Chapter 19
Creativity and Innovation in Science and Technology Education

Mehmet Aydeniz and Michael Stone

Abstract The STEM education community is in the midst of a paradigm shift. The foundations of traditional instructional context, curriculum, place and pace of learning and methods of learning have been challenged fundamentally. A combination of scholarly efforts and educational initiatives outside of formal education institutions, by entrepreneurs, have disrupted the fundamental assumptions of schooling. These efforts have led to an intentional focus on providing rich opportunities for students to create, collaborate and innovate. In this chapter, we first introduce a discussion related to the concept of creativity. Then, we discuss factors that contribute to individual and group creativity. Next, we introduce one exemplary program from the 'Fab Lab' initiatives. We then elaborate on the design features of these models and discuss how these features empower students to be creative and innovative. Finally, we will discuss the implications for teacher educators, researchers and practitioners, and opportunities for teachers to develop the pedagogical capacity needed for promoting creativity and innovation in their curricula.

Keywords STEM · Creativity · Fab lab · Innovation · Digital skills

Creativity: An Introduction

Creativity is a term that has been frequently used to describe a person, a thought process, or a product. Rhodes (1961) introduced a model of creativity where he subdivided creativity into four Ps: (1) creative Person; (2) creative Process; (3)

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creative Product; and (4) creative Press (conditions). This model suggests that one can find creative features in any of these four Ps. Focusing on the personal characteristics, Harris (1960) defined creativity as *'the ability to produce a number of original ideas when confronted with a problematic situation'* (p.254). Harris assumed that creative engineers: (1) are able to produce more ideas; (2) can change their frame of reference easier and quicker; (3) are more likely to produce uncommon ideas; and (4) are better equipped to visualize in space. While this definition limits creativity to personal characteristics, it suggests that creativity requires unique cognitive attributes and alludes to the domain specificity of creativity. Increasing student creativity has been a focus of K-12 educators and, more recently, educators have engaged in curriculum development in and out of school contexts to promote student creativity (Burke, 2014).

Creativity is an important term and skill across many industries and educational settings, yet K-16 students continue to have limited opportunities to develop this critical skill in formal academic settings. Two of the factors that have limited the teaching of creativity have been lack of resources/tools and time to engage in and finish creative experiences in K-12 settings. In this chapter, we focus on conditions that nurture acquisition of personal creativity, and spaces that allow personal creativity to thrive, through a real-world example. We first discuss factors that impact creativity. Next, we introduce digital tools that enable personal or group creativity. Then, we discuss skills that the students will need in the twenty-first century economy to engage in creative activity, followed by the processes that facilitate creative problem-solving. Finally, we make several recommendations for teacher educators and school administrators.

Factors Impacting Creativity

A review of relevant literature suggests that several factors can impact individual creativity, including context, processes, tools and personal attributes. While we do not aim to discuss the full details of these factors, we will provide an overview of each to guide our readers as an introduction for further exploration.

Context

Contexts that promote individual creativity are those that present disorderly situations and problems that require creative thinking, coupled with access to tools and resources that facilitate creative problem-solving (or creative making). Unfortunately, traditional school settings do not have these characteristics that enable, facilitate, or nurture student creativity. Such contexts include maker spaces or Fab Labs, STEM competitions and internships, among others. One characteristic of these contexts is that they allow students to tinker with their ideas, provide psychological safety for testing out-of-the-box ideas, and encourage authentic collaborative inquiry.

Curricular Focus

The second factor that can contribute to students' acquisition of creative problem-solving skills is the nature of the curriculum to which we expose our students. We know that most traditional curricula fail to afford rich opportunities for students to develop habits and skills for engaging in creative thought, creative problem-solving, and creative making. Firstly, traditional learning environments, by design, prioritize and reward acquisition of content knowledge over skill development. While some schools attempt to elevate skill development, they often default back to overemphasizing content mastery because of the extreme systemic focus placed on content standards and state testing. One thing that we need to keep in mind is that skills development is not a linear, prescriptive experience. Students develop skills through repeated experience, through failures, through collaboration with peers. So, the skills development process is messy and cyclic rather than linear. Secondly, traditional learning environments restrict creative making, as student experiences are bound by rigid school schedules, prescriptive curriculum-pacing guides, and measurements of student success that are solely content-focused. Thirdly, teachers' dispositions, knowledge and skills play a critical role. Most teachers are the products of a system that has emphasized, taught, assessed and rewarded content knowledge over skill development. Consequently, without extensive and explicit professional development, teachers resort to the way in which they learned STEM subjects when teaching STEM concepts.

The sole focus on content acquisition restricts opportunities for students to engage in divergent thinking, which has been associated with creative thought. We also know from the OECD report (OECD, 2014) that most countries' high school students underperform in creative problem-solving, which reflects the focus of curricula and the methods of teaching that fail to provide rich opportunities for students to engage in creative thinking and creative problem-solving. When the curriculum and instruction focus primarily on students' acquisition of scientific facts, and teachers hold only minimal subject matter knowledge, it becomes rare, if not impossible, for students to develop habits of minds, dispositions and skills necessary for creative thinking, creative problem-solving and creative making. Despite these problems, recent developments in STEM education have created contexts and tools for students to engage in creative thinking, creative problem-solving and creative making. We elaborate on these developments in the next section. However, we first introduce personal and contextual attributes that are associated with creative problem-solving.

Personal Characteristics

Personal characteristics that promote creativity include, but are not limited to: open-mindedness, curiosity, problem-solving skills, persistence, comfort with ambiguity, and metacognition. We must note, however, that these personal characteristics are the outcomes of the experiences the individuals have had in contexts that enable, facilitate and nurture creative thought and creative problem-solving. These characteristics are developed through consistent engagement in rich experiences that call for creative thinking, creative problem-solving and creative doing. Access to epistemic, mentoring, academic peer groups, and physical resources, makes a difference in how one thinks in academic and non-academic environments. Readers should keep this perspective in mind as they make sense of what we present in the following sections.

- ***The first*** of these personal characteristics is ***curiosity***. **Curiosity** refers to the level of discomfort with a gap in knowledge or the joy of and passion for exploring the unknown. ***Curiosity*** feeds creativity, because it encourages and ensures: (1) sustained inquiry mindset and behavior; (2) divergent thinking, which can lead to development of alternative approaches to problem-solving; (3) pursuit and development of alternative explanations for the observations; and (4) risk-taking. All of these are associated with creative thought, creative problem-solving and creative making.
- ***The second*** personal characteristic related to creativity is ***metacognition. Metacognition*** empowers creative people to see aspects of their cognition that facilitate, help and encourage problem-solving. It allows them to see gaps in their problem-solving journey, and gives them the opportunity to reflect on their knowledge and methodology. Therefore, any educational endeavor aiming to promote student creativity should focus on cultivating metacognition, as it is a critical component of learning through rich experience.
- ***The third*** personal characteristics is ***open-mindedness. Open-mindedness*** refers to the human attribute that allows one to be receptive to a variety of ideas, methods and arguments, and a willingness to consider relevance of alternative strategies to the problem in hand. *Open-mindedness* is a prerequisite to creative thinking, creative problem-solving, and creative making because it allows one to see multiple factors that may contribute to a problem, to consider divergent pathways that could inform a novel solution. Open-mindedness encourages acceptance of failure early on and a willingness to try new and alternative problem-solving methods. It also encourages use of alternative resources to achieve a creative goal, or to propose creative solutions to a complex problem.
- ***The fourth*** personal quality of creative people is grit or ***persistence. Grit*** refers to the ability of an individual to endure challenges and persist over time on a journey towards accomplishing important goals:

  'You have to be burning with an idea, or a problem, or a wrong that you want to right. If you're not passionate enough from the start, you'll never stick it out' (Steve Jobs).

People develop creative solutions and products partly because they do not give up easily. ***Grit or persistence*** is a personal quality that discourages people from giving up on problem-solving in the face of failures or adversaries. Instead of giving up, creative people model persistence as they work through multiple iterations, choosing to use failed attempts to inform future strategies, rather than giving up after initial methods do not yield the desired result.

Tools for Creativity

Digital learning has opened immense opportunities for teachers to design activities for promoting student creativity. Students also have access to a set of digital tools that they can use to engage in creative activity in the absence of a pedagogical guide such as the teacher. Firstly, digitized information/content can be accessed asynchronously and independently. This alleviates the need for learning within a rigid academic schedule and it frees the teacher to focus on skill development instead of disseminating content. Secondly, digital communication tools make collaborative problem-solving possible. They give immediate access to community resources and democratize where and how students learn – simultaneously providing access to global experts and local advocates. Students can interact with each other, give feedback, ask questions, and have immediate access to epistemic resources to make connections, address a knowledge gap that they may have, and access a diverse and robust set of relevant resources. One of the best examples of how digital tools can promote student creativity is the *Scratch* community. Digital tools allow for community-building, sharing of community resources, collective problem-solving and epistemic affordance. Collectively, these features of digital technologies make creativity possible. However, this possibility alone is not sufficient; the experiences should be scaffolded for creative thought, creative problem-solving, and creative products. Teachers should have the disposition, domain knowledge and pedagogical skills to design and facilitate learning activities for students to develop creative thought, creative problem-solving, and/or creative making. As teacher educators and administrators, we should help teachers develop such dispositions, domain knowledge and pedagogical skills so that they can effectively guide their students' skills acquisition. This can take place through ongoing professional development and community-building in disciplinary and interdisciplinary contexts.

Digital Skills for Creativity

While digital tools help students to collaborate more effectively across contexts, access important resources and more effectively learn about the abstract concepts, the role of technology should not be limited to accessing and sharing knowledge between the learners. Schools or educational entities should create contexts, space and learning activities that will allow students to develop digital skills for engaging in creative problem-solving and creative making. Paired with progressive pedagogical strategies, these spaces empower students to realize the full potential of digital skills. The first of these skills is computational thinking.

- **Computational thinking skills**

Computational thinking refers to the type of skills that involve the use of computational tools and computing power to solve real-world problems or to design services, experiences and products (Wing, 2006). We now live in a digital world. The breadth of our experiences is tailored for technologically rich spaces. The next generation already lives in the digital world through video games and VR. With the growing popularity of metaverse, social aspects of our lives will increasingly migrate deeper into digital space. As our experiences move to digital spaces, the new economy becomes the economy of makers. More specifically, it becomes the economy of making by programming or coding using digital tools. In order for us to prepare our students for this type of economy, we need to integrate computational thinking and coding skills across the curriculum, rather than isolating it to traditional STEM fields.

- **Data science skills**

The second skill is data science. In addition to computational thinking skills, we need to teach our students data science, data engineering and data management skills. These skills collectively enable students to practice with creative design, creative problem-solving, creative modeling, and creative making. These skills are the fuel of the new economy; therefore, any creative design will depend on computational and data science skills (Fig. 19.1).

- **Collaboration skills**

Another important skill for creative problem-solving is collaboration. Collaboration is critical across disciplines, industries, borders, contexts and skills. The new generation of employees must develop the ability to work collaboratively. Collaboration requires being open-minded and having excellent communication skills. Engaging students in collaborative learning and collaborative problem-solving early on not only helps students develop knowledge and skills, but also cultivates positive dispositions towards communal growth. Collaboration increases students' metacognition, as they monitor and evaluate their contribution to the project, and how those contributions serve or do not serve the accomplishment of the goal. They learn to integrate knowledge and skills across different domains, gain exposure to different perspectives, and learn to use evidence and data to share, challenge and defend ideas presented to the group.

- **Design thinking skills**

The fourth skill associated with creativity is design thinking. Design thinking draws on data, human imagination, and systematic reasoning to explore creative answers to complex problems. Design thinkers imagine creative possibilities

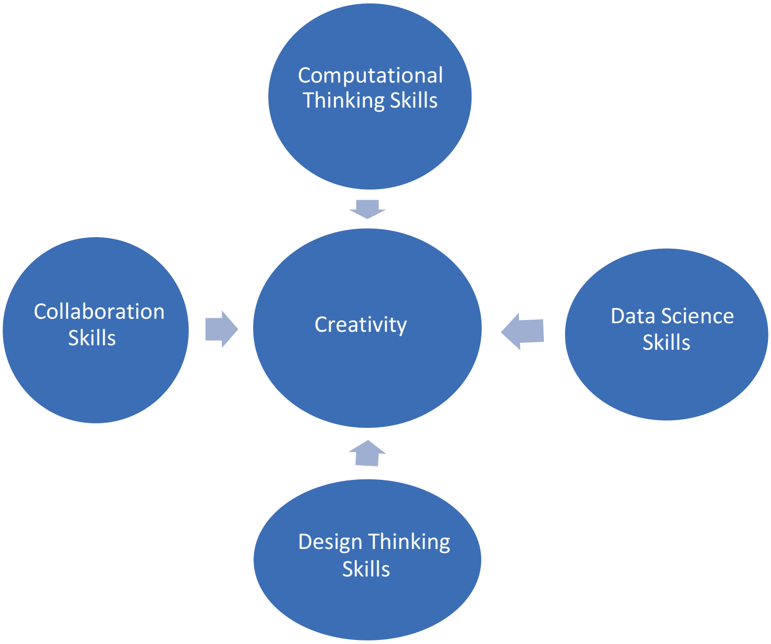


Fig. 19.1 Digital skills

informed by data and contextual expertise. There are multiple models and definitions of design-based thinking, but the core aspects of design thinking are: empathizing (understanding the problem through lived experiences), defining (which corresponds to defining stakeholders, challenges, roles and opportunities), and ideation. The next stage is prototype development. At this stage, the individual is expected to develop a prototype for testing the specifications of the target design product or service. The final stage of design thinking involves testing the product for its effectiveness, particularly through a lens of empathy for the end user. After the initial testing, the process is repeated to optimize the effectiveness and efficiency of the final design.

In a data-driven world, where computational power and tools are abundant and human experience has moved to a digital plane, these four fundamental skills should be at the core of any curriculum that aims to promote student creativity.

Processes That Facilitate Creative Problem-Solving

There are several processes that facilitate creative thought, creative problem-solving and creative making. These include collaborative inquiry, ***collaborative problem-solving***, opportunity for ***reflection on experience,*** and ***receiving feedback or***

criticism. School curriculum and instructional strategies should facilitate student engagement with processes that promote creative problem-solving skills through authentic collaborative inquiry.

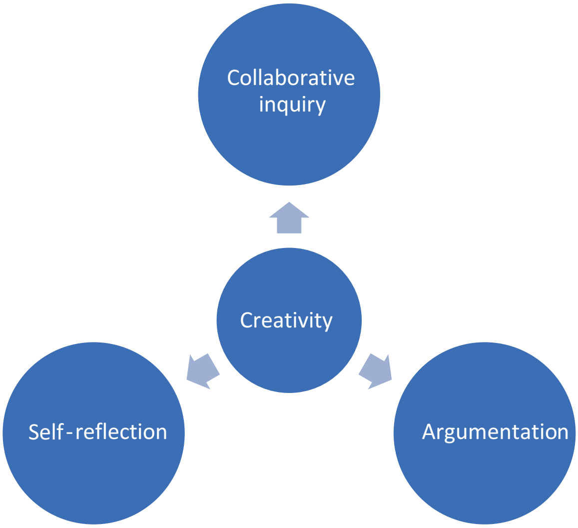
The First Process That We Believe Facilitates Such Opportunity Is *Collaborative Inquiry* When students engage in collaborative inquiry, they build on each other's contributions to advance the arguments or to improve their design or the quality of their arguments of products. Similarly, different members of the group can make different observations and highlight issues that otherwise may not surface. Each member can build on their observations, unique experiences and prior knowledge to ask different questions that can result in new knowledge. This new knowledge can be integrated to inform the design, product, or solution. The collaborative inquiry experiences can enrich students' domain knowledge repertoire, expose them to alternative explanations, and raise diverse questions, which, collectively, can influence the quality and effectiveness of the products, arguments and models.

The Second process That Helps Facilitate Creative Thought Is Reflection Reflection time is typically limited in traditional classroom settings, as the bell schedule does not allow for reflection over an extended period. Digital learning environments overcome this limitation, as the experience of learning is not limited to a typical class schedule. Moreover, the triggers of self-reflection in the classroom are limited to the teacher and classmates. However, in social digital communities, students have access to the resources and questions of a larger, global community. This provides a unique opportunity to reflect in a more diverse and more informed context.

The Third Process That Facilitates Creative Thinking Is Argumentation Argumentation provokes creative thought and creative problem-solving. Argumentation allows the learner to integrate knowledge across different domains to develop an articulate argument, encourages logical conclusions when presenting one's arguments, and clearly articulates the argument's rationale in an effort to demonstrate transparency and encourage critical discourse. Argumentation and the criticism received from peers can help the learner to identify gaps in their knowledge or models, deficiencies in their reasoning, and the quality and relevance of their evidence. This critical inquiry into one's evidence, model, reasoning, or argument is generative and cultivates creativity as students engage in authentic experiences.

After indicating the contexts, personal attributes and processes that contribute to creative problem-solving, we will now introduce the *Maker Movement,* which has allowed student creativity to thrive. After presenting a brief discussion of what the Maker Movement is, we provide a real example of what this type of education makes possible for students (Fig. 19.2).

Fig. 19.2 Processes



Maker Movement

Maker education is a movement that aims to empower students to develop robust skills as they design and create tangible products using imagination, creativity and technology. Maker spaces provide access to digital tools, materials and software necessary for students to develop functional solutions to real-world problems. One key aspect of maker spaces is that they encourage community building and collaborative learning (Burke, 2014). The Maker Movement has permeated formal and informal learning environments. Spaces have been embedded in museums, science centers, libraries, schools and community centers. Schools have been working to repurpose some of their classrooms to accommodate the rich learning that can occur in a maker space. Similarly, schools have been more purposeful in recruiting teachers who can help run the maker spaces and provide intentional guidance to their students to make the learning experiences meaningful and powerful.

- **A Makerspace example**

What content, skills and habits should all students master in school? It is clear that traditional content is important for student development, but it is also critical that students develop strong habits and skills. The team at the Public Education Foundation (PEF) in Chattanooga, TN, asked this question of more than 300 leaders from business, industry and higher education. Nearly all responses indicated skills and habits – so-called *STEM Essential Skills*. In particular, two primary categories emerged from the responses. Leaders are clamoring for students who have strong *interpersonal* skills (i.e., collaboration and communication) and strong *learning* skills (i.e., critical thinking, adaptability and creativity). Unfortunately, because content mastery is simpler to quantify and assess, over the last few decades the education pendulum has become stuck on the wall of content. Certainly, content areas such as mathematics, history, language and science are important. However, informal polling suggests that these STEM Essential Skills are at least as important as content mastery. This observation pushed the team at PEF to begin redesigning learning experiences that elevate opportunities for students to develop STEM Essential Skills alongside traditional content mastery.

Dr. Tony Donen, founding principal of STEM School Chattanooga (STEM Chatt), worked in partnership with Michael Stone, VP of Innovative Learning at PEF, to design these innovative learning experiences. STEM Chatt was founded as a platform school intended to identify, develop, incubate and deploy innovative learning strategies for public high school students. Based on the polling mentioned above, Dr. Donen led the original faculty to identify core tenets that became the hallmark of the school. The team chose critical thinking, creativity, and collaboration – STEM Essential Skills – as their core values. To ensure that students could begin developing these competencies alongside traditional content, the team decided to use multi-disciplinary, project-based learning (PBL) throughout the school. Additionally, they developed a faded scaffolding approach that strategically releases ownership and autonomy to the students in every facet of their high school experience. Two years into opening the school, one grade level per year, the leadership team realized that students were progressing in their development of essential skills, but their PBL presentations were void of functional solutions. The students would present rough analog models and nicely designed slide-decks, but they never had an opportunity to engage in design thinking where they could test and analyze their proposed solutions to real problems. They were not being afforded the opportunity to work through an iterative design process and glean understanding from the incidental learning moments that naturally occur in these strategic experiences. In researching opportunities associated with the Maker Movement, the team stumbled onto the Fab Foundation and the Fab Lab model that had been developed at MIT.

After some strategic design sessions, the team developed a plan to embed a Fab Lab into the high school using what is now considered an ‘open lab’ model. In this model, the lab serves as a room containing rapid prototyping tools, where students develop functional solutions to authentic problems as an integral part of their PBL experience. To embed this model, Dr. Donen made it clear that the goal of the lab was not to explicitly teach discrete technical skill sets (like 3D design or physical computing). Instead, the aim was to provide opportunities for students to develop STEM Essential Skills. Using the advanced technology in the lab (labs are fitted with 3D printers, laser cutters, vinyl cutters, CNC machines and physical computing components), the aim shifted from content mastery to empowering students to leverage the resources around them to quickly learn new skills and solve real problems. Students have full access to the lab as they engage in their multi-disciplinary PBL units. The teachers work to facilitate a ‘just-in-time’ learning environment where students acquire technical knowledge and skills as they are needed in their design process. To this end, teachers coach student teams through PBL product development, pointing them to resources instead of serving as the sole or primary access point for knowledge and information. Additionally, the Fab Lab teacher focuses all assessment solely on student mastery of STEM Essential Skills. Rather than assessing product quality or functionality, technical knowledge or content mastery (all discrete components whose assessment often discourages creative, innovative solution attempts), the Fab Lab teacher solely focuses on coaching and assessing student mastery of the targeted essential skills.

This explicit focus on essential skill development represents a subtle but powerful shift in student development. For too long, schools have solely focused on *what* students know, when the important question is actually *what can they learn and do*? Can they ask thoughtful questions, access relevant information, interpret it, analyze it, and then do something with it? Schools shouldn't be simply measuring what information students can recall. They should be measuring if students can leverage essential skills to ask relevant questions and then create something meaningful with the information that they discover.

To bring this model to scale in more traditional schools, the team had to recognize a critical and necessary shift. Much of modern schooling is still designed around relics of the **factory model** of education tailored for the industrial era. In this model, teachers serve as *content* experts who share knowledge with students in order to prepare them for specific, predictable roles in a relatively slow-moving world.

However, the modern world is dynamic. Today, students don't need teachers to serve as gatekeepers to information. They can't afford to sit through a static learning model. They need an adaptive model, where teachers serve as *learning* experts who empower students to thrive as learners and doers. Students need opportunities to imagine creative solutions to complex problems, and then bring those visions to life. Central to this model is a critical shift in the role of the teacher. Students need to learn *with* teachers, not *from* them. They need teachers to model how to use essential skills to thrive as agile learners who quickly learn new skills, apply innovative approaches to novel problems, and succeed in collaborative environments.

Unfortunately, many classrooms still reflect the didactic, prescriptive models designed for a world that passed us by decades ago. Mostly, if not entirely, content-focused, school systems and entire cottage industries work to prepare students to regurgitate information in a futile attempt to beat computers at fact recall and calculations. It is as if we have forgotten about the value of creativity and critical thinking entirely. Sadly, this is not a novel observation. Nearly 16 years ago, the late Sir Ken Robinson gave arguably the most famous TED Talk of all time as he made a moving case for embracing creativity and rethinking the goal of modern schooling. Around the same time, Tony Wagner began pushing for schools to embrace what he calls the *7 Survival Skills for the twenty-first Century:* competencies like critical thinking, agility and communication, which we know are important for student development, but which we have yet to effectively integrate into the learning experiences of our formal educational institutions.

In 2014, in Mr. Stone's first semester at STEM Chatt where he was hired to open the Fab Lab as the first teacher in the space, he met a student named Emma *(name changed to protect privacy)*. She was a 16-year-old high school junior who didn't identify as particularly tech savvy or mechanically inclined, but she had an experience in the school's Fab Lab that dramatically impacted her future. When presented with an opportunity to contribute ideas to a local art installation, Emma imagined what it might look like to build an ice castle for the company's holiday window display. In just 6 weeks, Emma learned enough design software to create a table-top model by laser-cutting a few pieces of acrylic and fitting them together to make a facade of a 'castle'. She then joined with other students in the business partner's boardroom to present her team's design. Her team was the last to make a presentation, and you could feel the excitement behind their nervousness as they began to share the model. A few minutes into the presentation, the Chief Executive interrupted to ask Emma and her team if they could 'actually build this to scale'. Emma didn't miss a beat. She eagerly responded 'YES' (despite lacking the discrete technical skills necessary to build the display). Over the next 5 weeks, Emma **collaborated** with a few engineers, **accessed** online resources to learn enough computer-aided design (CAD) to use the Fab Lab's computer-controlled router, **imagined** and **experimented** with how light interacts with different materials, and grew to **lead** her team to build a 12-feet tall by 10-feet deep by 30-feet long acrylic ice castle (see Fig. 19.3). By blending the essential skills that she had developed at STEM Chatt with access to the advanced technology in the school's Fab Lab, she was able to move from an idea in her head to a tangible, stunning solution.

When the design was revealed at a press event hosted by the company, Emma became an instant hit. The media rushed to get photos and interviews as her friends and family watched from the sidelines, beaming with pride. The moment was truly fantastic, but perhaps a bit fleeting. A week later, Emma joined her classmates as a new business partner pitched the next challenge. However, this project was a little less artistic. A local caving tour company explained that the students would design and create potential solutions to mitigate the spread and impact of white-nose

Fig. 19.3 Student product

syndrome (a highly contagious and deadly fungus that was beginning to afflict bat populations in the region). Despite the clear disconnect from the artistic ice castle model, Emma was ready to jump in! When she returned to school, she went straight to the Fab Lab, where she transferred the same skills that she had used in the previous project, **collaboration** and **leadership,** to rally her team to accomplish the task, **accessing** and **analyzing** new content to learn details about how bat colony behaviors aid the spread of the fungus, and engaging in **critical thinking** and **agility** to ask insightful questions and **imagine** potential solutions.

While the media celebrated the artistic value of the ice castle, classroom experiences that celebrated *process* over product and *essential skill development* over memorization equipped Emma with the confidence and capacity to create solutions to authentic problems – whether building a beautiful ice castle or mitigating the spread of a bat fungus.

Interestingly, this focus on essential skills doesn't have to come at the cost of content mastery. The two are not mutually exclusive. Emma went on to earn a Bachelor's degree and is now thriving in a full-time role at a national avionics company. Additionally, the opportunity that she had at STEM Chatt has grown from a pilot program at one extraordinary public school to a burgeoning movement, scaling to 30 K-12 public schools in Hamilton County, TN, and now growing to at least 19 additional labs across the country. Today, more than 45,000 students in public schools, spread across diverse communities throughout the United States, are using Fab Labs to cultivate essential skills through authentic learning experiences.

Pedagogical Design Features of the Learning Contexts That Promote Creativity

There are several design features of these learning environments. We discuss each of these design features below.

Creative Challenge

Students must be presented with a challenge or a problem that requires creative thinking, creative problem-solving, or creative making. If the curriculum engages students only in routine learning tasks that require memorization, students will not learn to engage in creative problem-solving. While traditional classrooms often cannot afford such opportunities, teachers can leverage constructivist learning strategies to overcome the challenges presented by traditional curricular goals and structures that prohibit teaching of creativity.

Project-Based Learning

Learning often occurs in a project-based format. Project-based learning (PBL) is an important pedagogical design feature of these environments. Firstly, PBL engages students in inquiry-based learning. Students engage in open-ended problems that facilitate rich learning experiences and extend well beyond the traditional class period. Secondly, PBL promotes student curiosity, as the problems are intentionally designed without simple, clear solutions. Students must think deeply about the problem, methods, data and efficacy of models proposed as solutions. Thirdly, the process of learning is collaborative. Students engage in brainstorming during the planning stage, and in argumentation over data, methods and models developed as a solution. They develop alternative explanations and challenge one another about the process and products of their inquiry. Creativity emerges as a natural bi-product of these processes.

Psychological Safety

Additionally, psychological safety is a key attribute of environments that promote creativity. When the learning culture provides psychological safety, students can think freely, express unorthodox ideas with their friends and teachers, and avoid the fear of making mistakes. In such learning environments, even the wildest ideas are considered with an open mind, and are discussed without cognitive bias. Collectively, these experiences and perceptions encourage divergent thinking and lead to student creativity.

Conclusion and Implications

In this chapter, we focused on factors that encourage student creativity. We will now discuss the implications of this understanding for teacher education, research and practitioners.

Teacher educators need to understand that learning is no longer restricted to the brick walls of classrooms. Learning is taking place everywhere, experienced by everyone, and taught by everyone. We must prepare teacher trainees for this reality. They should be exposed to innovative learning contexts, experience of digital tools, and communities that promote student creativity through both structured and unstructured learning tasks.

School administrators should understand that limiting learning to teacher lectures and designing learning goals around student test scores will only limit opportunities for students to learn and advance in their professional careers. The narrow focus on test scores should be mitigated by opportunities for students to develop creativity and other essential skills, alongside content mastery.

School leaders should be aiming to promote students' skill development. They should communicate the expectations to their teachers so that they can cross borders, moving from test-focused instruction to a skills-focused model.

School administrators should support professional learning opportunities for their teachers, through which they will acquire knowledge and skills related to designing rigorous learning environments, rich in content *and* interactions, to support student creativity through digital and physical tinkering, and through project-based and design-based activities.

Researchers should develop new assessments consistent with the evolving goals of STEM education: the transition from content understanding to skills development.

Summary

This chapter primarily covers the meaning of creativity, factors impacting creativity; tools for promoting creativity in STEM learning environments, processes that facilitate creative problem-solving, and learning contexts that promote creativity.

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