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To cite this article:

Dignam, C. (2025). Makerspace and the 5 C's of learning: Constructing, collaborating, communicating, critically-thinking, and creatively-thinking. *International Journal of Studies in Education and Science (IJSES), 6*(1), 104-127. https://doi.org/10.46328/ijses.135

International Journal of Studies in Education and Science

2025, Vol. 6, No. 1, 104-127 https://doi.org/10.46328/ijses.135

Makerspace and the 5 C's of Learning: Constructing, Collaborating, Communicating, Critically-Thinking, and Creatively-Thinking

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Article Info

Article History

Received:
03 March 2024

Accepted:
22 November 2024

Keywords

Makerspace
STEAM
Constructivism
Critical thinking
Experiential learning

Abstract

From early childhood settings to higher education, makerspaces provide opportunities for learners of all ages and backgrounds to engage in hands-on learning for designing and creating to solve problems. This study explores the advent of the makerspace movement and the benefits and future implications for Science, Technology, Engineering, Art, and Mathematics (STEAM) learning for interweaving makers philosophy. As our global society nears the close of the first quarter of the twenty-first century, the skills developed, refined, and improved through makers learning readies all learners with twenty-second century preparedness. The makerspace movement is innately centered on constructivism. Constructivism provides learners with both social discourse and the transmission of experiential knowledge for constructing understanding. This study examines the effect of constructivism and the roles of communicating and collaborating during makers discovery for motivating students and makerspace influence on social skills development. The prosocial benefits of makerspaces also serve as catalysts for inspiring personalized learning and group learning dynamics between cooperating students. Moreover, makerspaces incorporate elements of computing, engineering, and the arts in the aesthetics of student work products. When students design and construct, they employ critical-thinking skills for creating original works of art and science. The development of critical-thinking skills and creativity in learners are life skills students employ throughout a lifetime of learning. This study explores a spectrum of makerspace tools, ranging from cardboard and Legos to laser cutters and CNC machines for use by learners in early childhood centers through university settings. This study also provides recommendations for future makerspace utilization as both a course offering for students as well as strategies for embedding makers philosophy through interdisciplinary and transdisciplinary teaching and learning athwart a spectrum of STEAM and content areas.

Introduction

STEAM-Forged Beginnings

In educational settings, a makerspace is a learning environment that promotes inquiry, principles of design, and student-directed experiential learning, resulting in the construction of student artifacts. Makerspaces focus on an iterative approach for students to plan, create prototypes, and participate in practical learning activities for expressional original creations (Heredia & Tan, 2021). The activities students engage in within a makers learning environments are both personalized and group oriented. In addition, makerspaces provide opportunities for learners of all ages and backgrounds to engage in constructivist, hands-on learning for designing and creating to solve problems. This study explores the roles of constructing, collaborating, communicating, critically-thinking, and creatively-thinking for innovative solution-finding. As noted by Reynaga-Peña et al. (2020), makerspaces are defined by their role in fostering creativity and innovation, facilitating hands-on prototyping, and encouraging open collaboration practices.

This study concurrently explores the advent of the makerspace movement and investigates the role of Science, Technology, Engineering, Art, and Mathematics (STEAM) education in supporting student learning. The researcher delves into theoretical frameworks such as constructivism and experiential learning and the roles of interdisciplinary and transdisciplinary learning in supporting a STEAM-based makers learning environment. Makerspace learners, or makers, are personified by the products they design and construct within a philosophical STEAM-based, constructivist environment. Hughes et al. (2022) assert maker identities highlight the importance of inquiry-based learning, problem-solving, and perseverance, key elements of STEAM education. An overarching goal of the study is to present the benefits of nurturing the blended academic and social, emotional needs of all learners within a makerspace. Bertrand & Namukasa (2020) stated makerspaces foster creativity, problem-solving, collaboration, and critical thinking, aligning with STEAM education's goal of holistic learning experiences that transcend individual disciplines. This study provides perspective with respect to what is possible and how to create possibilities for all learners of every age and background for engaging in meaningful and relevant 21st century learning.

Cognition, Emotions, and Culture: Weldments of Experience

Making is connected to STEAM by integrating aspects of each discipline. Making fosters interdisciplinary teamwork and enables students to combine ideas from STEAM in their endeavors, promoting creativity, innovation, and problem-solving abilities for not only STEAM fields but for education and innovation (Beavers et al., 2019). Makerspaces positively influence student academic performance by directly involving students, promoting motivation through innovative teaching approaches and active engagement, enhancing students' self-assurance and skills, while also improving collaboration skills through problem-solving and knowledge sharing among students (Konstantinou et al., 2021). A maker’s culture fosters a collaborative and experiential, hands-on learning for project development, highlighting creativity, experimentation, and a strong sense of community among students (Tabarés & Boni, 2023).

Making empowers students to express their creativity, venture into uncharted territories, and collaborate with peers from diverse academic backgrounds, enriching their educational experience (Beavers et al., 2019). Making encourages creative exploration and skill development, while building connections creates a supportive network that enhances learning and collaboration within maker communities (Patton & Knochel, 2017). Makerspace supports the development of creativity, critical thinking, and teamwork skills, especially in STEAM fields, facilitating interdisciplinary projects and research and allowing students to create engineering solutions using advanced manufacturing technologies (Soomro et al., 2023). Makerspaces via a STEAM philosophical construct encourage collaborative learning through constructivism and constructionism, promoting students working together to design and create artifacts, which promotes motivation and emotional support, enabling students to overcome typical challenges in STEAM projects (Olabe et al., 2020; Papert, 1990). Makerspaces positively influence affective outcomes pertaining to the effects on the attitudes, beliefs, and emotions of students involved in the process of making (Mersand, 2021).

Maker culture is enriched through STEAM education by blending practical learning opportunities in science, technology, engineering, and mathematics with the cultivation of vital soft skills such as teamwork, communication, and critical thinking (Tabarés & Boni, 2023). The collaborative and practical environment of makerspaces corresponds with the comprehensive philosophy of STEAM education, empowering students to cultivate a diverse skill set that encompasses technical and artistic proficiencies (Kim, 2021; Soomro et al., 2023). Makerspaces enhance academic performance by offering collaborative hands-on learning experiences that promote teamwork, prosocial communications, and the development of empathy (Konstantinou et al., 2021). The essence of makers culture lies in the creation of objects by students through a shared ethos, values, and behaviors, driven by design innovation (Tabarés & Boni, 2023). Through the use of digital fabrication tools and creative tasks, makerspaces support the exploration of the convergence of art and technology, promoting the development of creativity and critical-thinking skills (Soomro et al., 2023). Makers culture and enrichment through STEAM education are reciprocal processes for supporting students in the development of a solution oriented mindset.

Constructivism and Experiential Learning: STEAM Engines of Wisdom

Vygotsky (1978) posits student acquisition of knowledge results through social interactions, resulting in the construction of knowledge. Vygotsky's constructivist paradigm links the social interactions of students during hands-on activities, such as maker experiences, to constructing meaningful understanding for knowledge-building. Schwichow et al (2016) noted that experiential, hands-on learning is key for enhancing learning outcomes, student engagement, and motivation, but task design is more important than the curricular materials used, highlighting the importance for educators to prioritize task development to optimize student learning. Kolb et al. (1984) theorized the act of learning includes a four-part cycle that includes concrete experience, reflective observation, abstract conceptualization, and active experimentation for acquiring knowledge. In addition, cognition via experiential learning is exemplified when students demonstrate knowledge by applying concepts, such as making, to learning (Kolb, 2014). Constructing and experiencing are key for meaningful STEAM-making knowledge building.

Makerspace teachers should give careful consideration to task design to enhance student learning experiences, emphasizing the creation of engaging hands-on activities that align with learning goals and foster deep conceptual understanding. Prioritizing task development over materials can elevate student engagement and motivation within makerspace settings. Experiential learning within the framework of hands-on, educational inquiry activities improves students' grasp of STEM concepts and involves students acquiring knowledge through direct experience and practical application of concepts (Budiyanto et al., 2020). The acquisition of knowledge through constructivism is greatly enhanced in makerspaces when students construct knowledge through experiential learning.

Integrating STEM education with art and experiential learning equips students with the skills needed for academic success and future career readiness (Remington et al., 2023). Kolb's cycle is a learning model that epitomizes maker's philosophy, comprising active experimentation, concrete experience, reflective observation, and abstract conceptualization, guiding individuals through hands-on activities, reflection on experiences, and practical application to enhance understanding of concepts. According to research conducted by Long et al (2020), in K-12 STEM educational settings, utilizing Kolb's cycle can engage students and enhance STEM literacy by integrating active experimentation and aligning hands-on activities with the experiential learning model, fostering the practical application of mathematical and scientific concepts through engineering design processes. The acquisition of knowledge and understanding of concepts is influenced by both sensory and motor experiences, as well as the processing of information from different sensory modalities, meaning conceptual knowledge is constructed through the amalgamation of sensory experiences and the fusion of information from diverse sensory modes, resulting in a more elaborate and holistic representation of concepts in the brain (Hayes & Kraemer, 2017). Makerspace learning occurs through both hands-on, experiential learning and constructivism (Figure 1).

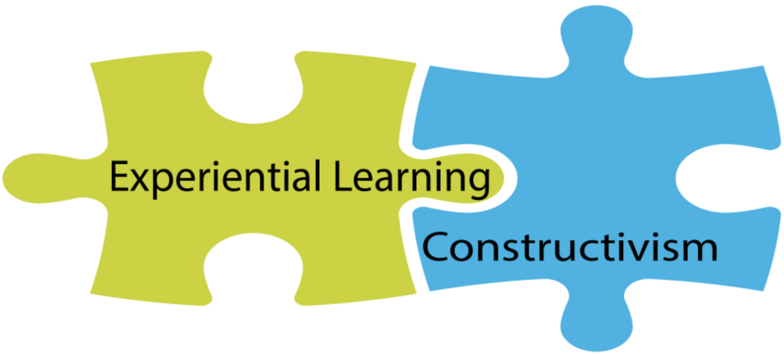

Figure 1. Experiential Learning and Constructivism in Makerspace

Makerspace: Manufacturing Historical Perspectives

The Maker Movement was influenced by the advent of the Electromechanical Age, a period of time characterized by do-it-yourself (DIY) electronic project-building, innovation, craftsmanship, knowledge sharing, and community engagement. The Electromechanical Age commenced in 1800 with Volta's creation of the electrical battery and extended into the early twentieth century with advancements such as the vacuum tube amplifier (Cheung & Brach, 2020). During the Electromechanical Age, the introduction of electrical power revolutionized factory operations, leading to enhanced flexibility and efficiency. While the discovery of electromagnetism through Volta's battery invention enabled the development of more potent devices such as the electromagnet, and the utilization of electrical power sources facilitated the establishment of groundbreaking communication networks such as the telegraph and telephone (Bull et al., 2022; Cheung & Brach, 2020).

The spirit of innovation through mechanical tooling, creating, and making continued throughout the latter part of the 20^{th} century and into the 21^{st} century, resulting in what is termed the Maker Movement. The Maker Movement originated from groups such as the Homebrew Computer Club in the United States in the 1970s and the Chaos Computer Club in Germany in 1981 and has evolved due to advancements in information and communication technologies (ICTs) and local manufacturing tools, resulting in the creation of makerspaces (Niaros et al., 2017). Makerspaces, as a community-driven aspect of the Maker Movement, offer a flexible and collaborative platform for individuals to share, create, and tailor their roles based on local needs, with community members taking the lead in planning and decision-making to sustain a maker culture (Sung, 2018). Both advancements, the Electromechanical Age and the Maker Movement, embrace communal DIY electronic project-building, innovation, craftsmanship, and knowledge sharing. Makerspaces can also be traced back to community centers for DIY projects, which emerged from computer clubs and hackerspaces in the 1980s, with making increasing in popularity in 2005 with the launch of Make magazine, which contributed to the development of the Maker Movement and its incorporation into educational settings (Bull et al., 2022; Stornaiuolo & Nichols, 2020).

Maker Movement in Education: Crafting Knowledge

The Maker Movement in education, influenced by project-based learning and technological tools, gained momentum due to societal trends, such as the acceptance of progressive education and the affordability of digital fabrication and hard fabrication technologies through FabLabs and makerspaces (Blikstein, 2018). The Maker Movement of the early 2000s, emphasizing the use of digital and physical fabrication tools, encouraged a collaborative and innovative approach towards creative projects. Maker Faires, which began in 2006 and have grown internationally, provide a platform for inventors, hobbyists, engineers, and educators to exhibit their work and share their expertise (Sung, 2018). The Maker Movement's integration into education led to the proliferation of makerspaces in schools, providing students with hands-on learning experiences to foster creativity, innovation, and collaboration. The Maker Educational Movement equips students with critical skills in problem-solving and teamwork, thereby enriching student learning and preparing learners for future challenges (Stornaiuolo & Nichols, 2020).

Maker Movement Aspirations: High Voltage Ignition

The objectives of integrating the Maker Movement in educational settings involve fostering innovative subject-specific approaches through technology, exploring the societal impact of cutting-edge apparati, encouraging youth to push boundaries between analog and digital realms, and promoting gender equality in digital fabrication endeavors (Eriksson, 2018). Makerspaces are central to this integration, supporting the development of a creative mindset in students through hands-on projects that allow them to explore and create tangible artifacts. According to Turakhia (2023), makerspaces enhance students' technical competencies, project management abilities, and interpersonal skills via collaborative, project-based activities. Moreover, Nadelson (2021), notes makerspaces are pivotal in supporting the principles of a growth mindset for maker students. Makerspaces create an environment where failure is seen as a natural part of the learning process, encouraging students to view challenges as opportunities for growth and learning, thereby enriching learners’ educational experiences and preparing them for future challenges.

Makerspaces are designed not only to foster creativity and innovation but also to support personal and academic growth in a structured environment. Fasso & Knight (2020) propose makerspaces aim to facilitate the Zone of Proximal Identity Development (ZOPID) by providing a supportive environment for learners to navigate new identities within a zone that challenges them while remaining attainable via experiential, hands-on activities and collaboration for exploring student interests and skills, with teachers playing a vital role in guiding and supporting the identity-building process. The ZOPID framework highlights the importance of aiding learners in constructing their identities within a zone that presents challenges yet remains within reach. It centers on establishing identity objectives that push individuals beyond their current abilities without causing excessive strain, mirroring Vygotsky's concept of the Zone of Proximal Development (ZPD) in cognitive learning (Fasso & Knight, 2020; Vygotsky, 1978). Focusing on these objectives, enables makerspaces offer a dynamic space where students are encouraged to push the boundaries of their current capabilities and explore new areas of interest. Makerspaces contribute to positively shaping students' learner identity by affording a distinct learning setting where students can achieve success, altering their perception of themselves as learners to feel effective and skilled in their creative endeavors (Nadelson, 2021). A holistic constructivist, ZOPID, and ZPD approach helps to ensure students not only develop skills, but they also build confidence and a strong sense of self, which are essential for lifelong learning.

Making STEAM: Spark Plugs of Potential Energy

Makerspaces provide an ideal environment for the practical application of STEAM education principles, fostering an interdisciplinary and transdisciplinary approach that integrates hands-on learning of STEAM concepts. A STEAM-Maker approach not only promotes creativity and innovation but also encourages the development of 21st-century skills through collaborative and experiential activities (Bowler & Champagne, 2016). Liu & Wu (2022) have further explored this connection by identifying strategies for helping educators and researchers develop STEAM activities that transcend disciplinary boundaries and stimulate learners' emotional experiences, thereby increasing interest in STEM content. Liu & Wu’s research underscores the importance of integrating arts and aesthetic elements into STEAM education, aligning closely with makerspace environments where such integrations with technology and computer science can enhance contextual understanding and creativity in maker-centered learning initiatives. By infusing makerspace projects with diverse art elements, educators can stimulate creativity, and inspire students to construct and make from STEM to STEAM. A STEAM-Maker integration enhances the design process within makerspaces, encourages innovation, and enables students to explore socio-cultural contexts while participating in collaborative, hands-on activities (Kim, 2021; Liu & Wu, 2022). Makerspaces serve as dynamic platforms where the fusion of making and STEAM not only enriches learning but also nurtures the inventive spirit necessary for tackling complex real-world problems.

Makerspaces are connected to STEAM education principles by offering an interdisciplinary learning setting that combines science, technology, engineering, arts, and mathematics (Bertrand & Namukasa, 2020; Kim, 2021). Transformative STEAM education employs transdisciplinary skills in conjunction with disciplinary knowledge for cultivating critical and creative thinking, ethical comprehension, and intercultural sensitivity to equip students for engaged citizenship in a dynamic global environment (Taylor & Taylor, 2019). Makerspaces facilitate the application of STEAM education principles through hands-on learning experiences and interdisciplinary collaboration, while also nurturing innovation and creativity by enabling design, prototyping, and testing activities in alignment with the creative aspects of STEAM education.

Makerspaces and principles of STEAM education provide a rich, interdisciplinary and transdisciplinary atmosphere that fosters a holistic educational experience for learners (Bertrand & Namukasa, 2020). Interconnected learning environments support transformative STEAM education, which emphasizes transdisciplinary skills alongside disciplinary knowledge. A unified STEAM and makers philosophical approach cultivates competencies such as critical and creative thinking, ethical comprehension, and intercultural sensitivity, all of which are essential for preparing students for engaged citizenship in a dynamic global environment (Taylor & Taylor, 2019). Makerspaces facilitate the practical application of STEAM education principles through hands-on learning experiences and interdisciplinary collaboration. Makerspaces further enhance the educational process by nurturing innovation and creativity, enabling design, prototyping, and testing activities that align with the creative aspects of STEAM education. The dynamic combination of these philosophical constructs ensure that learners are not only recipients of knowledge but also active creators, equipped to explore and solve complex problems in new and innovative ways through STEAM learning (Figure 2).

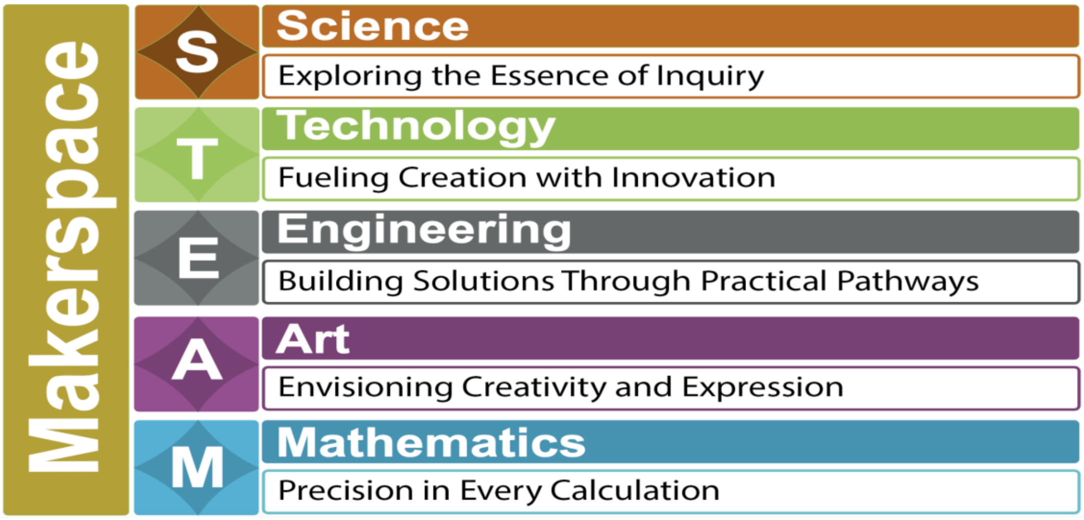

Figure 2. The Philosophical Constructs of STEAM and Makers

The 5 C's of STEAM-Making

Positionality: The Techno-Art of Locatrix

The research coined and employs the techno-art term "Locatrix" for positionality, as Locatrix is an apt term for makers research that evokes the concept of locating or positioning oneself within various frameworks or contexts, blending both technological precision and artistic exploration of identity and perspective. The researcher is an educator with approximately three decades of educational experience, including teaching high school biology, chemistry, and physics and serving as an instructional coach for the sciences, while later leading as a principal and school district superintendent in both urban and suburban learning environments. In addition, the researcher is a professor of higher education for educational leadership.

During his tenure as a PK-12 educational leader, the researcher established a variety of innovative STEAM curricular and facilities programmatic offerings in a large high school and middle school in an urban area, including aquaponics, sound engineering, robotics, and makerspace. These pioneering learning environments were student-centric and STEAM-based. In addition, the research utilizes a concept he developed and termed *Dignam's 5 C's of STEAM Education*, which he still employs with his university students (Dignam, 2021). The first C is *Constructing* and signified by the techno-art term "Architectonix," which denotes the educator as architect, as both frameworks tailor to their fields—architects plan physical buildings for optimal space utilization, and educators create and shepherd educational programs for effective learning outcomes.

The next set of C's are a dyad, *Collaborating* and *Communicating*. *Collaborating* is signified by the techno-art term "Synergetix" while *Communicating* is signified by the techno-art term "Harmonix." The techno-art term "Synergetix" suggests collaboration by highlighting the integration of various technologies and artistic disciplines to produce innovative, synergistic results, while "Harmonix" denotes communication by representing the harmonious blending of technology and art to convey ideas and emotions effectively. *Collaborating* and *Communicating* are interlinked and symbiotic.

Lastly, the final set of C's also form a dyad, *Critical Thinking* and *Creative Thinking*. *Critical Thinking* is signified by the techno-art term "Cognotix" while *Creative Thinking* is signified by the techno-art term "Synthetix." The techno-art term "Cognotix" represents critical thinking by highlighting the integration of technology and art to stimulate and develop analytical and reflective thinking, while "Synthetix" embodies creative thinking by highlighting the blending of various technological and artistic elements to produce unique and innovative results. *Critical Thinking* and *Creative Thinking* are interdependent and entwined. The researcher's 5 C's are customized to the type of STEAM learning taking place, in this case, makerspace (see Figure 3).

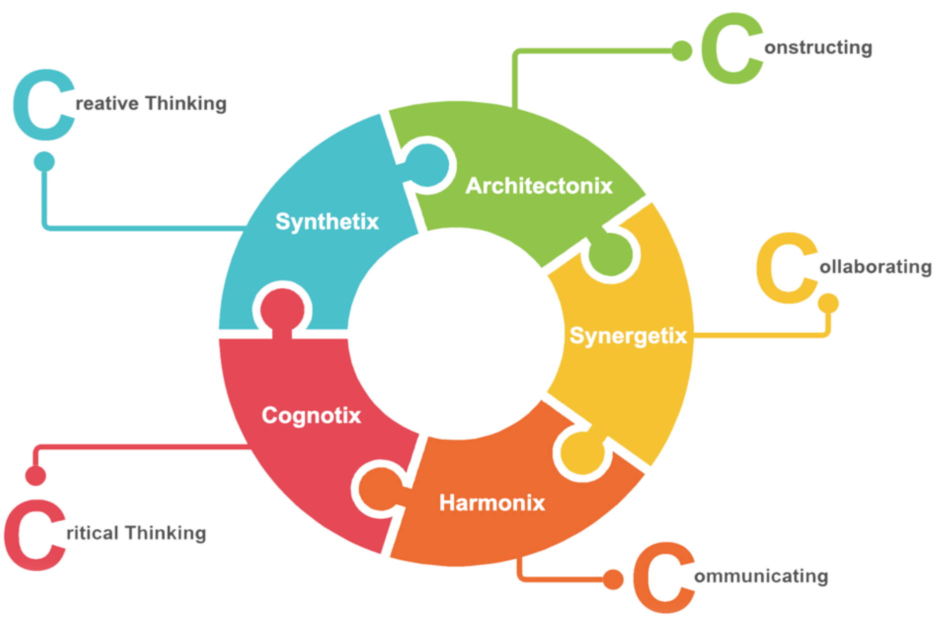

Figure 3. Dignam's 5 C's of STEAM Education (Figure reproduced from Dignam 2021 with permission)

Constructing: The Techno-Art of Architectonix

Makerspace learning environments utilize constructivist principles that prioritize student-centered learning by employing constructivist principles for emphasizing active engagement, hands-on experiences, and creating solutions to problems (Efgivia et al., 2021). Educational architects build programs for the space between teaching and learning and student outcomes. By focusing on the active role of students in constructing knowledge, makerspaces promote the development of deeper understanding, problem-solving skills, and meaningful learning experiences. A makers-constructivist approach enhances student engagement, motivation, and fosters a sense of ownership and empowerment in the learning process.

Makerspaces provide an ideal platform for applying constructivist principles in education for prioritizing active involvement over passive engagement and reception in the learning process. Constructivism in makerspace classrooms promotes active learning, fosters collaboration among students, and supports critical thinking through hands-on experiences and real-world projects (Shah, 2019). A constructivist educational approach is further enhanced by the principles of experiential learning, which are key in makerspace environments. Constructivism and experiential learning in makerspace environments foster collaborative, hands-on learning experiences where students actively engage in creating, experimenting, and problem-solving to deepen their understanding of concepts through practical application (Braga & Guttmann, 2019).

A constructivist-experiential methodological approach not only facilitates the acquisition of knowledge but also encourages students to apply their learning in diverse contexts, thereby enhancing their overall educational experience. Experiential learning in a makers constructivist learning environment encourages a transition from structured design to intuitive play and problem-solving, enabling creative expression and exploration of abstract ideas (Horst et al., 2020). A constructivist-experiential paradigm shift enables learners to develop a deeper connection with concepts and content, fostering both cognitive and emotional engagement with educational subject matter.

The Special Role of Social Discourse

Social constructivism is particularly important in the architectural, educational dynamics of makerspaces, promoting an interactive learning atmosphere where students actively engage in building individual and collective, group knowledge. In a study conducted by Mørch et al. (2023), the researchers identified that social discourse in makerspace learning facilitates collaborative knowledge construction through discussions about problem-solving and the integration of everyday and scientific concepts, enhancing students' practical understanding. Furthering this notion, social discourse within makerspace learning is essential for guiding students in their collaborative knowledge practices and shapes how students approach information, interpret ideas, and broadens comprehension (Kajamaa & Kumpulainen, 2020). Additionally, constructivist discourse emphasizes the significance of communication and collaboration in bridging theoretical knowledge with hands-on experiences within the makerspace environment (Mørch et al., 2023).

Saleem et al. (2021) noted that social constructivism nurtures student motivation in makerspace environments by promoting active engagement and teamwork through practical tasks, collaborative efforts, and idea exchange. Similarly, employing constructivism motivates students in makerspace environments by promoting hands-on projects, real-world problem-solving, collaboration, and autonomy, fostering intrinsic motivation (Cetin-Dindar, 2015). A social discourse approach facilitates a holistic, deep and meaningful learning experience where students not only acquire knowledge but also develop essential life skills.

Collaborating: The Techno-Art of Synergetix

Makerspaces can be viewed as hubs for interactive, experiential learning, where the synergy of collaboration is a key component in enhancing educational outcomes. Students are empowered in makerspaces through collaboration, which accelerates learning, aids in problem-solving, and encourages a supportive community for knowledge exchange and skill enhancement (Oswald & Zhao, 2021). Furthermore, collaboration in makerspace learning environments promotes teamwork, facilitating idea exchange, and encouraging collective problem-solving among students (Rios et al., 2020). The synergistic dynamic of working together not only builds technical skills but also interpersonal abilities. Collaborative problem-solving in makerspaces fosters communication skills development by promoting effective articulation of ideas and encouraging constructive dialogue among students (Herro et al., 2021). These interactions enrich a makers environment, making it more engaging and welcoming to diverse thoughts for constructing meaning and competencies.

Collaborating in makerspaces supports student learning by creating a community environment where learners can engage with peers, feel connected to a larger purpose, and enhance problem-solving abilities (Culpepper & Gauntlett, 2020). A collaborative, community-driven approach is particularly effective in fostering holistic thinking and innovative product development, as collaboration in designing makerspace curricula utilizes teamwork and leverages the diverse backgrounds of peers (Berg et al., 2020). Moreover, collaboration in makerspaces extends beyond just technical skills; it facilitates the development of social skills by encouraging teamwork, communication, and empathetic development among students (Harmer et al., 2021; Vongkulluksn et al., 2018). A multi-faceted, collaborative approach not only enhances learning but also prepares students to effectively communicate in diverse teams, which is a life skill students can employ in future careers.

Communicating: The Techno-Art of Harmonix

In makerspace learning environments, communication is the cornerstone that supports all collaborative endeavors, ensuring an atmosphere for idea-sharing subsists and that communicative teamwork occurs in harmony. Communication skills are vital in makerspace learning environments for effective idea sharing and collaboration (Rios et al., 2020). When students are able to communicate effectively in harmonious settings, they exchange and acquire knowledge, receive peer support, and engage in a collaborative community, enhancing their ability to work together successfully on projects (Berg et al., 2020; Oswald & Zhao, 2021).

Project-based tasks that require students to reflect on their makers design experiences can further enhance their communication effectiveness within interdisciplinary teams (Berg et al., 2020). Furthermore, communication in makerspaces supports the development of students' social skills by promoting effective interaction, collaboration, and relationship-building (Harmer et al., 2021). The ability to articulate and discuss ideas clearly in makerspaces helps students develop social skills, fostering collaboration and teamwork when working on design creation and fabrication (Vongkulluksn et al., 2018). The harmony communications enhance the overall learning experience and contribute to the development of well-rounded individuals capable of navigating complex interpersonal dynamics.

Critical Thinking: The Techno-Art of Cognotix

Makerspaces are dynamic environments that promote not only technical skills but also forge essential cognitive abilities through critical thinking and collaborative learning for facilitating creative thinking. Enabling individual students and student groups to make decisions regarding the learning fosters a culture of creativity, experimentation, and critical thinking, enabling learners to develop skills and knowledge in a supportive and technology-rich environment (Koondhar et al., 2021). Decision-making processes are integral to the growth of critical thinking as students assess options, make choices, and reflect on their outcomes.

In prosocial cooperative makers learning environments, students work together to explore new ideas, seek out resources, and coordinate joint efforts, fostering a sense of community and mutual learning (Leskinen et al., 2021). Collaboration not only enhances interpersonal skills but also deepens cognitive processing as learners discuss and debate various approaches to problems. Additionally, prosocial makerspace learning environments enable students to collaborate on exploring original ideas, addressing challenges, and co-constructing knowledge, thereby improving their problem-solving capabilities, critical thinking skills, and overall educational achievements for group dynamics (Li et al., 2022). Collaborative, communicative makers environments are key to developing a robust cognitive framework, equipping learners with the ability to navigate and innovate within any learning context.STEAM programs integrated with reflection and collaboration for cognition form the basis for advancing students' critical thinking and learning abilities (Bassachs et al., 2020). Papert, 1990, as cited in Wong and Partridge, 2016, assert Papert's theory of constructionism in makerspace is an effective method for knowledge acquisition for students through hands-on creation and problem-based learning. Offering makerspace students opportunities to develop personal projects leads to critical-thinking and creative-thinking for experimentation of ideas. The process of constructionism occurs through deep learning as students investigate phenomena and experiment with concepts they choose for personalized, self-directed endeavors. Affording students choice for personalizing projects and experimentation aligns with constructionism's focus on hands-on creation and problem-based learning, leading to the development of knowledge (Wong & Partridge, 2016). Critical thinking within STEAM-based makerspaces promotes creativity by stimulating student analysis, evaluation, and problem-solving, essential for fostering innovative thinking (Bassachs et al., 2020).

Makerspaces provide a unique cognitive platform for students to actively engage in diverse learning modalities, blending constructing with collaborating, communicating, critically thinking and creatively thinking. Makerspace students are involved in self-directed learning, collaborative learning, and knowledge exchange for the co-creation of comprehension, fostering dynamic interactions that promote experimentation, education, research, and production, all contributing to the development of lifelong learning competencies (Dos Santos & Benneworth, 2019). Makers holistic approach not only nurtures a range of competencies but particularly emphasizes cognition through the development of critical and creative thinking. When students and student groups engage in personal makers projects, they are provided experimentation of ideas and opportunities to engage in alternative learning experiences (Wong & Partridge, 2016). Makers activities encourage students to think critically about their work, reflect on feedback, and creatively solve problems, thereby enhancing both their cognitive and creative abilities in a supportive environment.

Creative Thinking: The Techno-Art of Synthetix

Makerspaces serve as catalysts for synthesizing personalized learning, allowing students to tailor their educational experiences to their individual interests through STEAM-based design and construction of artifacts. Makerspaces inspire personalized learning by promoting creative problem-solving, soft skill development, and STEAM knowledge enhancement (Nagle & Bishop, 2021). Makers environments also provide a variety of tools and resources for introspective thinking, analytics, reflection, and hands-on experiential constructivist problem-solving. Makerspaces catalyze personalized learning by empowering students to explore innovative ideas, collaborate, and tackle real-world challenges through hands-on projects (Koondhar et al., 2021).

A makerspace learning environment nurtures creativity in STEAM education by synthesizing a collaborative setting for students to participate in hands-on experimentation and innovation. The synthesis of STEAM-making and creativity-building provides a dynamic setting that motivates and encourages students to conceptualize and artistically design, promoting a holistic educational experience. Through exploration, design, and creation, makerspaces support the development of critical thinking, problem-solving skills, and creativity for success in STEAM disciplines. Integrating art into STEM to create STEAM curricula synthesizes and enriches makers learning processes. The integration of art in STEM for STEAM encourages students to think creatively, solve problems, and tackle challenges from diverse viewpoints, thereby fostering creativity within STEM educational settings (Borg Preca et al., 2023). Furthermore, critical thinking processes facilitate the synergy of creativity. Critical thinking processes nurture creativity by encouraging students to innovate and think creatively, draw interdisciplinary and transdisciplinary connections, and explore unconventional problem-solving methods (Bassachs et al., 2020). The synthesis of critical thinking and creative thinking provides students with skills to not only construct meaning from complex concepts but to also to innovate and create for solution finding.Makerspaces serve as dynamic learning environments for synthesizing Interdisciplinary Learning, transdisciplinary learning, experiential learning, constructivism, and STEAM philosophy for fostering student innovation and personal development. Makerspaces provide students collaborative, hands-on creation opportunities that support problem-based learning for enhancing students' knowledge for use as a lifelong learning skill (Wong & Partridge, 2016).

Beyond providing practical experience, makerspaces offer students a setting that encourages creativity, innovation, and the exchange of knowledge, facilitating the acquisition of skills essential for lifelong learning (Dos Santos & Benneworth, 2019). The unique qualities of makers environments allow students to practice and develop a multitude of lifelong learning skills. Examples of lifelong learning skills developed in makerspace environments include recognizing the need for continuous learning, acquiring the capacity to engage in lifelong learning, setting learning targets, planning to achieve them, fostering creativity, innovation, knowledge sharing, experimentation, education, research, and production (Dos Santos & Benneworth, 2019). Lifelong solution-oriented skills development empowers students to adapt to evolving technologies and global challenges, making the synthesis of critical thinking for creative thinking invaluable in their lives. In concert, interdisciplinary learning, transdisciplinary learning, experiential learning, constructivism, and Dignam's 5 C's of Learning are components in the gearbox of makerspace for making meaning (Figure 4).

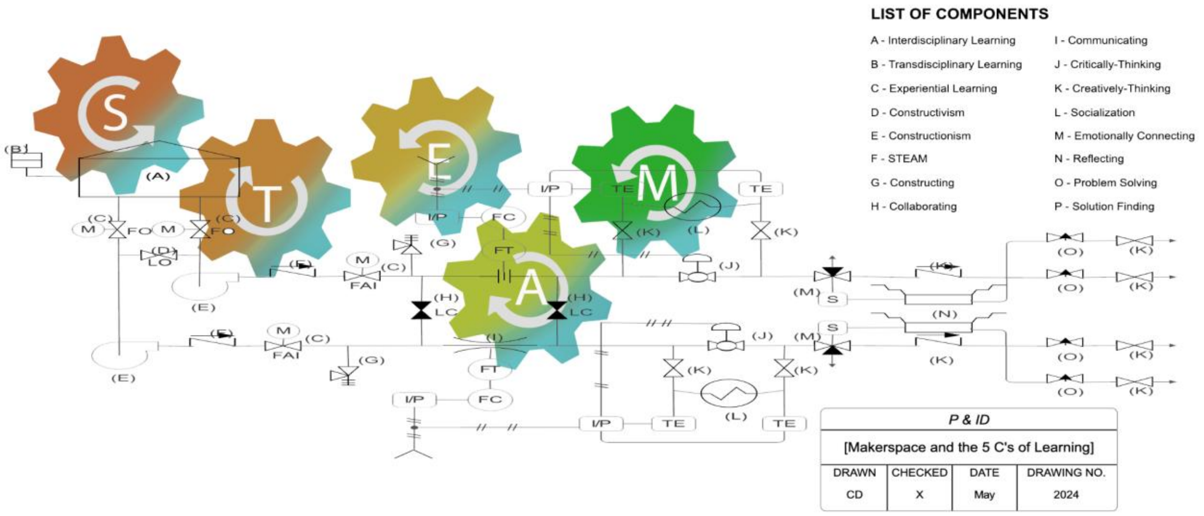

Figure 4. The Components of Makerspace for Making Meaning

Tools and Technologies in Makerspaces: Fueling Combustion

The design of makerspaces needs to consider providing space for students to work in groups, move freely around the room, and provide age-appropriate tools and resources for fostering a culture of creativity and innovation. When designing makerspaces, it is important to afford a diverse range of tools and equipment to meet the needs of a wide variety of users, promoting inclusivity and accessibility in creative endeavors (Vecchione, 2020). The thoughtful arrangement and selection of resources influence how effectively makerspaces serve teachers and students. Student engagement in makerspaces and the resulting outcomes are influenced by the physical location, access, and tool availability, shaping activities, purpose, and communal dynamics within the space (Mersand, 2021).

Considerations must also be made in terms of the creative projects students may choose and a spectrum of makerspace tools, ranging from cardboard and Legos, to tools for woodworking, electronics, 3D printing, laser cutters, CNC (Computer Numerical Control) machines, crafting, and prototyping for use by learners in early childhood centers through university settings. Age and grade-level appropriate tools enable users to engage in a wide range of creative projects and support innovation and experimentation, allowing individuals to bring their ideas to life and explore new possibilities in a collaborative environment (Vecchione, 2020). Additionally, for younger users, Rouse et al. (2020) recommend that makerspaces in elementary schools maintain a variety of high-and low-tech tools and materials available for student use, including items such as yarn, 3D printers, paper, Minecraft, sand, glitter, Legos, computers, Dot and Dash, and Little Bits in mobile containers with storage bins and dry-erase boards. A thoughtful makers-tool-approach ensures that makerspaces are versatile and accessible, providing every student the opportunity to learn and create for sparking interests and imagination.

Educational Design Considerations: The Mechanics of Compression

Early Childhood Education

Makerspaces possess educational value for early childhood learners. Makerspaces provide unique learning opportunities for early childhood learners by nurturing creativity, innovation, exploration, and investigation in supportive environments for cultivating cognition and socialization. Recognizing the importance of introducing young learners to critical educational themes, extending STEM for STEAM experiences to infants, toddlers, and preschool-aged children is vital for establishing a solid knowledge base during the phase of early childhood development. Introducing these concepts early in life can help close educational disparities and offer children of all backgrounds opportunities for academic achievement and long term future career possibilities (Johnston et al., 2022).

An inclusive makers approach ensures that children develop essential skills from a young age. Pre-K students derive advantages from makerspaces through hands-on learning, the cultivation of twenty-first century skills, and the exploration of interdisciplinary links to STEM subjects. Furthermore, makerspaces foster creativity, problem-solving abilities, and collaborative skills essential for early learners. Moreover, makerspaces afford a supportive and innovative environment for young students to experiment, create, and learn (Rouse & Rouse, 2022). A holistic makers approach is instrumental in preparing young minds for a future of continuous learning and adaptation.

Early Childhood Education to Kindergarten

When planning makerspaces tailored for early childhood education, it is important to create environments that not only accommodate the unique developmental needs of young learners but also support exploration, foster creativity, and encourage innovation (Johnston et al., 2022). In pre-K makerspaces, the selection of tools and materials is specifically geared towards engaging young minds in meaningful ways. Tools commonly consist of materials suitable for young children, such as building blocks, art supplies, basic robotics kits, craft materials, and sensory play items (Rouse & Rouse, 2022). Items such as these are carefully chosen to foster creativity, exploration, and hands-on learning in a secure and stimulating setting for early learners.

Additionally, advanced educational tools such as programmable blocks from Resnick's Lifelong Kindergarten lab are incorporated to allow children to build, explore, and program interactive materials for early childhood as well as kindergarten learners. Martin (2015) suggests the integration of technology enhances young children's understanding of engineering and programming concepts, ensuring a comprehensive educational experience that marries traditional play with modern learning techniques.

Primary Education

Makerspaces are conducive settings for effectively blending STEAM disciplines and student emotional engagement during collaborative, communicative design and artifact construction. The integration of computing, engineering, and arts within elementary and high school makerspaces enhances STEAM learning and promotes collaboration via constructivism, motivates learners, and provides emotional support through collaborative group work (Olabe et al., 2020). Makerspaces enhance elementary school student learning by providing hands-on projects that improve skills and foster creativity, nurturing confidence and increasing engineering and design education skills. When students engage in real-world problem-solving, they develop technical knowledge and work collaboratively in a community-based participatory culture, which enhances their learning experience (Taheri et al., 2019).

Secondary Education

Makerspaces in STEAM primary and secondary education should incorporate design in all subjects. Principles of design should also offer self-directed learning opportunities to empower students to take ownership of their education, fostering exploration, experimentation, and innovation in a student-centered environment (Lee et al., 2020). A design consideration, as described by Lee et al. (2020) for secondary education makerspace implementation includes establishing a versatile environment that leaves a lasting impact on students. This includes setting up a space with accessible materials, catering to diverse learning styles, and encouraging students to think creatively to solve challenges presented to them. Additionally, design considerations involve providing adequate support and training for teachers less experienced with Makerspaces to effectively incorporate them into STEAM educational practices (Lee et al., 2020).

Higher Education

Makerspaces in higher education foster collaboration, knowledge exchange, peer learning, and experimentation within a community of practice (CoP) (Pettersen et al., 2020). A community of practice, as described by Peterson et al. (2020), is a group of individuals united by a common interest in a particular field, engaging in collaborative knowledge sharing and mutual learning within a defined community framework. A CoP-focused makers environment encourages learners to discover phenomena with and from their peers, engage in collaborative projects, and experiment with new ideas and technologies, fostering a culture of peer learning and hands-on experimentation. Important design aspects for university makerspaces involve encouraging collaboration, facilitating hands-on learning, promoting experimentation, and establishing a community of practice for knowledge exchange and peer learning (Pettersen et al., 2020).

Art, Engineering, and Computer Science: Releasing the Clutch

Art adds a vital dimension to the makers learning environment by incorporating abstract concepts, fostering creativity, promoting innovation, and eliciting emotional attachment and engagement. Art is an essential element for holistic STEAM-making education (Olabe et al., 2020). As a result of integrating art with engineering and computer science, makerspaces not only enhance aesthetic and functional design abilities but also encourage interdisciplinary student collaboration. Such collaborations are particularly effective in innovating engineering projects that emphasize aesthetic appeal (Park et al., 2018). Blending art, engineering, and computer science in makerspaces supports makers by equipping each learner with a diverse skill set that combines technical expertise with creative design abilities. The unique combination of art, engineering, and computing enables the development of innovative projects that possess both technical functionality and aesthetic appeal, thus broadening the impact and application of makerspace projects (Olabe et al., 2020; Park et al., 2018).

Integrating engineering and computing into makerspaces enables students to participate in practical design tasks, hands-on learning, and utilize advanced tools, promoting innovation and novel perspectives (Galaleldin et al., 2019; Pettersen et al., 2020). Integrating makerspace along with engineering and computing enhances into disciplines such as robotics supports the curricular and the academic experiences of students by affording hands-on, inquiry-driven learning opportunities that foster collaboration, problem-solving skills, and interdisciplinary problem-solving (Cooke et al., 2020; Peltonen, & Wickström, 2014). In addition, engineering and computing embedded in makerspace curricula and enriches education in areas such as robotics by providing students opportunities to engage in hands-on, experiential, constructivist learning, fostering innovation through real-world application of theoretical, technical concepts (Budiyanto et al., 2020; Villanueva et al., 2021). A makers art, engineering, and computing construct enhances makerspace curriculum, promotes key skills such as collaboration and interdisciplinary and transdisciplinary problem-solving, and prepares students for professional technical content. The integration of engineering and computing into makerspaces nurtures a community of practice by affording students with a collaborative learning environment, technical knowledge exchange, and skill enhancement, cultivating a supportive and educational atmosphere (Galaleldin et al., 2019).

Maker Tools and Student Learning: Firing on All Cylinders

Digital and physical tools in makerspace learning environments provide learners of all ages with manipulatives for designing and fabricating student work products. Makers tools, such as 3D printers, touch pads, board games, and controllers, play a crucial role in enhancing the educational experiences of students within maker education. According to Hynes & Hynes (2018), makers tools support experiential, hands-on, project-based learning that promotes creativity, critical thinking, and collaborative teamwork. Additionally, as detailed by Schön et al. (2014), the Maker Movement utilizes these digital tools and fabrication spaces to emphasize creative education that is grounded in hands-on learning and problem-solving. Age-appropriate tools are resources that allow learners of various ages to engage in practical, real-world tasks that not only foster creativity and technical proficiency but also enhance critical thinking skills. Culpepper & Gauntlett (2020) highlight in makerspaces, tools are meant to serve as enablers, not the focal point, with the primary goal of fostering a creative mindset among students. The overarching objective in utilizing digital and physical tools is to promote a culture of experimentation, collaboration, and tool utilization in a supportive learning environment, thereby encouraging students to explore ideas and develop innovative solutions. A table with examples of makerspace tools and manipulations at various education levels is provided below (Table 1).

Table 1. Makerspace Tools and Manipulatives Exemplars

Education Level	Examples of Makerspace Tools and Manipulative
Early Childhood Education	Large building blocks (LEGO Duplo), Playdough or clay, Crayons and markers, Simple puzzles, Finger paints/art supplies, Sensory play items
Kindergarten	Regular-sized LEGO blocks, Programmable blocks from Resick's Lifelong Kindergarten lab, Introductory robotics kits (Bee-Bots), Watercolor paints, Simple woodworking tools
Primary Education	More advanced LEGO kits, Electronics kits (e.g., Little Bits), Computers, Dot and Dash, Scratch or other beginner coding tools, 3D printers, Minecraft, Yarn, Paper, Sand, Glitter, Mobile containers, Dry-erase boards
Secondary Education	3D printers, CNC machines, Arduino or Raspberry Pi kits, Advanced robotics kits, Laser cutters, Hand and power tools, CAD software
Higher Education	Professional-grade 3D printers, CNC machines, Advanced electronics and circuitry kits, High-end laser and plasma cutters, Sophisticated robotics and AI projects, VR development tools

The Maker Movement and Future Kinetix: Machines of Motion

Makerspaces afford hands-on learning opportunities that boost creativity among students of all ages. Hughes et al. (2016) emphasize the need for educators to receive adequate training and professional development to effectively integrate makerspaces into educational settings. The integration of teacher training is vital for ensuring not only student success, but the continued evolution of the Maker Movement. Shively et al. (2021) notes continued Maker Movement advancement necessitates teachers embrace significant changes, including adopting a maker mindset and adapting their teaching methods to foster the development of 21st century skills. In addition, educational leaders must provide ongoing support and professional growth opportunities for teachers to develop and maintain skills to support students constructing, collaborating, communicating, critically thinking, and creatively thinking. According to Han et al. (2017) and Shively et al. (2021), creating a supportive culture that encourages collaboration and innovation within makerspaces is essential. A unified professional growth mindset among educators and educational leaders ensures makerspaces not only succeed in preparing students to thrive in a continuously evolving and competitive world, but teachers also continue evolving and refining creative and innovative pedagogical skills (Bloomquist, & Georges, 2022; Oliver, 2016).

Makerspaces equip students for the future by fostering critical thinking, collaboration, and creativity through hands-on learning experiences. Makerspaces impact learners' psychological future needs by fostering autonomy, competence, and relatedness through hands-on activities, enhancing intrinsic motivation and preparing students for future challenges (Han et al., 2017). Enhancing autonomy, competence, and relatedness through makerspaces facilitates students' continued and future critical thinking, creative thinking, problem-solving abilities, innovation, and social skills development for learners to employ as life skills.

Establishing a supportive learning community that fosters collaboration, innovative ideas, and the value of experiential, student-centered learning is key to effectively integrating makers philosophy into curriculum design. Makers' philosophy and curricular design also includes contextualizing STEAM concepts in student-led inquiry, establishing interdisciplinary and transdisciplinary learning norms, and encouraging intellectual risk-taking and resilience to failure (Jalal & Anis, 2020). Integrating maker's philosophy into curriculum design benefits students by offering a holistic, interdisciplinary, and transdisciplinary learning approach that extends beyond the classroom. A unified STEAM approach fosters practical application of knowledge in real-world settings, enhances student engagement, and deepens understanding of curricular content (Becker & Jacobsen, 2020).

Conclusion

Idle Turbochargers

Makerspaces embody a transformative educational approach, emphasizing experiential and constructivist learning for stimulating curiosity and creativity in students. Affording engaging hands-on activities for students that mirror real-world challenges develops a deep makers understanding of concepts through the act of creating. Making and constructing through hands-on experiences exemplifies constructivism by providing learners with opportunities to engage in social interactions for both knowledge sharing and cognition. Whether in early childhood settings or in higher education, makerspaces facilitate myriad dynamic approaches to learning by enabling students to design, prototype, construct, and reflect, thereby embedding problem-solving skills that are essential for lifelong learning.

Makerspace environments are inherently interdisciplinary, bringing together elements of science, technology, engineering, arts, and mathematics (STEAM) for fostering a holistic educational experience. The integration of both interdisciplinary and transdisciplinary learning encourages, enriches, and facilitates student learning and creative processes. Situating STEAM within the philosophical framework of makerspaces empowers students to develop and leverage skill sets and perspectives to innovate and think critically about complex problems. Interdisciplinary and transdisciplinary STEAM-making provides students with a learning environment that supports the cognitive and social, emotional needs of all learners.

Makerspaces are centers for cultivating Dignam’s 5 C's of STEAM Education: constructing, collaborating, communicating, critically thinking, and creatively thinking. Makerspaces provide learners with the tools and opportunities to build and share ideas, engage in teamwork, and navigate complex problem-solving tasks. The collaborative aspect of makerspaces is particularly significant, as it fosters communication and social skills among learners for working together and sharing knowledge to achieve common goals. A STEAM-making cooperative learning environment enhances motivation and enables students to learn from one another, thereby enriching student learning experiences. In addition, the prosocial aspects of makerspaces assist in developing a supportive community where personalized and group learning is nurtured and flourishes.

Finally, makerspaces epitomize the evolution of educational practices, reflecting a shift towards more interactive, student-centered learning environments that prepare learners for the complexities of a global society. With a range of tools from simple craft materials to advanced digital fabrication technologies, makerspaces are equipped to support a wide spectrum of creative learning, making a degree of instruments and gadgets accessible to learners at all levels of education. Through active participation, experimentation, and the integration of multiple disciplines, makerspaces not only enhance educational outcomes, but also inspire lifelong learners, capable of tackling future challenges with confidence and creativity. Lastly, makerspaces provide opportunities for students of all ages to engage in knowledge-sharing as well as knowledge acquisition, instilling a desire for learners to search for solutions about the world around them.

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