?

After problem exposure and discussion around all the possible problems that could be affecting the equatorial penguins, students are given an ill structured problem: How might we keep equatorial penguins cool? Although this design problem does have a direction, how to keep equatorial penguins cool, students are encouraged to think of the other problems they discussed as a class during problem exposure and problem scoping. Again, the design problem is relatively simple without criteria or constraints allowing students to ideate without restriction.

At this point, Blue-Sky Ideation (BSI) is introduced as a creativity training intervention. BSI is an open-ended form of brainstorming. Kudrowitz and Wallace explain that BSI "is a term used in the design industry that means free from constraints and expected outcomes" (p. 122) [67]. BSI involves brainstorming for the quantity of ideas based on the design problem (How might we keep equatorial penguins cool?) over a 15-20 minute period. There are some very specific rules for how to carry-out BSI for divergent thinking: 1. Each idea is a quick sketch on its own piece of paper with a title and the initials of who came up with it; 2. The quick sketch idea is immediately shared with the group, explaining the idea, and then taped on the wall; 3. Everyone defers judgement on the quick sketch idea; 4. Build on others' ideas. (It is not cheating, it is teamwork.); 5. No hoarding of ideas. (As soon as you have an idea sketch done, share it with the group to promote group creativity.); and finally, 6. Keep the tempo up. At the completion of this activity, each group has myriad design solutions. Each group takes five minutes to group the different solutions into categories of their choosing. Some categories that student groups have created have been titled: water cooling, shelter eggs, doors, fun, and sharks with lasers. At the end of the BSI session, students are told that they will be coming back to their designs after moving deeper into problem scoping.

C. Forward Gazing

While students have been participating in problem exposure and creativity training, they have already activated a forward gazing stance. What they have been instructed to do is to ignore failure and success scenarios. After the BSI intervention, students are then exposed to the same criteria and constraints used in the original Save the Penguins curriculum. The criteria and constraints also include how the students' designs will be tested and encourages students to think about other problems they may encounter in their design. This process illustrates the recursive process of the IFCF by bringing students back to problem exposure. While the criteria and constraints are as restricted as in the original curriculum, the opportunities to move back into problem exposure and problem scoping provides student agency, by allowing them to ask broader, important questions: How will penguins get in and out of a structure? How will the penguins breathe? Is a structure really necessary, if a solution works that does not meet the criteria? When students are given the opportunity to move into creativity experiences and problem exposure repeatedly before selecting a solution, creativity becomes a positive reaction to criteria and constraints of a design problem.

Finally, students go back to their ideas from the BSI where they can select or modify a solution to test, combine ideas, or generate new ideas. This provides the opportunity for multiple creative solutions to be generated, accepted or adapted before trying to build them and moving toward *Failure* or *Success*.

D. Failure and Success

When students move from Forward Gazing into the Failure and Success domains of the IFCF, they are completing the Build/Try phase of the EDP. While the IFCF shows creativity potential being activated at the outset of problem exposure, it is continually nurtured throughout the IFCF, especially when students encounter failure. Lottero-Perdue and Perry identify the risk for failure in the iterative nature of the EDP stating "initial attempts to solve a particular problem may fail to meet design criteria or not meet those criteria as well as subsequent designs" (p. 2) [68]. They revealed teachers' hesitancy in using "fail words" defined as "fail, failing, failed, failure" (p. 1). Educators' discomfort in identifying failure in student designs or failing in providing opportunities where failure may or should occur, results in more narrowly defined problems and a lockstep, rather than iterative, EDP. This often leaves educators discouraged by the lack of creativity and innovation in students' ideas, paralleling the concern of business leaders and the nation at large.

In the Save the Penguins curriculum, the most "successful" way to limit melting of the ice cube is to create an insulated capsule in which the ice cube is sealed, place the capsule on a platform (minimizing heat transfer by conduction from contact with the black floor of the solar cooker), and then cover the capsule with mylar (minimizing heat transfer by radiation). Most students in the original curriculum come up with something very similar in their final designs [65]. While the science content set out by the curriculum is achieved by these designs, creativity and innovation are not.

Alternatively, students in the modified curriculum using the IFCF address the needs of the penguin beyond the central scope of the science concepts of insulation, conduction, convection, and radiation. Their design solutions showed creativity through the diversity of science content knowledge acquired and its application into possible solutions. For example, one design solution focuses on camouflage. Instead of simply protecting the ice cube from melting, students decided to also focus on the safety of the penguin's eggs from predators while the penguins were cooling off in the ocean. Their design included camouflage barriers made out of mylar as a "roof" over the nests, the mylar protected the eggs from overheating, in addition to screening the eggs from predators. The science content included both the target concepts related to heat transfer, as well as an understanding of predator-prey relationships. Another design solution focused on Green energy and the Earth's convection cycle. Their design solution used geometric shaped hutches with multiple entrances and exits to utilize wind energy created by the heating of the Earth's surface, atmosphere, and ocean by the sun. A different design utilized technology of sensors, circuitry, and coding. This design used a sensor to read the inside temperature of a shelter. When a certain temperature was reached it activated mini fans to cool off the eggs and the penguin. These designs creatively incorporated the provided materials, as well as proposing purposeful additions.

E. Redesign and Knowledge, Skills, Acquisition and Application in the IFCF

Unlike in the EDP (Fig. 2), in the IFCF, students may not have pre-learned the STEM content needed to fully understand how to make their solutions successful. Instead, it is when students encounter Failure or Success, that they begin to ask (or are guided by a teacher) "Why didn't this work?", "What do I need to understand about the problem, that I do not?", "How can I learn about that?", "What did work well that I can use in my next design?", or "I need to test x, to see if this is the problem or part of the solution.". All of these questions and discussions are part of *Backward Gazing* and lead students into the Knowledge & Skills/Application & Acquisition (KSAA) areas of the IFCF. Thus, guiding students back to problem exposure and forward gazing. This iterative processing of failure provides further opportunities for creativity and new content learning that students may need for the design of a more successful solution, instead of front-loading content which narrows the solution space.

For students, who have more limited STEM content knowledge than expert engineers, the opportunity to explore KSAA after a failed or minimal success event provides a recursive loop of learning. Kapur defines productive failure in the classroom as "designing conditions that may not maximize performance in the shorter term but in fact maximize learning in the longer term" (p. 289) [69]. Kapur's research indicates that students' ability in these learning situations utilize their prior knowledge to "generate suboptimal or even incorrect solutions to the problem" is beneficial in priming students' interest for learning from the subsequent instruction that would follow such experiences (p. 290) [69]. The IFCF models productive failure by providing problem solving experiences where the solutions include content the students do not yet possess. The Failure and Success and Backward gazing aspects of the IFCF leads into the KSAA, where students are guided through the process of exploring new knowledge and skills specific to the problem they are trying to solve.

In comparison, the original curriculum front loads the science content in the *Learn* phase (see Fig. 2). Whereas the modified curriculum following the IFCF uses Kapur's model of productive failure by moving the *Learn* phase (KSAA) after students build/try their initial solutions. Students are then able to acquire the knowledge and skills they need to reexamine their design and apply the new understanding while moving back through problem exposure and forward gazing. Many of the science lessons in the original Save the Penguins curriculum could be utilized during the KSAA, once the students have a need to develop a more nuanced understanding of heat transfer than their everyday experiences. In addition, lessons focused on students' interest related to the problem statement and their initial creative designs may lead students to other STEM content knowledge such as, hinge structure (engineering), coding and use of sensors (technology and mathematics), learning about the predator prey relationships (biological and environmental sciences), or the Earth, atmosphere, and ocean (earth science). There are many different learning objectives that can be explored through an ill-structured problem and the innovation of students who are involved in a creativity learning process, such as the IFCF. Although the broad scope of STEM content knowledge and application is a benefit to students' learning and interest in STEM, teachers are concerned about how far outside the specified standards the curriculum could go and the additional time needed to execute student based STEM interest through the KSAA process. These are valid concerns in an educational system based on efficiency models, however if integrated STEM is to reach its potential for innovation within the future workforce, it is critical that students have some opportunities to truly engage in creative problem solving.

F. Knowledge, Skills, Acquisition, and Application towards a Creative Outcome

Integrated STEM curriculum which focuses on creativity and reflection on failure, similar to Kapur's productive failure, provides for stronger knowledge acquisition and transfer in students' creative output and overall learning. We posit that the intersection between failure and creativity can support learners' ability to transfer understanding and competencies to new or unfamiliar situations which results in an increase in creative outcome solutions [13]. Knowledge acquisition and transfer is illustrated in the IFCF where failure and success are the middle ground within the creative process and affixed to the importance of reflection (forward gazing and backward gazing). When these elements are combined it affords the knowledge and skills to solve problems with a *Creative Outcome* (see Fig. 1).

VI. Conclusion

The grand challenge of Covid-19 is illustrative of the need for creativity in STEM professions. Without creativity leading to innovation in the rapid development of products and processes, STEM professionals cannot meet the needs of our society. These needs and challenges cannot always be predicted, as was the case with Covid-19, thus the future STEM workforce needs to be equipped to bring creativity to novel problems. Thus, K-12 STEM educators need not only to focus on the learning and application of STEM content, but also developing the 21st century skills necessary to solve problems we don't even yet know exist and as illustrated in the IFCF, creativity and failure are central to the needs of our global society [6], [10], [11]. Like Maltese and colleagues, we make the connection that "creativity and innovation is a long-term cyclical process of small successes and frequent mistakes or failures" (p. 120) [70]. The development of the IFCF incorporates the critical role of creativity and learning from failure within the engineering design process and expands on the need for the explicit recognition of failure in creative outcomes in K-12 classrooms.

This paper has endeavored to explain the importance of creativity within STEM professions and the need for creativity to be included in K-12 integrated STEM curriculum. The IFCF explains the intersection between creativity and failure and their central role in the engineering design process. Further research is needed to explore how we might eliminate “off ramps” when students encounter failure or minimal success instead of moving back into the recursive process of the IFCF, as persistence is a critical attribute of 21st century problem solvers and innovation. Implementation of the IFCF in classrooms requires strong pedagogy, thus it is important to conduct more research on how teachers utilize and approach failure opportunities within their classrooms. The continuation of this work will aid in the expansion of 21st Century Skills, specifically creativity, in K-12 integrated STEM education.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, ES; framework development and theory, ES and GR; formal analysis of framework, ES and GR; writing-original draft preparation, ES; writing-review, contribution and editing, ES and GR; supervision, GR. The author(s) read and approved the final manuscript.

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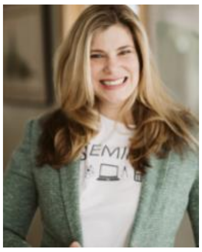

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