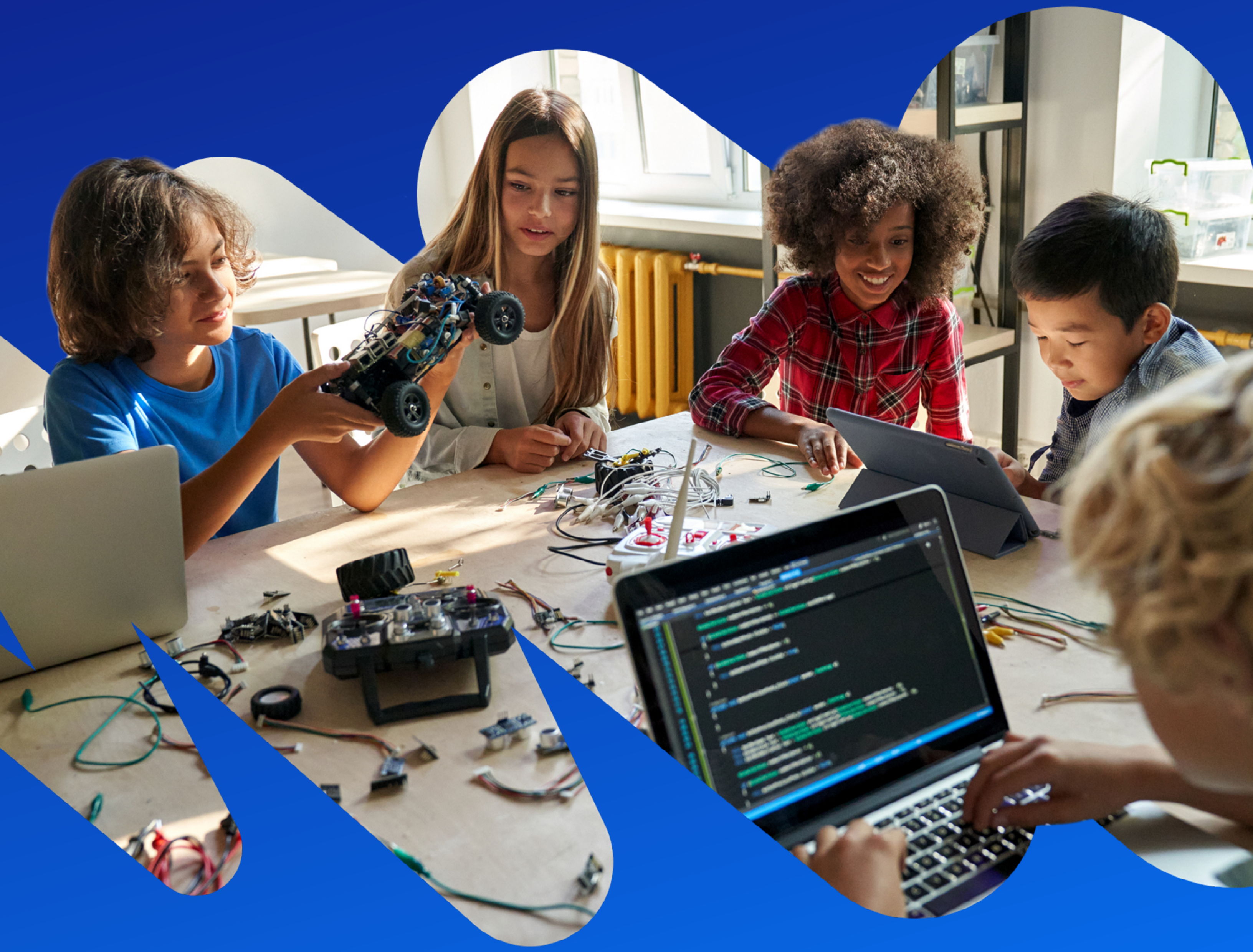
White Paper

STEM Instruction and the Four Cs



CRITICAL THINKING • COMMUNICATION • COLLABORATION • CREATIVITY

Workforce skills have changed dramatically in the 21st century. Jobs with more "routine" work have decreased and have been replaced with jobs that require adaptability for nonroutine work and analytic, interactive communication skills (National Education Association, n.d.). To prepare for college and careers, K–12 students need to acquire skills aligned with the realities of today's work environments. In response to changes in demand for skilled labor, the National Education Association (n.d.) identified the Four Cs of science, technology, engineering, and math (STEM) as essential for all students to acquire. Specifically, the Four Cs are: critical thinking, communication, collaboration, and creativity (defined in Table 1).

The Four Cs are part of a broader range of skills defined by contemporary literature as 21st-century skills. Enhancing the quality of STEM education is important to support all students in acquiring skills needed to obtain jobs in the current environment. The Four Cs of STEM are vital for college and career readiness, regardless of whether students choose college, careers in STEM, or careers after high school in non-STEM fields such as education, hospitality, or transportation.

Table 1: The Four Cs of STEM

	Definition	Importance
Critical Thinking	Critical thinking involves reasoning effectively, using systems thinking, making judgments and decisions, and solving problems.	Learning requires critical thinking. Critical thinking leads students to develop other skills, such as improved thought processing and higher levels of concentration.
Communication	Communication is the ability to articulate thoughts, listen and extract meaning, and interact in diverse environments.	Students must be able to clearly communicate and effectively analyze and process various forms of communication for success in school and careers.
Collaboration	Collaboration is the ability to work effectively with others to achieve common goals.	Considering the complexity of issues and challenges companies, institutions, and governments face, collaboration with diverse individuals is critical for identifying relevant solutions and making informed decisions.
Creativity	Creativity encompasses exploring and analyzing a wide range of ideas and perspectives, generating original and inventive solutions, viewing failure as an opportunity to learn, and turning ideas into tangible solutions.	The rapid pace of change in the 21st century requires adaptation and continual innovation. Students will need to know how to create and innovate to successfully address workforce and social challenges.

Moreover, 21st-century skills have a broader purpose than just improving today's workforce, as individuals' careers are but a partial manifestation of human development (Bronfenbrenner, 2005; Kegan, 1982). The purpose of education is to provide the necessary tools and a healthy environment to support individuals as they develop, grow, and thrive as human beings (Shirley, 2020; Greenlaw, 2015). Developing workforce skills is simply an integral part of human development. Twenty-first-century skills are important because they are career skills that apply to all aspects of life. It is therefore crucial to foster the development of such skills for all students by making high-quality STEM education accessible to them. The purpose of this paper is to explore how 21st-century skills are integral to STEM education and to describe research recommendations for fostering the development of these 21st-century-skills in STEM education.

The Research

As previously discussed, STEM refers to science, technology, engineering, and mathematics. For the purposes of this paper, we focus on science, technology/engineering (computer science specifically), and mathematics. Each of these disciplines is defined as follows. Science is the observation, identification, description, experimental investigation, and theoretical explanation of phenomena. Computer science, a component of the technology and engineering portion of STEM, is "the study of computers and algorithmic processes, including their principles, their hardware and software designs, their applications and their impact on society" (Computer Science Teacher Association, 2011, p. 1). Mathematics is the study of the measurement, properties, and relationships of quantities and sets, using numbers and symbols.

These STEM branches offer much more than simply teaching students scientific theories, mathematical theorems or formulas, or how to build computers, write code and manage data, or explain natural phenomena. In the process of learning STEM subject-matter content, students develop computational and critical thinking, including skills such as problem solving and creative thinking. These disciplines also require strong collaboration and communication, which foster persistence and the development of confidence as students engage with others in solving scientific, technological, and mathematical problems (Bottoms & Sundell, 2016; Burbaite et al., 2018).

Science

Science is knowledge or a system of knowledge concerned with the physical world and its phenomena, covering the operation of general laws as obtained and tested through the scientific method. Therefore, science cannot be defined outside of scientific inquiry. The study of science naturally supports the development of critical thinking. Science education fosters the development of critical thinking through scientific reasoning (Friedler et al., 1990), formal reasoning (Lawson, 1985), and the identification of logical fallacies (Jungwirth & Dreyfus, 1980). However, critical thinking is more than a range of behaviors or activities such as problem solving or inquiry activities. Critical thinking requires not only following specific scientific procedures, but doing so while evaluating evidence, questioning emerging results, and drawing conclusions using one's scientific knowledge (Bailin, 2002; Facione, 1990). Thus, scientific thinking processes and scientific knowledge are both integral parts of critical thinking.

Collaboration is also an essential part of scientific work, and has increasingly become so in the last century (Subramanyam, 1983; Lu & Zhang, 2009). Scientific work includes scientific reviews and collaboration on scientific projects and research. Feedback associated with scientific reviews is essential for refining scientific theories and improving and validating scientific work. Some research indicates that collaborative science interactions in schools can improve attitudes toward science and decrease anxiety (Hong, 2010). Collaboration in science education can be achieved as students work with peers to complete science projects and assignments, engage in purposeful classroom and/or online discussions, and share research in science fairs and competitions at the classroom, school, and/or regional level.

In applying these teaching strategies, scientific discourse and communication skills are essential. Scientific discourse and communication skills in the classroom "hold the key to how students frame their positions, build a case for argument, [and] become aware of fallacious reasoning" (Zeidler, 2003). Thus, fostering communication skills in science education naturally occurs, as both richness in content and scientific literacy are included in the curriculum. As Duschl and Osborne (2002) state, "developing an understanding of science and appropriating the syntactic, semantic and pragmatic components of its language requires students to engage in practicing and using its discourse in a range of structured activities."

Finally, science fosters creativity (Curriculum Development Council, 2017). McCormak and Yager (1989) proposed a science-education taxonomy comprising imagination and invention. Creativity is fostered through both experience and existing knowledge. Scientific knowledge supports creativity through visualization, the multiple interactions between objects or physical observation and ideas, the exploration of diverse uses of objects for alternative solutions, the suggestions of reasonable explanations for observable phenomena, the design of tests to validate explanations, and the communication of new evidence (Yager, 2005). According to (Cheng, 2011), students need to observe, classify, ask questions, form scientific hypotheses, plan tests, apply measurement methods, and analyze empirical data to develop scientific reasoning.

Engineering/Technology

Computer science is a branch of science that studies automation, solving computing problems, computational theory, the design of computers including hardware and software design, and ways to use technology. Computational theory is based on theoretical and algorithmic foundations. Computer science incorporates techniques from probability and statistics, as it extensively uses hypothesis testing and experimentation in the process of writing and testing algorithms. Computer science, therefore, involves science, technology, engineering, and mathematics; it blends STEM subjects.

An aim of computer-science education is to develop students' ability to engage in computational thinking and creative problem solving (Burbaite et al., 2018). Cognitive processes involved in computational thinking are integral to computer-science concepts and approaches. Computational-thinking elements most referenced in computer science are decomposition, abstraction, algorithms, and debugging (Shute et al., 2017). Decomposition involves breaking down a problem into manageable units. Abstraction entails modeling the main facets of complex problems. Algorithms refer to the design of logical and ordered instructions that are used to execute a solution to a problem. Debugging occurs when a solution does not function as it should; the process involves detecting and fixing errors. These cognitive processes are closely related to fundamental programming concepts used in the field of computer science.

The curricula presented in programming, robotics, and game design each emphasize different elements of computational thinking, and can be utilized to foster computational thinking (Shute et al., 2017) as well as creative problem solving. Programming is often used to promote computational-thinking skills and creative problem solving because writing and using efficient programs entail abstraction, generalization, and debugging. Students apply these processes by determining a goal to achieve, identifying sub-goals and steps to achieve their goal, and proposing efficient solutions. The programming code is meant to be reused to solve similar problems, with minor adjustments. Also, debugging is necessary to test the accuracy and efficiency of the program. The acquisition of programming concepts and practices through programming is considered the most effective way to learn computational thinking (Kong, 2019).

Computer-science education can foster communication, collaboration, and creativity through active-learning tasks such as open-ended projects and the design of creative artifacts (Goldberg et al., 2013; Santo et al., 2019; Vogel et al., 2017). Studies recommend the use of collaborative activities in computer-science education (Clear et al., 2020). Computer science supports the development of creativity and communication through what Resnick (2006) calls creative computing and personal expression. He defines this term through Vogel et al.'s (2017) argument that computers are means to personal expression and creativity. They refer to the "computer as a paintbrush." They postulate that "computers will not live up to their potential until we start to think of them less like televisions and more like paintbrushes. That is, we need to start seeing computers not simply as information machines, but also as a new medium for creative design and expression" (Vogel et al., 2017, p. 1). Their argument is that, though computers can stifle children's creativity and learning through "passive consumption and mindless interaction," computer consumption need not be mindless and passive like television consumption (Vogel et al., 2017; Cordes and Miller, 2000; Oppenheimer, 2003). Much like how the use of a paintbrush allows creating an infinite number of images through the use of diverse colors, computers and computer science are powerful tools that open the horizon to manifold explorations and creations, such as graphic animation, musical composition, robotic constructions, and so forth (Vogel et al., 2017).

Mathematics

The word mathematics comes from the Greek máthēma and means “that which is learnt.” Mathematics has its own language, which is a powerful structure that enables students to come to a deep knowledge and understanding of various abstract concepts. Its language is used in science, technology, and engineering. Therefore, it is the mortar of communication within the STEM sciences and enables interdisciplinary communication between all these fields of study. Mathematics includes a rich variety of subdisciplines such as algebra, arithmetic, geometry, analysis, probability, and statistics. These subdisciplines of mathematics are, in essence, the epitome of critical thinking.

Mathematics fosters a creative mind through the richness of its conceptual content, within both its abstract sphere and its application sphere. Mathematics touches the realm of pure abstraction and influences the world of physical observation and realities. Inventions in the scientific and technological world are all based on mathematical concepts and language. Additionally, mathematics history shows a substantial portion of mathematics advancement is due to collaboration between researchers (Singh, 2017). The very rich and dense nature of mathematics naturally brings practitioners to work, think, and elaborate collaboratively.

Mathematics in General

Mathematical literacy is critical for our society, and students need opportunities to apply mathematics to their everyday lives (Wijaya et al., 2015), whether they end up choosing a STEM-related career or not. Real-world contexts, or contextual representations, are a powerful tool for promoting 21st-century skills such as problem solving (National Council of Teachers of Mathematics, 2014). Real-world contexts are often presented as word problems, which provide a meaningful basis for students to transform the context of a situation into a mathematical form. Grounding mathematics in contexts that are relevant to students (Ladson-Billings, 2009) enriches their understanding (Van de Walle et al., 2018), honors their lives outside of the classroom, affirms their cultural experiences (Ukpododu, 2011), and promotes agency (Schoenfeld, 2014).

Mathematical discourse fosters communication skills. The National Council of Teachers of Mathematics (2014) describes mathematical discourse as “the purposeful exchange of ideas through classroom discussion, as well as other forms of verbal, visual, and written communication” (p. 24) and a “primary mechanism for developing conceptual understanding” (p. 30). Thus, mathematical discourse supports the development of both communication and critical-thinking skills. Studies show positive associations between mathematical discourse that emphasizes reasoning and problem solving and student learning outcomes (Michaels et al., 2008). According to Smith and Stein (2018), mathematical discourse provides benefits for students across grade levels, including those with learning disabilities and struggling in mathematics. It fosters students’ language development by promoting their use of words, symbols, and models to represent their mathematical thinking, make sense of their ideas, form connections across concepts, and clarify their understanding (Huinker & Bill, 2017).

Opportunities like journal writing help students learn to express their understanding of vocabulary through written text. Graphic organizers help students communicate using multiple representations (e.g., equations, models, examples and non-examples). Through multimodal communication (e.g., verbal, written, or pictures) students learn how to communicate clearly, while strengthening their conceptual understanding of key mathematics concepts.

To engage students in using mathematical communications and vocabulary, online learning environments should actively engage students in the learning process by incorporating talk moves, such as probing and purposeful questions (e.g., how and why, "What strategy might you use to solve this problem?" etc.) that ask students to explain, elaborate, or clarify their understanding of mathematics concepts, specific questions (e.g., explicit and direct) to draw attention to critical mathematics content and scaffold learning (Banse et al., 2016), or concrete support for students who are struggling ("Could you draw a picture to help you solve this problem?") (Harbour & Denham, 2021). With consistent opportunities to strengthen mathematical discourse, language development, and vocabulary, students' ability to communicate in productive and effective ways deepens, broadens, and becomes increasingly complex.

Finally, as students engage in mathematic discussions and in solving mathematics problems, they are likely to encounter problems that require new ways of thinking. Cognitively demanding tasks in mathematics foster productive struggle, or the struggle to make sense of unfamiliar concepts and procedures that are not immediately apparent (Hiebert & Grouws, 2007). Students who engage in productive struggle delve "more deeply into understanding the mathematical structure of problems and relationships among mathematical ideas, instead of simply seeking correct solutions" (National Council of Teachers of Mathematics, 2014, p. 48), fostering the development of critical thinking and other 21st-century skills. While these tasks may be challenging, they fall within a student's ability to solve without the direct help of a teacher (Smith et al., 2018). Experts agree that productive struggle is a critical part of the learning process because it encourages persistence in problem solving, leads to a stronger conceptual understanding, fosters agency, and improves metacognitive strategies (Kapur, 2014; Sinha & Kapur, 2021).

Geometry

Because mathematics involves a wide and deep variety of subdisciplines, we also highlight the development of the Four Cs within two subdisciplines: geometry, because of its importance in fostering the Four Cs of STEM (Clements & Sarama, 2021); and statistics, because statistical literacy is one of the main 21st-century skills needed today in the workforce (Battelle for Kids, 2019).

The van Hiele Model of Geometric Thinking catalogues students' progressive understanding of geometric reasoning into five levels (van Hiele, 1986). Levels 3 and 4 are levels of deductive reasoning that are part of the broader skill of critical thinking:

- Level 3 (informal deduction)—recognizes and describes the relationships between objects and shapes, and engages in "if…then" reasoning.
- Level 4 (formal deduction)—constructs proofs, analyzes informal arguments and the structure of a system, and begins to establish geometric truth based on logic.

Level 5, which van Hiele calls rigor, is the level at which students understand abstract geometry and see the "construction" of geometric systems. Understanding abstract geometry and visualizing geometric constructions and concepts, such as higher dimensions, are a powerful part of creativity. Having what we often call "vision"—an understanding, or at least a sense, of that which potentially exists but hasn't been created yet—is the initial step of the creative process (Battelle for Kids, 2019).

Despite the importance of this domain, geometry typically receives less attention than other domains (Clements & Sarama, 2021) and instruction often emphasizes vocabulary over application or concept development (Geddes & Fortunato, 1993; Sinclair & Bruce, 2015). To strengthen students' geometric thinking and foster connections between geometry and other mathematics domains, instruction should:

- Provide opportunities for students to reason about two- and three-dimensional shape attributes and properties using precise language, decompose shapes, compare examples and non-examples, and make connections between concepts and the real world (Clements & Sarama, 2021; Dobbins et al., 2014; Groth, 2013; Resnick et al., 2020; Seah & Horne, 2020). These skills encompass communication and critical thinking, as well as creativity.
- Integrate the use of dynamic technology to explore the visual nature of geometry (e.g., interactive manipulatives or geoboards) (Chan & Leung, 2014; NCTM, 2014; Sinclair & Bruce, 2015) and concepts like geometric measurement and transformations (Groth, 2013), thus fostering creativity through the development of computer skills.

Statistics

As the demand for statistical literacy grows, opportunities to reason about data, statistics, and probability have assumed a much deeper and wider role in mathematics curricula (Bargagliotti et al., 2020; Groth, 2013; Leavy et al., 2018). Statistical reasoning involves interpreting real data sets, graphic representations, and statistical summaries (Garfield, 2002). It also includes concepts like distribution, sampling, measures of center, measures of variability, probability, and inferences. While the goal of statistics is to understand the interaction between data and context, research has found many students struggle to make sense of these concepts (Bryant & Nunes, 2012; Groth, 2013; Rahmi et al., 2021) and are unable to develop reasoning skills at the level that is needed (Glancy et al., 2017). A growing body of research recommends the following instructional practices to expand students' statistical-reasoning skills:

- Provide real and motivating data sets; organize and display data using different representations (e.g., tables, charts, graphs); explore statistical concepts beyond measures of center (e.g., variability, inferences); and employ different statistical tests (Biehler et al., 2013; Groth, 2013).
- Utilize technology to make statistics visual, interactive, and dynamic, as this helps emphasize concepts over computation and offers engaging opportunities to analyze data (Biehler et al., 2013).

Conclusion

Considering how technology is rapidly changing work environments and how we interact with our world, providing all students access to STEM education is critically important for preparing them for a future that will continue to evolve and change in ways that we may not yet imagine. As discussed throughout this paper, education in STEM subjects inherently supports the development the Four Cs—critical thinking, collaboration, communication, and creativity—in ways that allow students to acquire skills needed for future employment and careers, regardless of whether students pursue STEM careers. Providing all students with access to high-quality STEM education prepares them to thrive in future endeavors.

References

Alshammari, M. T. (2020). Evaluation of gamification in e-learning systems for elementary school students. *TEM Journal, 9*(2), 806–813. doi.org10.18421/TEM92-51

Bai, S., Hew, K. F., & Huang, B. (2020). Does gamification improve student learning outcome? Evidence from a meta-analysis and synthesis of qualitative data in educational contexts. *Educational Research Review*, *30*. doi.org/10.1016/j.edurev.2020.100322

Bailin, S. (2002). Critical thinking and science education. *Science & Education, 11*(4), 361–375.

Bandura, A. (2012). On the functional properties of perceived self-efficacy revised. *Journal of Management, 38*(1), 9–44. doi.org/10.1177/0149206311410606

Banse, H., Palacios, N., Merritt, E., & Rimm-Kaufman, S. (2016). 5 strategies for scaffolding math discourse with ELLs. *Teaching Children Mathematics, 23*(2), 100–108. doi.org/10.5951/teacchilmath.23.2.0100

Bargagliotti, A., Franklin, C., Arnold, P., Gould, R., Johnson, S., Perez, L., & Spangler, D. (2020). *Pre-K-12 guidelines for assessment and instruction in statistics education II (GAISE II): A framework for statistics and data science education.* American Statistical Association.

Barr, D., Harrison, J., & Conery, L. (2011). Computational thinking: A digital age skill for everyone. *Learning & Leading with Technology, 38*(6), 20–23.

Battelle for Kids. (2019). Framework for 21st century learning definitions. https://static.battelleforkids.org/documents/p21/P21_Framework_DefinitionsBFK.pdf

Biehler, F., Ben-Zvi, D., Bakker, A., & Makar, K. (2013). Technology for enhancing statistical reasoning at the school level. In M. A. Clement, A. J. Bishop, C. Keitel, J. Kilpatrick, & A. Y. L. Leung (Eds.), *Third international handbook on mathematics education* (pp. 643–689). Springer.

Birk, M. V., Atkins, C., Bowey, J. T., & Mandryk, R. L. (2016). Fostering intrinsic motivation through avatar identification in digital games. *Proceedings of the 2016 CHI Conference on Human Factors in Computing* Systems (pp. 2982–2995). ACM. doi.org/10.1145/2858036.2858062

Bottoms, G., & Sundell, K. (2016). *The future of K–12 computer science instruction.* National Association of State Boards of Education.

Bronfenbrenner, U. (2005). *Making human beings human: Bioecological perspectives on human development.* Sage.

Bryant, P., & Nunes, T. (2012). *Children's understanding of probability: A literature review.* Nuffield Foundation.

Burbaite, R., Drasute, V., & Stuikys, V. (2018). Integration of computational thinking skills in STEM-driven computer science education. *2018 IEEE Global Engineering Education Conference (EDUCON),* 1824–1832.

Cameron, J. (2001). Negative effects of reward on intrinsic motivation—a limited phenomenon: Comment on Deci, Koestner, and Ryan (2001). *Review of Educational Research, 71*(1), 29–42. doi.org/10.3102/00346543071001029

Chan, K., & Leung, S. (2014). Dynamic geometry software improves mathematical achievement: Systematic review and meta-analysis. *Journal of Educational Computing Research, 51*(3), 311–325. doi.org/10.2190/EC.51.3.c

Cheng M. Y. V. (2011). Infusing creativity into Eastern classroom: Evaluations from students' perspectives. *Journal of Thinking Skills and Creativity, 6,* 67–87.

Chui, M. (2017). Self-concept, self-efficacy, and mathematics achievement: Students in 65 regions including the US and Asia. In J-W. Son, T. Watanabe, & J-J. Lo (Eds.), *What matters? Research trends in international comparative studies in mathematics education* (pp. 267–288). Springer International Publishing.

Clark, R. C., & Mayer, R. E. (2016). *E-learning and the science of instruction: Proven guidelines for consumers and designers of multimedia learning.* John Wiley and Sons.

Clear, A., Clear, T., Vichare, A., Charles, T., Frezza, S., Gutica, M., ... & Szynkiewicz, J. (2020). Designing computer science competency statements: A process and curriculum model for the 21st century. *Proceedings of the Working Group Reports on Innovation and Technology in Computer Science Education* (pp. 211–246).

Clements, D. H., & Sarama, J. (2021). *Learning and teaching early math: The learning trajectories approach* (3rd ed.). Routledge.

Computer Science Teachers Association. (2011). *CSTA K–12 Computer Sciences Standards—revised 2011.* CSTA.

Cordes, C., & Miller, E. (2000). *Fool's gold: A critical look at computers in childhood.* Alliance for Childhood.

Craft, A. (2003). Creative thinking in the early years of education. *Early Years. 23*(2), 143–154.

Curriculum Development Council. (2002). *Supplement to the science education key learning area curriculum guide: Science (Secondary 1–3).* Education Bureau Kowloon Education Services Center. https://www.edb.gov.hk/attachment/en/curriculum-development/renewal/SE/SE_KLACG_Supp_S1-3_Eng_2017.pdf

Daly, I., Bourgaize, J., & Vernitski, A. (2019). Mathematical mindsets increase student motivation: Evidence from the EEG. Trends in Neuroscience and Education*, 15*(1), 18–28. doi.org/10.1016/j.tine.2019.02.005

DeCoito, I. (2012). Digital games in science education: Developing students' 21st century learning skills. In Z. Karadag & Y. Devecioglu Kaymakci (Eds.), *Proceedings of the International Dynamic, Explorative, and Active Learning (IDEAL) Conference.* Bayburt University.

DeCoito, I. (2014). Focusing on science, technology, engineering, and mathematics (STEM) in the 21st century. *Ontario Professional Surveyor,* Winter, 34–36.

Dobbins, A., Gagnon, J. S., & Ulrich, T. (2014). Teaching geometry to students with math difficulties using graduated and peer-mediated instruction in a response-to-intervention model. *Preventing School Failure, 58*(1), 17–25. doi.org/10.1080/1045988X.2012.743454

Dreyfus, A. & Jungwirth, E. (1980). Students' perceptions of the logical structure of curricular as compared with everyday contexts—study of critical thinking skills, *Science Education 64*(3), 309–321.

Duschl, R. A., & Osborne, J. (2002). Supporting and promoting argumentation discourse in science education. *Studies in Science Education, 38,* 39–72. doi:10.1080/03057260208560187

Elliot, A., & Harackiewicz, J. (1996). Approach and avoidance achievement goals and intrinsic motivation: A mediational analysis. *Journal of Personality and Social Psychology, 70(3*), 461–475. doi.org/10.1037.0022-3514.70.3.461

Facione, P.A. (1990). Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction: Research findings and recommendations (the Delphi report). Prepared for the Committee on Pre-College Philosophy of the American Philosophical Association. ERIC ED 315–423.

Filsecker, M., & Hickey, D. (2014). A multilevel analysis of the effects of external rewards on elementary students' motivation, engagement and learning in an educational game. *Computers & Education, 75*(1), 136–148. doi.org/10.1016/j.compedu.2014.02.008

Friedler, Y., Nachmias, R., & Linn, M. C. (1990), Learning scientific reasoning skills in microcomputer laboratories, *Journal of Research in Science Teaching 27*(2), 173–191.

Garfield, J. (2002). The challenge of developing statistical reasoning. *Journal of Statistics Education, 10*(3), 323–341.

Geddes, I., & Fortunato, D. (1993). Geometry: Research and classroom activities. In D. T. Owens (Ed.), *Research ideas for the classroom: Middle grade mathematics* (pp. 199–222). Macmillan Publishing Company.

Glancy, A., Moore, T., Guzey, S., & Smith, K. (2017). Students' successes and challenges applying data analysis and measurement skills in a fifth-grade integrated STEM unit. *Journal of Pre-College Engineering Education Research, 7*(1), 68–75. doi.org/10.7771/2157-9288.1159

Gnauk, B., Dannecker, L., & Hahmann, M. (2012). Leveraging gamification in demand dispatch systems. *Proceedings of the 2012 Joint EDBT/ ICDT Workshops* (pp. 103–110). ACM. https://doi.org/10.1145/2320765.2320799

Goldberg, D., Grunwald, D., Lewis, C., Feld, J., Donley, K., & Edbrooke, O. (2013, March). Addressing 21st century skills by embedding computer science in K-12 classes. *Proceeding of the 44th ACM Technical Symposium on Computer Science Education* (pp. 637–638).

Greenlaw, J. (2015). Deconstructing the metanarrative of the 21st century skills movement. *Educational Philosophy and Theory, 47*(9), 894–903.

Groth, R. (2013). Teaching mathematics in Grades 6–12: *Developing research-based instructional practices.* Sage.

Harbour, K., & Denham, A. (2021). Supporting all students: Productive mathematics discourse in online environments. Intervention in School and Clinic*, 57*(2), 87–94. doi.org/10.1177/10534512211001849

Harris, K. R., Graham, S., & Adkins, M. (2015). Practice-based professional development and self-regulated strategy development for tier 2, at-risk writers in second grade. *Contemporary Educational Psychology, 40*(1), 5–16. doi.org/10.1016/j.cedpsych.2014.02.003

Hartnett, M. (2016). *Motivation in online education.* Springer.

Hiebert, J., & Grouws, D. A. (2007). The effects of classroom mathematics teaching on students' learning. In J. Frank & K. Lester (Eds.), *Second handbook of research on mathematics teaching and learning* (pp. 371–404). Information Age.

Hong, Z. R. (2010). Effects of a collaborative science intervention on high achieving students' learning anxiety and attitudes toward science. *International journal of science education, 32*(15), 1971-1988.

Huinker, D., & Bill, V. (2017). *Taking action: Implementing effective mathematics teaching practices (K-Grade 5).* National Council of Teachers of Mathematics.

Israel, M., Pearson, J., Tapia, T., Wherfel, Q., & Reese, G. (2015). Supporting all learners in school-wide computational thinking: A cross-case qualitative analysis. *Computers & Education, 82,* 263–279. https://doi.org/10.1016/j.compedu.2014.11.022

Israel, M., Wherfel, Q. M., Pearson, J., Shehab, S., & Tapia, T. (2015). Empowering K–12 students with disabilities to learn computational thinking and computer programming. *TEACHING Exceptional Children, 48*(1), 45–53. doi.org/10.1177/0040059915594790

Kapur, M. (2014). Productive failure in learning math. *Cognitive Science, 38*(5), 1008–1022. doi.org/10.1111/cogs.12107

Kegan, R. (1982). *The evolving self.* Harvard University Press.

Kong, Siu-Cheung. (2019). Components and methods of evaluating computational thinking for fostering creative problem-solvers in senior primary school education. In S. C. Kong & H. Abelson (Eds.), *Computational thinking education* (pp. 119–141). Springer. doi.org/10.1007/978-981-13-6528-7_8

Kuhn, T. S. (1970). *The structure of scientific revolutions* (Vol. 111). University of Chicago Press.

Labusch, A., Eickelmann, B., & Vennemann, M. (2019). Computational thinking processes and their congruence with problem-solving and information processing. In S. C. Kong & H. Abelson (Eds.), *Computational thinking education* (pp. 65–78). Springer. doi.org/10.1007/978-981-13-6528-7_5

Ladson-Billings, G. (2009). *The dreamkeepers: Successful teachers of African American children* (2nd Edition). Jossey-Bass.

Lawson, A. E. (1985) A review of research on formal reasoning and science teaching, *Journal of Research in Science Teaching 22*(7), 569–617.

Leavy, A., Meletiou-Mavrotheris, M., & Paparistodemou, E. (2018). *Statistics in early childhood and primary education: Supporting early statistical and probabilistic thinking.* Springer.

Lemos, M., & Verissimo, L. (2014). The relationship between intrinsic motivation, extrinsic motivation, and achievement, along elementary school. *Procedia—Social and Behavioral Sciences, 112*(1), 930–938. doi.org/10.1016/j.sbspro.2014.01.1251

Lewis, J., Ream, R., Bocian, T., Cardullo, R., Hammond, K., & Fast, L. (2012). Con carino: Teacher caring, math self-efficacy, and math achievement among Hispanic English learners. *Teachers College Record, 114*(7), 1–42.

Liao, C., Chen, C., & Shih, S. (2019). The interactivity of video and collaboration for learning achievement, intrinsic motivation, cognitive load, and behavior patterns in a digital game-based learning environment. *Computers & Education, 133*(1), 43–55. doi.org/10.1016/j.compedu.2019.01.013

Lu, S., & Zhang, J. (2009, July). Collaborative scientific workflows. In *2009 IEEE International Conference on Web Services* (pp. 527–534). IEEE. doi:10.1109/ICWS.2009.150

Margolis, H., & McCabe, P. (2006). Improving self-efficacy and motivation. *Intervention in School and Clinic, 41*(4), 218–227. doi.org/10.1177/105 34512060410040401

Marinak, B. A., & Gambrell, L. B. (2008). Intrinsic motivation and rewards: What sustains young children's engagement with text? *Literacy Research and Instruction, 47*(1), 9–26. doi.org/10.1080/19388070701749546

McCormack, A. J., & Yager, R. E. (1989). A new taxonomy of science education. *Science Teacher, 56*(2), 47–48.

Michaels, S., O'Connor, C., & Resnick, L. (2008). Deliberative discourse idealized and realized: Accountable talk in the classroom and in civic life. *Studies in Philosophy and Education, 27*(4), 283–297. doi.org/10.1007/s11217-007-9071-1

Moos, D. C., & Marroquin, E. (2010). Multimedia, hypermedia, and hypertext: Motivation considered and reconsidered. *Computers in Human Behavior, 26*(3), 265–276. doi.org/10.1016/j.chb.2009.11.004

Mueller, C., & Dweck, C. (1998). Praise for intelligence can undermine children's motivation and performance. *Journal of Personality and Social Psychology, 75*(1), 33–52. doi.org/10.1037/0022-3514.75.1.33

National Council of Teachers of Mathematics. (2014). *Principles to actions: Ensuring mathematical success for all.* National Council of Teachers of Mathematics.

National Education Association. (n.d.). *Preparing 21 century students for a global society. An educator's guide to the "Four Cs."* dl.icdst.org/pdfs/files3/0d3e72e9b873e0ef2ed780bf53a347b4.pdf

Noonoo, S. (2019). *Computational thinking is critical thinking. And it works in any subject.* Edsurge. https://www.edsurge.com/news/2019-05-21-computational-thinking-is-critical-thinking-and-it-works-in-any-subject

Oppenheimer, T. (2003). *The flickering mind: Saving education from the false promise of technology.* Random House.

O'Rourke, E., Haimovitz, K., Ballweber, C., Dweck, C., & Popovic, Z. (2014). Brain points: A growth mindset incentive structure boosts persistence in an educational game. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '14) (pp. 3339–3348). ACM. dx.doi.org/10.1145/2556288.2557157

Papert, S. (1980). *Mindstorms. Children, computers and powerful ideas.* Basic Books.

Papert, S. (1991). Situating constructionism. In S. Papert & I. Harel (Eds.), *Constructionism.* MIT Press.

Parker, P., Marsh, H., Ciarrochi, J., Marshall, S., & Abduljabbar, A. (2014). Juxtaposing math self-efficacy and self-concept as predictors of long-term achievement outcomes. *Educational Psychology: An International Journal of Experimental Educational Psychology, 34*(1), 29–48. https://doi.org/10.1080/01443410.2013.797339

Patston, T. J., Kaufman, J. C., Cropley, A. J., & Marrone, R. (2021). What is creativity in education? A qualitative study of international curricula. *Journal of Advanced Academics, 32*(2), 207–230. doi.org/10.1177/1932202X20978356org/10.1016/j.edurev.2017.09.003

Piaget, J. (1976). *To understand is to invent.* Penguin.

Rahmi, F., Sampoerno, D., & Ambarwati, L. (2021). Building relational understanding through hypothetical learning trajectory of probability. *International Journal of Elementary Education, 5*(1), 150–157.

Resnick, M. (2006). Computer as paint brush: Technology, play, and the creative society. *Play= learning: How play motivates and enhances children's cognitive and social emotional growth.* Oxford University Press.

Resnick, I., Harris, D., Logan, T., & Lowrie, T. (2020). The relation between mathematics achievement and spatial reasoning. *Mathematics Education Research Journal, 32*(2), 171–174. doi.org/10.1007/s13394-020-00338-7

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist, 55*(1), 68–78. doi.org/10.1037/0003-066X.55.1.68

Santo, R., Vogel, S., & Ching, D. (2019). *CS for what? Diverse visions of computer science education in practice.* CUNY Academic Works.

Shirley, D. (2020). Beyond well-being: The quest for wholeness and purpose in education. *ECNU Review of Education, 3*(3), 542–555.

Schoenfeld, A. (2014). What makes for powerful classrooms, and how can we support teachers in creating them? A story of research and practice, productively intertwined, *Educational Researcher, 43*(8), 404–412. doi.org/10.3102/0013189X14554450

Schunk, D. H., & Usher, E. L. (2012). Social cognitive theory and motivation. In R. M. Ryan (Ed.), *The Oxford handbook of human motivation* (pp. 13–27). Oxford University Press.

Seah, R., & Horne, M. (2020). The influence of spatial reasoning on analyzing about measurement situations. *Mathematics Education Research Journal, 32*(2), 365–386. doi.org/10.1007/s13394-020-00327-w

Shute, V. J., Sun, C., & Asbell-Clarke, J. (2017). Demystifying computational thinking. *Educational Research Review, 22,* 142–158. doi.org/10.1016/j.edurev.2017.09.003

Sinclair, N., & Bruce, C. (2015). New opportunities in geometry education at the primary school. *ZDM, 47*(3), 319–329.

Singh, S. (2017). *Fermat's enigma: The epic quest to solve the world's greatest mathematical problem.* Anchor.

Sinha, T., & Kapur, M. (2021). Robust effects of the efficacy of explicit failure-driven scaffolding in problem-solving prior to instruction: A replication and extension. *Learning and Instruction, 75*(1), 1–16. doi.org/10.1016/j.learninstruc.2021.101488

Skaalvik, E., Federici, R., & Klassen, R. (2015). Mathematics achievement and self-efficacy: Relations with motivation for mathematics. *International Journal of Educational Research, 72*(1), 129–136. doi.org/10.1016/j.ijer.2015.06.008

Smith, M., Bill, V., & Raith, M. (2018). Promoting a conceptual understanding of mathematics. *Mathematics Teaching in the Middle School, 24* (1), 36–43. doi.org/10.5951/mathteacmiddscho.24.1.0036

Smith, M. S., & Stein, M. K. (2018). *5 practices for orchestrating productive mathematics discussions* (2nd Ed.). National Council of Teachers of Mathematics.

Subramanyam, K. (1983). Bibliometric studies of research collaboration: A review. *Journal of Information Science, 6*(1), 33–38.

Theodotou, E. (2014). Early years education: Are young students intrinsically or extrinsically motivated towards school activities? A discussion about the effects of rewards on young children's learning. *Research in Teacher Education, 4*(1), 17–21. doi.org/10.14123/uel.859y7

Ukpokodu, O. (2011). How do I teach mathematics in a culturally responsive way?: Identifying empowering teaching practices. *Multicultural Education, 19*(3), 47–56.

Van de Walle, J., Lovin, L., Karp, K., & Bay-Williams, J. (2018). *Teaching student-centered mathematics: Developmentally appropriate instruction for grades 3–5* (3rd Edition). Pearson.

Vogel, S., Santo, R., & Ching, D. (2017, March). Visions of computer science education: Unpacking arguments for and projected impacts of CS4All initiatives. In *Proceedings of the 2017 ACM SIGCSE Technical Symposium on Computer Science Education* (pp. 609–614).

Wang, A. Y., Fuchs, L. S., Fuchs, D., Gilbert, J. K., Krowka, S., & Abramson, R. (2019). Embedding self-regulation instruction within fractions intervention for third graders with mathematics difficulties. *Journal of Learning Disabilities, 52*(4), 337–348. doi.org/10.1177/0022219419851750

Wijaya, A., van den Heuvel-Panhuizen, M., & Doorman, M. (2015). Opportunity-to-learn context-based tasks provided by mathematics textbooks. *Educational Studies in Mathematics, 89*(1), 41–65. doi.org/10.1007/s10649-015-9595-1

Wing, J. M. (2006). Computational thinking. *Communications of the ACM, 49*(3), 33–35.

Yadav, A., Gretter, S., Hambrusch, S., & Sands, P. (2016). Expanding computer science education in schools: Understanding teacher experiences and challenges. *Computer Science Education.* doi.org/10.1080/08993408.2016.1257418

Yager, R. E. (2005). A vision for what science education should be like for the first twenty-five years of a new millennium. *School Science and Mathematics, 100,* 327–341.

Zainuddin, Z., Chu, S., Shujahat, M., & Perera, C. (2020). The impact of gamification on learning and instruction: A systematic review of empirical evidence. *Educational Research Review, 30*(1), 1–23. doi.org/10.1016/j.edurev.2020.100326

Zeidler, D. L., & Zeidler, L. (Eds.). (2003). *The role of moral reasoning on socio-scientific issues and discourse in science education* (Vol. 19). Springer Science & Business Media.

imagine learning

imaginelearning.com
877-725-4257 • solutions@imaginelearning.com

1033816332 2301