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BOARD # 209: More Than Just a Toy: Uncovering the Complexities and Untapped Potential of Robotics in K-12 STEM Education (Work in Progress)

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Introduction:

Robotics has garnered tremendous attention in this decade, given the rise of Industry 4.0 and the recent advancements in computing prowess. Robots transitioned from dull, dirty, and dangerous roles in heavy industries to more dear roles like assisting doctors in delicate surgeries. Thus coining the new 4Ds (Dull, Dirty, Dangerous, and Dear) of Robotics [1].

Robotics presents a versatile educational launchpad for STEM education because of its interdisciplinary nature. Starting with the LEGO Mindstorms launched in 1993 [2] , Robotics was quickly absorbed into STEM education and soon became a member of the classrooms and homes by the early 2000s. Robotics competitions like FIRST and FLL and other informal education avenues also helped kick off engagements in robotics for the youth [3], [4]. Interestingly, all these interventions focused on the educators' intentions of using robotics as a tool to teach and nurture students' interest in STEM, however, the students remained silent about expressing what they'd like to pursue Robotics for or apply robotics to.

The idea of giving students agency—encouraging them to explore robotics through play and integrate robots into their hobby projects—drives our work to shift the conversation from 'Robots in Education' to 'Robotics Education' in the K-12 space. This work-in-progress research paper examines the Robotics Education landscape for innovative approaches to introducing robotics in K-12 education. Our goal is to design and develop interventions inspired by this study in the future. Here, we share some preliminary insights from our review of 20 research articles, investigating two key research questions:

1. Why are K-12 educators using robotics?
2. How are K-12 educators using robotics?

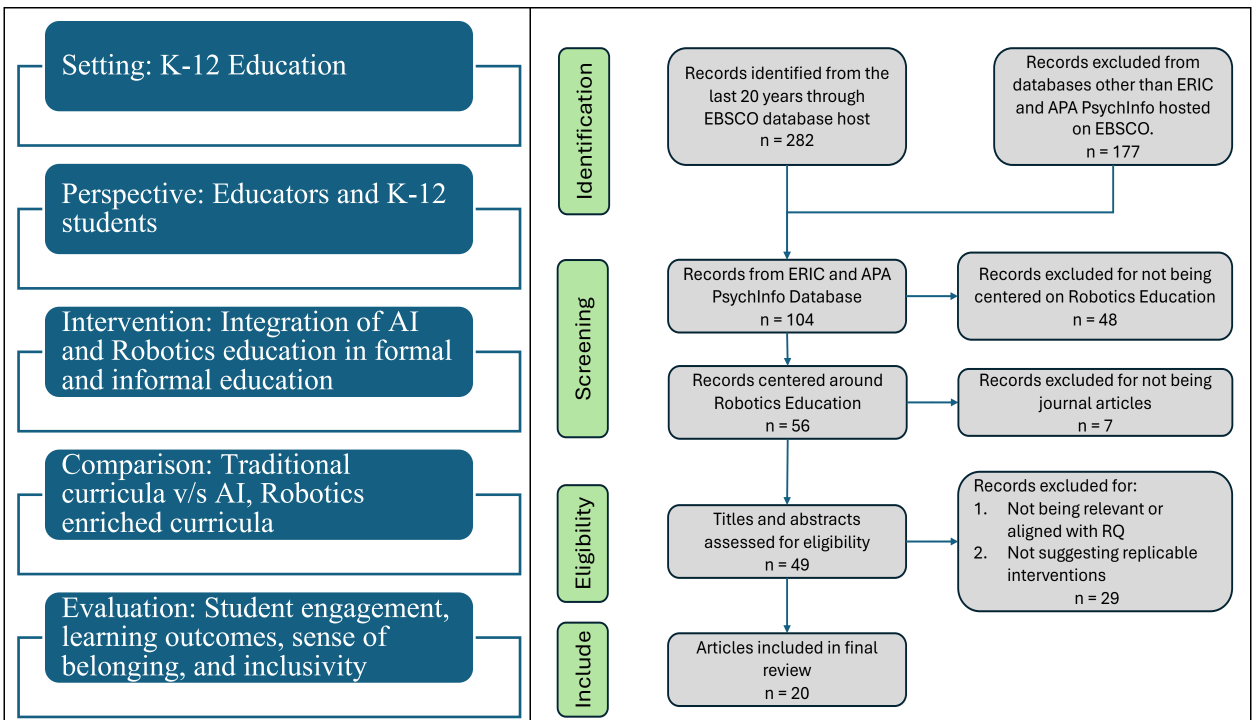
We discuss four broad themes/research topics in the field of robotics education and conclude with a set of innovative interventions from the literature that could be inspiring examples for advancing robotics education.

Method

We used the SPICE (Setting, Perspective, Intervention, Comparison, and Evaluation) framework [5] to identify and define a research space and the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [6] to systematically scope the literature to study the research question and arrive at a set of 20 research papers. Figure 1 illustrates the scoping process described in this section.

To define the scoping parameters for the SPICE framework, we first focused the search on K-12 age groups across both formal and informal education spaces. Second, we scrutinized the articles from the perspective of an educator and a K-12 student eager to excel at robotics. Third, we filtered research on interventions that integrated robots into the classroom or got students physically engaged with robotics. Last, we identified studies that compared traditional curricula and robotics-enriched curricula, and evaluated the factors influencing student engagement, learning outcomes, sense of belonging, and inclusivity in the program. At the end of this process, we arrived at a collection of 282 articles on the EBSCO Information Service database.

We used the PRISMA framework to identify, screen and then include 20 articles for this study. From the 282 articles identified on EBSCOhost, we retain 104 entries which are from authoritative and trusted databases like the Education Resources Information Center (ERIC) and the American Psychological Association's APA PsychInfo. We then screened the 104 entries for not merely referring to robotics but instead being centered around the subject of robotics education, leaving us with 56 entries. We retained 49 of these entries by eliminating all non-academic journal entries. For the final round of filtering, we followed three criteria to include 20 articles in the final study. The three criteria were: first, examining the relevance of the abstract to our research question; second, evaluating its alignment with the potential outcomes of our research question; and finally, assessing the usability and replicability of the suggested interventions for designing informal education programs.



SPICE framework parameters (Figure 1a) | PRISMA report of systematic reviews (Figure 1b)

Figure 1 SPICE and PRISMA frameworks for literature scoping

Findings:

RQ 1: Why are K-12 educators using robotics?

Robotics offers three advantages, which make it a top priority for K-12 educators - a broad and adaptable portfolio to achieve STEM competencies, potential to enhance educational experiences, and assist in broadening participation in STEM [3], [7], [8], [9], [10]. Hence, K-12 educators find robotics to be a promising choice to integrate into STEM education. In this section we dive into each of these three areas in more detail.

Achieve STEM competencies and provide career awareness: Integration of robotics invites critical thinking, communication, collaboration, and creativity into the learning environment [4], [10]. These skills, when paired with problem-solving, help build connections between academic and social knowledge [11]. Thus, robotics creates a platform to learn 21st-century skills and paired with models like project-based learning, robotics helps train learners to thrive in the current scientifically and technologically progressing times. It serves as a tool to introduce design thinking and system thinking skills to students, thus preparing them for higher education and careers in STEM [12].

Enhance the educational experience: Robotics helps to grow out of siloed thinking into an interdisciplinary mindset [13]. Robotics has become an interdisciplinary tool for STEM education, starting with LEGO Mindstorms in 1993 [2]. These robots became classroom icons, supported by constructionism [14] and constructivism [15], [16], [17] theories. Technical and vocational schools with Project-based curricula became early adopters of robotics because of the versatile learning opportunities it presents[18], [19], [20]. Robotics encourages students to be a jack of multiple trades, catalyzing the process of exploring their interests and fit in STEM. Thus, creating opportunities for diversifying and enriching their overall learning experiences.

Versatile pedagogical tool to broaden STEM participation: Robotics creates space to celebrate talents across art, craft, music, literature, and entertainment in educational settings [21]. Informal education avenues help garner student interest and engagement in STEM with innovative and socially engaging activities [22]. Initiatives like the 4H club use robotics to tie in technical and social aspects, introducing students to real-world socio-technical problems. These problems are sometimes simplified to allow a wide range of age groups to interact and learn from each other [10]. Competitions like FIRST and FLL inspire students to engage with robotics, which foster students' skills in writing, reading, collaboration, and communication [23], [24], [25]. Thus, accommodating a wide spectrum of learner interests and needs, which then translates into broader participation and likelihood of higher retention in STEM.

RQ 2: How are K-12 educators using robotics and what are its implications?

Robotics in STEM education has been primarily implemented in two ways. First, as a toy to either teach STEM subjects, and second, as a fire starter or an interest-building educational block to motivate students to pursue STEM education. This section provides deeper insights into how robotics delivers on these educational promises.

Robots as toys to motivate and situate interest in STEM: Educators are using robotics in the classroom as a motivational factor to introduce and teach STEM content [26]. Robotics is integrated into math and science (physics) curricula to explain concepts like force and friction and serves as an introduction tool for programming and coding. Robots are used to teach computational neuroscience where students get to run and refine their neuron models to get a desired behavior from a robot [27]. Pedagogical approaches like storytelling and storyboarding pair well with robotics and enable teachers and students to explore organic and intuitive aspects of being human, connecting these to STEM subjects. Thus broadening contextual connections and fostering expression, engagement, and retained interest [10], [11], [21].

In the informal education space, robotics is often paired with project-based and hands-on learning frameworks to get students engaged with STEM content. For example, the FLL and FIRST robotic competitions challenge participants to accomplish robotic tasks that are not typically encountered in traditional classroom settings [7]. Additionally, these competitions require students to present their design stories, promoting interdisciplinary project workflows and engineering thinking[28]. This competitive spirit incentivizes skill-learning beyond the classroom and students choose to invest their time after school to work towards learning not only design, computational and fabrication skills but also supplementary technologies like video and audio processing, enhancing students' ability to communicate their work [10]. The interdisciplinary nature of robotics projects emphasizes hands-on and minds-on learning and encourages students to engage in engineering design processes and problem-solving, helping them think like engineers [7]. Such initiatives invite industry leaders and mentors to coach students who are willing to learn and grow from these experiences and thus sparking the conversations about building and nurturing this budding interest in robotics into potential career paths. Teamwork, engineering design, documentation, testing and meticulousness are just some of the 21st-century skills that students get to informally learn through these engagements. And improve attitude towards STEM [29].

Robotics as fire starters and foster interest in STEM: Educators use robotics to foster curiosity in STEM and empower students to independently pursue their interests and find their STEM identity [3], [30]. Competitions and hackathons create forgiving environments to foster grit and resilience, which are essential for long-term retention in the STEM fields [10]. The embodied play and tactile engagement from building and construction help develop mental representations of abstract ideas and aid in students seeing the connections and disconnections between theory and practice [11], [21]. Mentoring, volunteering, and internships related to robotics competitions promote youth engagement and development. S. Ludi and T. Reichlmayr [31], K. Fisher et al. [32] note that robotic competitions also support students with disabilities to develop teamwork, collaboration, and social skills to contribute to the project. Thus, robotics facilitates in creating a symbiotic ecosystem involving industry, academia, governments, and students, fostering collaboration and mutual growth [4], [9].

Discussion

Based on the reviewed literature, we notice that robotics education spans four broad categories – Robotics Culture, Resources, Activities/Opportunities, and Impact Assessment.

Robotics Culture: This category studies the cultural change that robotics programs like FLL and FIRST are inculcating in students. For example, these programs portray a spirit of ‘coopertition’, which means that teams cooperate with each other, even as they compete. These cultural changes also bring in fundamental changes like shifting from a deficit to a growth mindset and building an open and inclusive learning environment to broaden and retain participation [3], [7], [8], [9], [31], [32], [33].

Resources: Studies in this category discuss the influence of 3Ms (Man (Human), Machine, and Material) resources on robotics education and highlight the need and means to develop these resources for improving robotics education [21], [32], [34].

Activities/Opportunities: This category studies the curricular and instructional design aspects of robotics to personalize education and broaden and retain STEM participation. The research in this space focuses on designing activities, opportunities, and pathways into robotics. This category ensures that cutting-edge robotics research from academia and industry is disseminated through educational platforms [7], [8], [10], [12], [13], [21], [26], [28], [35].

Impact Assessment: This category assesses the impact of robotics on student learning across genders, demographics, learning outcomes, and disabilities [34], [35], [36], [37], [38].

Conclusion:

Robotics helps nurture and create space for creative expression and a healthy educational environment. The following examples highlight some innovative and intentional approaches to presenting robotics to students.

F. Bravo et al. [21] developed drama activities involving robotics, encouraging students to use robots to perform as characters in a drama and think about incorporating emotions and behavioral expression in robots. Students developed intuitive programming strategies to express emotions and behaviors through robots. Wellesley College, an all-girls institution skipped the competition and instead had an exhibition at the end of their robotics course [33]. Switching the end product to not being about competing, lowered the stakes of public repercussions of 'failure' – a leading cause for lower female participation and leadership in STEM and robotics. This example, framed robotics to be more human-centered by switching from competitive learning to a cooperative learning experience. I. Verner et al. [36] suggested being accommodative toward different engagement structures (engagement styles indicating student needs and corresponding behaviors) to create a safe and nurturing space to personalize the educational experience. By varying teaching and thereby being flexible with structures of engagement and representations, students from a wider spectrum of interests, achievements, and experience levels feel comfortable sharing a robotics class. Thus, elevating a sense of belongingness and equal opportunities. F. Sullivan et al. [35] share the experiences of Kelly and Kristina, who are peripheral learners (learners who are not leading a task and whose ideas are not taken up) from two different robotics groups, and how their approach and the team environment influenced their experience with robotics. Sharing such insights from robotics education research could help new students to appreciate the innovative program designs and this information could set a good precedent for students to engage with robotics. Students are more likely to be accommodative, exhibit conscious engagement, and succeed in having a good experience.

These studies made us realize that robots are more than toys to teach science or retain interest, and despite the integration of robotics into STEM education, the potential of robotics seems to be underutilized. Most programs focus on teleoperated robots, thereby limiting students' exposure to purely mobile robotics. Thus, leaving a large space in robotics, like medical robots, collaborative robots, musical robots, etc., hidden and unexplored. In our future projects, we aim to explore this space of robotics to broaden participation and make robotics accessible.

References:

[1] B. Marr, “The 4 Ds Of Robotization: Dull, Dirty, Dangerous And Dear.” Accessed: Jan. 14, 2025. [Online]. Available: https://www.forbes.com/sites/bernardmarr/2017/10/16/the-4-ds-of-robotization-dull-dirty-dangerous-and-dear/

[2] S. Papert, *The Children's Machine: Rethinking School in the Age of the Computer*. BasicBooks, 10 East 53rd St, 1993.

[3] M. Graffin, R. Sheffield, and R. Koul, “‘More than Robots’: Reviewing the Impact of the FIRST® LEGO® League Challenge Robotics Competition on School Students' STEM Attitudes, Learning, and Twenty-First Century Skill Development,” *J. STEM Educ. Res.*, vol. 5, no. 3, pp. 322–343, Dec. 2022, doi: 10.1007/s41979-022-00078-2.

[4] A. Sullivan and M. U. Bers, “Robotics in the early childhood classroom: learning outcomes from an 8-week robotics curriculum in pre-kindergarten through second grade,” *Int. J. Technol. Des. Educ.*, vol. 26, no. 1, pp. 3–20, Feb. 2016, doi: 10.1007/s10798-015-9304-5.

[5] A. Booth, “Clear and present questions: formulating questions for evidence based practice,” *Libr. Hi Tech*, vol. 24, no. 3, pp. 355–368, Jan. 2006, doi: 10.1108/07378830610692127.

[6] M. J. Page *et al.*, “The PRISMA 2020 statement: an updated guideline for reporting systematic reviews,” *BMJ*, vol. 372, p. n71, Mar. 2021, doi: 10.1136/bmj.n71.

[7] M. C. Ayar, “First-Hand Experience with Engineering Design and Career Interest in Engineering: An Informal STEM Education Case Study,” *Educ. Sci. Theory Pract.*, vol. 15, no. 6, pp. 1655–1675, Dec. 2015.

[8] B. Brand, M. Collver, and M. Kasarda, “Motivating Students with Robotics,” *Sci. Teach.*, vol. 75, no. 4, pp. 44–49, Apr. 2008, doi: 10.2505/3/tst08_075_04.

[9] R. T. Johnson and S. E. Londt, “Robotics Competitions: The Choice Is up to You!,” *Tech Dir.*, vol. 69, no. 6, pp. 16–20, Jan. 2010.

[10] M. Wallace and W. Freitas, “Building Teen Futures with Underwater Robotics,” *J. Ext.*, vol. 54, no. 2, Apr. 2016, doi: 10.34068/joe.54.02.12.

[11] A. Eguchi, “Educational Robotics Theories and Practice: Tips for how to do it Right,” in *Robotics: Concepts, methodologies, tools, and applications: concepts, methodologies, tools, and applications*, IGI Global, 2014, pp. 193–223. doi: 10.4018/978-1-4666-4607-0.ch011.

[12] A. S. Gomoll, C. E. Hmelo-Silver, E. Tolar, S. Šabanovic, and M. Francisco, “Moving Apart and Coming Together: Discourse, Engagement, and Deep Learning,” *Educ. Technol. Soc.*, vol. 20, no. 4, pp. 219–232, Jan. 2017.

[13] D. Bernstein, G. Puttick, K. Wendell, F. Shaw, E. Danahy, and M. Cassidy, “Designing biomimetic robots: iterative development of an integrated technology design curriculum,” *Educ. Technol. Res. Dev.*, vol. 70, no. 1, pp. 119–147, Feb. 2022, doi: 10.1007/s11423-021-10061-0.

[14] S. Papert, *Mindstorms: children, computers, and powerful ideas*. USA: Basic Books, Inc., 1980.

[15] J. Bruner, “Celebrating Divergence: Piaget and Vygotsky,” *Hum. Dev.*, vol. 40, no. 2, pp. 63–73, Jan. 2010, doi: 10.1159/000278705.

[16] J. Piaget, “Part I: Cognitive development in children: Piaget development and learning,” *J. Res. Sci. Teach.*, vol. 2, no. 3, pp. 176–186, 1964, doi: 10.1002/tea.3660020306.

[17] L. S. Vygotsky, *Mind in Society: Development of Higher Psychological Processes*. Harvard University Press, 1978. doi: 10.2307/j.ctvjf9vz4.

[18] D. Alimisis, A. Karatrantou, and N. Tachos, “Technical school students design and develop robotic gear-based constructions for the transmission of motion,” Jan. 2005.

[19] E. Danahy, E. Wang, J. Brockman, A. Carberry, B. Shapiro, and C. B. Rogers, "LEGO-based Robotics in Higher Education: 15 Years of Student Creativity," *Int. J. Adv. Robot. Syst.*, vol. 11, no. 2, p. 27, Feb. 2014, doi: 10.5772/58249.

[20] N. Rusk, M. Resnick, R. Berg, and M. Pezalla-Granlund, "New Pathways into Robotics: Strategies for Broadening Participation," *J. Sci. Educ. Technol.*, vol. 17, no. 1, pp. 59–69, Feb. 2008, doi: 10.1007/s10956-007-9082-2.

[21] F. A. Bravo, J. A. Hurtado, and E. González, "Using Robots with Storytelling and Drama Activities in Science Education," *Educ. Sci.*, vol. 11, 2021, Accessed: Jul. 22, 2024. [Online]. Available: https://eric.ed.gov/?id=EJ1303972

[22] C. Kim, D. Kim, J. Yuan, R. B. Hill, P. Doshi, and C. N. Thai, "Robotics to promote elementary education pre-service teachers' STEM engagement, learning, and teaching," *Comput. Educ.*, vol. 91, pp. 14–31, Dec. 2015, doi: 10.1016/j.compedu.2015.08.005.

[23] D. Alimisis and C. Kynigos, "Constructionism and robotics in education," *Teach. Educ. Robot.-Enhanc. Constr. Pedagog. Methods*, pp. 11–26, 2009.

[24] S. Atmatzidou, I. Markelis, and S. Demetriadis, "The use of LEGO Mindstorms in elementary and secondary education: game as a way of triggering learning," *Workshop Proc. Int. Conf. Simul. Model. Program. Auton. Robots SIMPAR*, pp. 22–30, Jan. 2008.

[25] M. Carbonaro, M. Rex, and J. Chambers, "Using LEGO Robotics in a Project-Based Environment," *Interact. Multimed. Electron. J. Comput.-Enhanc. Learn.*, vol. 6, no. 1, Jan. 2004.

[26] A. Koray and F. G. Duman, "Subject-Oriented Educational Robotics Applications with Arduino in Science Teaching: Digital Dynamometer Activity in Accordance with 5E Instructional Model," *Sci. Act. Proj. Curric. Ideas STEM Classr.*, vol. 59, no. 4, pp. 168–179, Jan. 2022, doi: 10.1080/00368121.2022.2093824.

[27] C. A. Harris *et al.*, "Neurorobotics Workshop for High School Students Promotes Competence and Confidence in Computational Neuroscience," *Front. Neurorobotics*, vol. 14, 2020, Accessed: Oct. 15, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fnbot.2020.00006

[28] M. Koca and İ. Türkoğlu, "Secondary School Students' Opinions on Educational Robotic Applications," *Turk. Online J. Educ. Technol.*, vol. 21, no. 4, 2022.

[29] A. G. Welch, "Using the TOSRA to assess high school students' attitudes toward science after competing in the FIRST robotics competition: An exploratory study," *Eurasia J. Math. Sci. Technol. Educ.*, vol. 6, no. 3, pp. 187–197, Aug. 2010, doi: 10.12973/ejmste/75239.

[30] A. Sullivan and M. U. Bers, "Dancing robots: integrating art, music, and robotics in Singapore's early childhood centers," *Int. J. Technol. Des. Educ.*, vol. 28, no. 2, pp. 325–346, Jun. 2018, doi: 10.1007/s10798-017-9397-0.

[31] S. Ludi and T. Reichlmayr, "The Use of Robotics to Promote Computing to Pre-College Students with Visual Impairments," *ACM Trans. Comput. Educ.*, vol. 11, no. 3, Oct. 2011, doi: 10.1145/2037276.2037284.

[32] K. M. Fisher, B. Gallegos, and T. Bousfield, "Students with Autism Spectrum Disorders Who Participate in FIRST Robotics," *Proc. Interdiscip. STEM Teach. Learn. Conf.*, vol. 3, pp. 57–76, Jan. 2019.

[33] A. Sullivan and M. Umashi Bers, "VEX Robotics Competitions: Gender Differences in Student Attitudes and Experiences," *J. Inf. Technol. Educ. Res.*, vol. 18, pp. 097–112, 2019, doi: 10.28945/4193.

[34] A. Gomoll, C. E. Hmelo-Silver, S. Šabanovic, and M. Francisco, “Dragons, Ladybugs, and Softballs: Girls’ STEM Engagement with Human-Centered Robotics,” *J. Sci. Educ. Technol.*, vol. 25, no. 6, pp. 899–914, Dec. 2016, doi: 10.1007/s10956-016-9647-z.

[35] F. R. Sullivan, K. Keith, and N. C. Wilson, “Learning from the Periphery in a Collaborative Robotics Workshop for Girls,” *Univers. J. Educ. Res.*, vol. 4, no. 12, pp. 2814–2825, Jan. 2016.

[36] I. M. Verner, H. Perez, and R. Lavi, “Characteristics of student engagement in high-school robotics courses,” *Int. J. Technol. Des. Educ.*, vol. 32, no. 4, pp. 2129–2150, Sep. 2022, doi: 10.1007/s10798-021-09688-0.

[37] Feng-Kuang Chiang, Zhonghua Tang, Dan Zhu, and Xianqing Bao, “Gender Disparity in STEM Education: A Survey Research on Girl Participants in World Robot Olympiad,” *Int. J. Technol. Des. Educ.*, vol. 34, no. 2, pp. 629–646, Jan. 2024, doi: 10.1007/s10798-023-09830-0.

[38] E. B. Witherspoon, C. D. Schunn, R. M. Higashi, and E. C. Baehr, “Gender, Interest, and Prior Experience Shape Opportunities to Learn Programming in Robotics Competitions,” *Int. J. STEM Educ.*, vol. 3, Jan. 2016, doi: 10.1186/s40594-016-0052-1.