Community for Advancing Discovery Research in Education

The Potential of Using AI to Improve Student Learning in STEM: Now and in the Future

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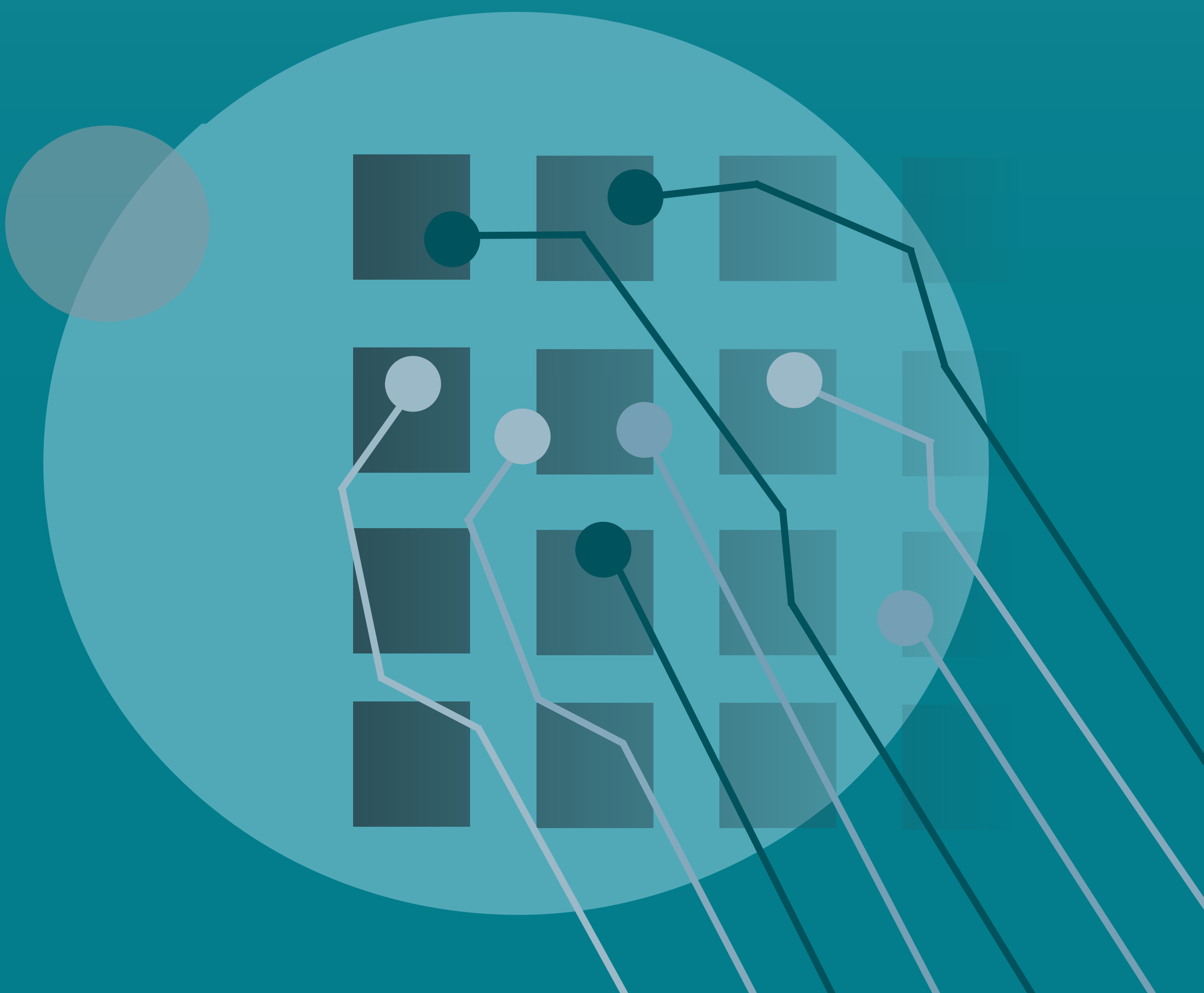

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Foreword

By Christopher J. Harris and Eric Wiebe

Research and development work in Artificial intelligence in Education (AIED) is wide ranging and rapidly growing in support of all areas of science, technology, engineering, and mathematics (STEM) teaching and learning. With its broad applicability and transformative potential, AIED represents what could arguably be the most fundamentally game-changing technology for education to emerge since the Internet. Building from prior decades of work on AI and AI-based learning and teaching technologies, the recent advances in AIED – especially the leaps in generative AI – are pushing us to reimagine what is possible for STEM teaching and learning. AIED research initiatives are being speedily funded and AIED advances are quickly becoming integrated into STEM education. It is transforming how teachers teach and how students learn. It is also transforming how education developers and researchers conduct their expansive work. There is excitement about the promise of AIED as well as growing concern that the breakthroughs in AIED are impacting everyday education practice in ways that may perpetuate long standing biases and diminish the potential for positive outcomes. As the research and development work continues to push the boundaries of what is possible, it is important to keep the dual promise and peril of AIED in mind.

In this brief, *The Potential of Using AI to Improve Student Learning in STEM: Now and in the Future*, the authors Namsoo Shin, Kevin Haudek, and Joseph Krajcik examine how AI is ushering in transformative changes to teaching and learning that promise to improve learning experiences and outcomes for all students. They begin with the theoretical foundations for using AI in K–12 STEM education, emphasizing the importance of "knowledge-in-use" and integrated understanding, which enable students to apply STEM knowledge in varied and demanding ways to tackle complex real-world problems, analyze phenomena, and make informed decisions. This lays the groundwork for describing an emerging future where AI stands to serve as an interactive partner with students, offering personalized support to foster learning, motivation, and collaboration. The authors also explore how AI as a learning partner can scaffold cognitive, metacognitive, motivational, and collaborative processes of learning. Importantly, they consider how AI can potentially foster inclusivity and ensure equitable access to STEM learning. Yet, they caution that designing AI to be a learning partner that can reach a broad and diverse population of students, especially those who have been historically underserved and marginalized in STEM education, will require that designers actively identify and mitigate underlying and potential biases in the development of AI systems. They put forth that this is an imperative for any AI tool or system that is intended to work side by side with students as a learning partner, promoting deep usable knowledge development and supporting long-term STEM learning and success.

Shin and colleagues' brief is the third in a three-part series on AIED related to STEM research, teaching, and learning. The series' topics address ethical approaches to AI in STEM education research, AI for STEM teaching, and AI for STEM learning.

- Brief #1: *Toward Ethical and Just AI in Education Research* – Authored by Tiffany Barnes and colleagues (Barnes et al., 2024), this brief is concerned with the ethical reasoning and decisions made in the development, study, and use of AIED technologies. The authors illustrate how ethical AI research can be strengthened by building from well-established ethical principles used in research and society at large. Taking into account these principles, they propose an ethical AIED framework and a set of tools that they have found to be supportive of continuous reflection, communication, and improvement toward inclusive and equitable AIED research and development.
- Brief #2: *Generative AI in STEM Teaching: Opportunities and Tradeoffs* – Written by Jeremy Price and Shuchi Grover (Price & Grover, 2025), this brief explores the possibilities and critical challenges of GenAI for STEM teaching. The authors examine how GenAI may shape STEM classrooms in the near future and identify promising trajectories for integrating GenAI into STEM teaching, including the potential for personalized teaching approaches. They delve into the current state of GenAI research and development around five dimensions of STEM teaching: (1) justice, equity, and inclusion; (2) curricular decision-making and lesson planning; (3) pedagogy and instruction; (4) assessing student work and progress; and (5) teacher learning and leadership. Throughout, Price and Grover reaffirm the essential role of teachers and emphasize the need to include teachers in efforts to design, develop, and study GenAI tools that are intended to benefit STEM education.

The series was sponsored by the *Community for Advancing Discovery Research in Education* (CADRE), an NSF-funded resource network for STEM education researchers endeavoring to improve STEM teaching and learning through research, development, and various information-sharing and community-building mechanisms. Researchers in the CADRE network are part of a portfolio of projects funded through the National Science Foundation's (NSF's) *Discovery Research PreK-12* (DRK-12) program. The DRK-12 portfolio is wide ranging, with an extensive collection of projects that focus on applied research and development to generate innovative research-informed and field-tested tools, products, and approaches that are intended to enhance STEM teaching and learning. Over the past several years, the portfolio has grown to include an increasing number of projects that leverage AIED to achieve their goals related to teaching or learning. It is expected to continue to grow. This series has been inspired by the question, "What are the essential considerations for researchers and developers who are designing, studying, and using AI in K–12 STEM classrooms?" Our hope is that the opportunities and challenges discussed in this series will generate reflection and rich discussion for the better as well as support the transformative use of AI to achieve positive and wide-reaching impact for all STEM educators and learners.

Introduction

In the last several years, the emergence of artificial intelligence (AI) has influenced many aspects of society, including automation, health care, and education. In automation, advancements in AI are revolutionizing the way tasks are performed, leading to increased efficiency, accuracy, and innovation across various domains. AI is overhauling medical practice by enhancing diagnostics, treatment planning, drug discovery, and patient care. AI influences education by introducing transformative changes to teaching and learning that promise to improve learning experiences and outcomes. Since the fall of 2022, large language models (LLM) such as Generative Pre-Trained Transformers (GPT) have become more publicly available, significantly impacting education. These models can interpret and generate human-like text, enabling them to interact meaningfully with students and educators. AI's ability to provide real-time, personalized feedback helps students understand complex concepts, reflect and modify their thinking, and stay engaged in their learning. Moreover, AI can adapt various learning materials to suit individual needs, ensuring every student receives the support required to succeed academically.

The National Science Foundation's (NSF's) *Discovery Research PreK–12* (DRK–12) and *Innovative Technology Experiences for Students and Teachers* (ITEST) programs have been instrumental in funding research and development projects exploring AI's potential to enhance student learning in STEM education. Examining these initiatives' goals can help us gain insights into the current state of AI in STEM education, the challenges of using AI, and the opportunities it presents for the future.

In this brief, we explore the following question: "What role can AI play in supporting learners in developing an integrated understanding of science, technology, engineering, and mathematics (STEM) and enhancing their engagement and interest in STEM to solve complex or ill-structured problems, make sense of compelling and challenging phenomena, and make informed decisions?" We first discuss our goals for K–12 STEM education and the importance of fostering an integrated understanding of STEM content. Next, we present various learning and motivational theories that drive our view of how AI should be used in K–12 STEM education, focusing mainly on formal settings and how AI can serve as a learning partner. Finally, we describe the potential functions of AI in transforming educational practices in support of student learning.

Theoretical Foundations of Using AI in STEM Education

STEM is integral to modern life and holds the potential to address pressing global challenges, such as food scarcity, climate change, and quantum computing cybersecurity. Improving STEM education has become increasingly critical as society faces complex real-world problems that require a scientifically knowledgeable citizenry.

Goals of STEM Education

STEM education should equip students with the knowledge, skills, and STEM identities needed to apply what they learn in real-life situations and to pursue STEM-related careers. This fusion of knowledge and interpersonal skills leads to integrated understanding, a critical goal for 21st-century STEM education (Pellegrino & Hilton, 2012). Achieving excellence in STEM education requires all students develop deep, usable knowledge of STEM's big ideas and practices. However, this development will not "just happen"; students must have opportunities to engage with one another on challenging material through well-designed learning environments. Teachers play a critical role in providing optimal opportunities to ensure learning is accessible to *all* students, regardless of their differences in backgrounds and learning abilities (Schneider et al., 2020). In addition, the learning environment should encourage students to feel a sense of belonging and engagement with STEM fields by drawing on students' cultural resources and backgrounds. These are important to aid students in developing a STEM identity (i.e., how students perceive themselves in relation to learning STEM and STEM careers) and seeing the relevance of STEM to their lives (Barton & Tan, 2010; Singer, et al., 2020).

Too many people, including those in developed nations, lack fundamental STEM knowledge, which hampers their ability to make informed decisions and contribute productively to society. To address this gap, STEM education has shifted away from focusing on *inert knowledge,* where students memorize facts and procedures but cannot solve novel problems (Whitehead, 1959), to supporting students in developing knowledge-in-use. Inert knowledge is characterized by understanding limited to rote memorization without the ability to apply the knowledge in new situations. It typically results when individuals learn STEM ideas or procedural steps without grasping the underlying meanings or implications. As a result, although students may appear knowledgeable, they may not have the adaptive expertise to flexibly apply their knowledge and skills in different situations, particularly in unfamiliar or unstructured contexts (Pellegrino & Hilton, 2012; Spiro et al., 2020). The new focus in STEM education is toward performance-based learning goals, emphasizing an approach known as *knowledge-in-use* (National Research Council, 2012b).

What Is Knowledge-in-Use?

Knowledge-in-use focuses on students developing abilities to apply their knowledge to explain phenomena, solve real-world problems, and make informed decisions based on evidence and scientific reasoning. It requires individuals to integrate concepts across various STEM domains, enabling them to apply their understanding in varying and new contexts and use their knowledge to solve complex problems, make sense of compelling and challenging phenomena, and make informed decisions (National Research Council, 2012a). By fostering knowledge-in-use, educators can prepare students to navigate and thrive in a world increasingly shaped by scientific and technological advancements.

What Is Integrated Understanding?

The ability to apply knowledge to novel situations is often described as the development of *integrated understanding*, which emerges as learners synthesize relationships and connections among ideas and personal experiences. This concept has been supported by such educational theorists as Bransford, Brown, and Cocking (National Research Council, 2000); Linn and Eylon (Linn & Eylon, 2006); and Spiro and colleagues (Spiro et al., 2020). Integrated understanding equips learners to utilize their knowledge in unique scenarios and aids them in solving ill-structured problems (i.e., those that are characterized by ambiguity and complexity and the absence of a single correct solution path) (Shin et al., 2003). Such problems often require students to consider multiple variables and perspectives and demand a flexible and deep understanding of the subject matter (Spiro et al., 2020).

We can conceptualize an individual's understanding of STEM content as it progresses from inert knowledge to integrated understanding to adaptive expertise. *Adaptive expertise* is the ability to use knowledge and skill flexibly to solve novel problems. STEM education should foster integrated understanding, enabling students to develop knowledge and skills that are retainable and applicable in varying and challenging situations. When students have a rich integrated understanding characterized by essential connections among ideas and experience, they are more equipped to use their knowledge in new situations (National Research Council, 2012a). The question then arises: "What conditions influence the development of integrated understanding?"

Fostering Integrated Understanding

To develop and promote integrated understanding, learners need learning environments that support their (1) cognitive development, (2) metacognitive skills and strategies, (3) motivational and emotional engagement, and (4) collaboration and discourse skills. Each aspect is described in more detail below.

We view learning as an ongoing process of linking new ideas with existing knowledge and experiences (Krajcik & Shin, 2022). *Cognitive development* requires learners to exert sufficient effort to persist in understanding a complex idea or situation or solve challenging or ill-structured problems by searching for relevant information in their knowledge structure and linking new ideas to their old knowledge. The more learners grapple with challenging situations, ideas, and experiences, the more connections they make, allowing them to adaptively apply their knowledge in new situations and make sense of compelling and complex phenomena. (In contrast, the fewer the connections learners form, the less able they are to apply their knowledge in new situations.)

Developing integrated understanding also requires various regulative *metacognitive skills and strategies*, including deep processing of information, problem-solving (Blumenfeld et al., 2005; Fredricks et al., 2004; Rotgans & Schmidt, 2011), and allocating mental resources, such as attention and persistence, to a learning task. Metacognitive engagement calls for learners to exert mental energy and use higher-order thinking processes—such as synthesizing and analyzing information, considering other points of view, and applying all prevailing information—to solve challenging and/or poorly structured problems. Self-reflection (i.e., understanding what one knows and needs to know more about and how and under what conditions one learns best) is also critical to the development of integrated understanding. Learners need opportunities to reflect on what they know and don't know to solve ill-structured problems and make sense of phenomena. Posing questions such as "What else do I need to know?," "What am I missing?," and "What other ideas can I bring in to help solve this problem?" can support learners in staying engaged, learning more, and solving problems.

Motivation and emotional engagement are also key to integrated understanding, as how students feel about and perceive a situation significantly affects their cognitive and metacognitive engagement and drives their learning. *Situated cognition*—learning that takes place in a meaningful real-world context and involves working with others—plays a critical role in students' learning and motivation. If learners are highly interested in something—not just a fleeting interest but a long-term and sustained one—and are committed to understanding a problem, they will invest more time and energy in the cognitive process. However, without motivation and emotional engagement, most learners will not cognitively engage or stay engaged. STEM education can support learners' emotional engagement by influencing their challenge, skill, and interest levels when engaged in various tasks. *Challenge* refers to the level of difficulty or complexity a task or learning experience presents to a learner. It is the extent to which a learning experience pushes students beyond their current abilities, requiring them to think critically, problem-solve, or apply knowledge in new ways. However, the push cannot be too far, or students will not have the skills to solve the challenge. *Skill* refers to the learner's abilities, knowledge, and competencies in a particular area. It encompasses both foundational capabilities (e.g., reading, mathematics, and science) and higher-order skills (e.g., critical thinking, creativity, problem-solving, and the use of scientific practices). *Interest* refers to a learner's emotional engagement or curiosity in a particular subject, activity, or problem. Interest motivates learners to invest attention and effort in learning (Schneider et al., 2020).

In designing educational learning environments, the designer needs to develop a balance between challenge, interest, and skill. Tasks and learning experiences should align with and slightly exceed a learner's current skill level to present an engaging challenge while leveraging their interests and cultural resources to maintain motivation. These three conditions—interest, challenge, and skill—are necessary to support and sustain cognitive engagement.

Another strategy to enhance students' emotional engagement is *culturally responsive teaching* (Mathis et al., 2023), which aims to build students' interest in STEM by creating connections between STEM content and students' cultural backgrounds and lived experiences. Educators can build on students' cultural knowledge, resources, and experiences to present situations in which learners need to advance and apply STEM principles to solve problems. For instance, with students of Latino heritage, physics teachers can use the accomplishments of Mayan astronomers in tracking the solar year, which was vital for predicting rainy and dry seasons and for planting and harvesting their crops.

The fourth learning process essential to promoting integrated understanding is *collaboration and discourse* —a vital aspect of modern education. Collaboration is an interpersonal and intellectual effort of students, peers, teachers, and community members to investigate and make sense of phenomena or ill-structured problems. In collaborative learning environments, students are encouraged to challenge and support their conceptions and ideas or argue from evidence and to work with others in the class to test their ideas and build understanding. It's important to note that learning to collaborate doesn't occur on its own; instead, learners need to experience contexts in which collaboration is fostered. Learners need opportunities to consider and discuss one another's ideas by asking questions, providing feedback, and building on one another's contributions.

Learning processes are not only located within an individual mind; they are also distributed and work collectively across individuals, resources, and the environment (e.g., physical external contexts around individuals, including the objects, spaces, and interaction within that space) (Pea, 1993). Knowledge and reasoning are often socially constructed through collaboration and the use of various resources, such as tools, computer interfaces, and diagrams. The learning environments should be designed to use distributed resources to foster collaboration and to support the use of resources that expand cognitive abilities. Individuals can demonstrate a more refined integrated understanding by using such resources and collaborating with others than they can on their own without using distributed resources. For example, using a drawing tool to build scientific models, students can collaboratively build their models to explain complicated phenomena. Such modeling tools promote cognitive ability by visually representing their knowledge and skills, as well as collaboration and discourse skills by addressing and resolving disagreements while developing a group model. Formal educational settings should provide an environment that distributes cognitive work across individuals and offers tools to allow individuals to do more complex collaborative work, thereby developing a more integrated understanding of the content.

Based on these theoretical foundations, we explore the following question: "How can STEM educators leverage AI as a learning partner for students to maximize their cognitive and metacognitive skills, motivation and emotional engagement, and opportunities to effectively collaborate?"

AI as a Learning Partner

We envision AI as a learning partner that helps students develop an integrated understanding and engagement in STEM. By *learning partner*, we mean a person or entity that collaborates with another individual to enhance their thinking, creativity, problem-solving, learning, communication, and motivation. This partnership involves the exchange of ideas, knowledge, and perspectives. Learning partners challenge each other's thinking, offer critical feedback, help refine each other's ideas (Vygotsky, 1978), and provide motivational support.

This is where more knowledgeable others and scaffolds come into play, allowing individuals to accomplish more than they could without those supports (Vygotsky, 1978). Researchers have explored using scaffolds to enable students to participate in cognitively complex tasks that they normally could not do without the scaffolds. For instance, many learners struggle with writing evidence-based scientific explanations. Educators can scaffold the process by dividing evidence-based scientific explanations into various components—claim, evidence, and reasoning (McNeill et al., 2006). However, to promote independent learners' applying their knowledge and skills in new situations, educational designers should fade scaffolds over time; otherwise, they become crutches rather than help learners perform tasks independently (Pea, 2004). As learners become familiar with writing explanations, teachers can withdraw or fade these supports.

AI in STEM education should also consider both social aspects, such as the culture of school stakeholders (e.g., students, parents, teachers, and school administrators), and technical aspects, such as the technology infrastructure needed to implement AI within school organizations to create rich environments to support student learning. AI has the potential to share some of the roles of teachers within school systems and other adults in nonformal environments that require frequent and immediate attention (e.g., analyses of student responses to assessment tasks), thereby serving as a learning partner to facilitate students' learning.

We envision AI working alongside students as a learning partner to support all learners in building integrated understanding they can use to solve novel or ill-structured problems, make sense of complex and compelling phenomena, and learn more when needed. While teachers, tutors, parents, friends, classmates, and other caregivers can serve this role, AI can be an additional learning partner—one that calibrates its support to meet an individual's dynamic learning needs that evolve over time. Pea (1993) discusses how traditional views of intelligence focus too narrowly on the individual, neglecting the critical role of external resources (e.g., artifacts as tools, diagrams, and computer interfaces) and collaborative practices in shaping cognitive processes. These resources carry embedded intelligence that can aid in problem-solving, learning, performing complex tasks, and motivation and engagement.

Our conceptual framework for AI as a learning partner (see Figure 1) outlines the connections between theoretical perspectives and student learning outcomes. Above, we summarize the theoretical principles that support AI as a learning partner, drawing on theories of situated and distributed cognition and active construction, motivational and emotional variables, cultural foundations of learning, and social interaction constructs such as collaborative interactions with others and the importance of metacognition. Below, we show how these ideas lead to various ways AI as a learning partner can support students in developing integrated understanding (e.g., providing scaffolds, encouraging hints, offering language support, and prompting self-reflection).

Figure 1. A Model for AI as a Learning Partner

AI as a Learning Partner

Driving Question: How can AI support all students in developing a deep integrated understanding of STEM and enhancing engagement and interest in STEM?

Theoretical Foundations

Situated Cognition

- Authentic real-world context
- Seeing value in the cognitive work

Active Construction

- Using and applying knowledge
- Experiencing phenomena
- Making meaning

Motivational and Emotional Variables

- Attitude
- Value
- Interest
- Cognitive and emotional engagement

Metacognition

- Knowledge of cognition
- Knowledge of regulation

Distributed Cognition

- Work collectively across individuals, tools, and the environment
- Share and shape knowledge between humans and their tools

Social Interaction

- Collaborative interactions with peers and more knowledgeable others
- Content-specific discourse

Cultural Foundations of Learning

- Cultures
- Home and communities
- Cultural resources

Supports from a Learning Partner

Cognitive Supports

- Promote integrated understanding of core ideas
- Promote integrated understanding of scientific practices
- Offer actionable, constructive, and comprehensible feedback

Motivation and Emotional Supports

- Promote emotional and cognitive engagement
- Align with values
- Promote situational engagement
- Offer timely and personalized feed-back

Metacognitive Supports

- Promote self-evaluation
- Promote self-regulation
- Promote self-monitoring
- Promote task completion and performance progress

Collaboration and Discourse Supports

- Help students take part in discourse
- Help students listen to a different perspective
- Help students to synthesize various points of view and ideas

Generative AI as a Learning Partner

Adaptive Learning System to monitor learners' progress and provide personalized support based on learners' needs, characteristics, and preferences.

AI Cognitive Supports

- Provide timely feedback on learners' performance, including actionable suggestions for improving their performances

AI Motivational and Emotional Supports

- Develop learning materials based on individual needs, preferences, and characteristics

AI Metacognitive Supports

- Support learners to design their learning plan, activities, or assessment based on their knowledge
- Provide performance progress visually to review their learning

AI Collaborative and Discourse Supports

- Monitor discourse participation, analyze collaboration patterns, and prompt learners on how to improve their involvement

Outcomes

Student Learning

- Increased performance in applying STEM knowledge to make sense of phenomena
- Increased performance in applying STEM knowledge to solve ill-structured problems and make informed decisions

Motivation and Emotion

- Increased engagement to explore STEM using scientific practices
- Increased value for STEM
- Increased interest in future STEM stud-ies and careers

Metacognition

- Increased ability to learn more when needed
- Increased ability to self-monitor

Collaboration

- Increased student collaboration

Distal Outcomes

- Increased Achievement
- Increased STEM career
- Increased skill in solving complex STEM problems related to societal issues
- Develop STEM identity

AI as a Learning Partner to Support Personalized Learning

Humans have always used tools to extend their cognition—for example, using one's fingers to count or using a pencil to aid in mathematical reasoning and problem-solving. The individual's fingers serve as tools to support counting, and the pencil serves as a tool to aid calculations. *Distributed intelligence* emphasizes the interaction between internal cognitive processes and external resources. Educational contexts that leverage distributed intelligence, such as using AI as a learning partner, can potentially enhance learning in K–12 classrooms. Situated cognition and cultural foundations of learning focus on developing contexts relevant to learners to promote learning. AI tools can help customize learning tasks and experiences to better leverage the pedagogical assets in learners' backgrounds, prior experiences, characteristics, and needs, making the learning process more meaningful. AI tools act as cognitive, metacognitive, and social extensions, augmenting human cognitive abilities by providing support in various forms.

Personalized learning environments have drawn on AI-based approaches to serve as a learning partner for several decades. *Personalized learning* refers to learning contexts and materials based on an individual learner's needs (e.g., performance level, interests, personal characteristics) and provides guidance or support in a timely manner (National Research Council, 2000). Curriculum developers should design learning contexts and materials based on learning theories and robust research data, enabling personalization through various supports that work together to promote learning. Personalization is a cornerstone of effective education, and AI has the potential to excel as a personalized learning partner.

Researchers and designers have integrated AI into teaching and learning to enhance human intelligence, allowing for more effective adaptation and precision in personalized learning. Researchers have implemented various AI techniques to create intelligent adaptive learning environments using heterogeneous data collection, predictive model building, and learning recommendations (e.g., ASSISTments[1]). Many past efforts at personalized learning provided a limited range of learning supports (due to technology limitations of the systems), gave predefined or programmatic responses or paths, or collected limited data about the learner to make predictions. Although these systems made critical contributions and did have an impact on student learning, they relied on a restricted model of the student as a learner to make predictions, offer suggestions, or direct learners. New approaches more broadly referred to as Generative AI (GenAI) may provide more real-time, interactive support and merge multiple data sets to broaden the model of the student as a learner.

GenAI differs from previous approaches using machine learning, data analytics, and natural language processing (NLP) due to its ability to create content rather than merely analyze or

[1] See https://new.assistments.org

classify existing data. While traditional machine learning and data analytics in science education focus on identifying patterns and making predictions based on historical data (Zhai et al, 2020), GenAI's NLP emphasizes understanding human language. GenAI leverages advanced models (e.g., GPT-4, Dall-E) to create content, such as text, audiovisual data, and computer code. This capability provides possibilities for enhancing personalized student learning experiences through automated content generation. GenAI can fill multiple roles as a learning partner by adapting to students' needs and achievements on the fly, providing tailored explanations, creating personalized learning materials, providing supportive comments and hints that allow learners to advance to the next steps, and being interactive—all of which were challenging to achieve with previous AI methods.

In addition to systems becoming more interactive through advances in AI algorithms, these newer approaches benefit by including additional data, when necessary, using validated and trustworthy data appropriately to create richer, more expansive models of learners by gathering key information, such as body movement, visual, and voice data. These newer applications also benefit from faster and more powerful computing, thus enabling the analysis of more real-time responses and interactions. This shift from traditional reactive systems to generative systems opens the door to more relevant, personalized, and rich educational environments, thus potentially fostering students' deeper and more integrated understanding of STEM.

Learning Partners to Create Personalized Learning

Personalized learning supports individual learning by adjusting various functions within learning systems—such as an adaptive learning system—including user interfaces, content, and learning paths tailored to each learner's needs and status (e.g., InQITS[2]). When integrated into such adaptative systems, AI can collect and analyze performance, motivation, and emotional data, in addition to individual student characteristics, to automatically adjust the learning content and mode to effectively meet learners' needs. For example, a platform that includes teaching and learning materials, learning tasks, and assessment features and allows for multifaceted extensive data analysis and real-time feedback can collect various student performance and learning data immediately. These features will enable the system to monitor students' learning progress, identify where students need additional support, and provide timely feedback with appropriate learning tasks to support students in developing their understanding and motivation to learn.

[1] See https://www.inqits.com

Since it has become easier to collect more relevant data in systems and to merge various analytic pipelines in current AI applications, this provides an opportunity for these personalized adaptive learning systems to develop a richer model of students and potentially offer multiple types of support from a single AI agent, a software program that uses AI to perform tasks without human intervention, as a learning partner. For example, the same teaching and learning system may capture students' facial expressions, nonverbal bodily motion, lip-synchronized speech, and interactions with non-playing characters in a game environment. These additional data facilitate personalized adaptive learning environments that monitor students' progress, engagement, and emotions and could provide a variety of real-time supports appropriate to students' needs at a given moment.

Support Provided by AI as a Learning Partner: Types, Strategies, and Examples

In this section, we highlight current projects that use a range of AI-based approaches, both traditional and generative, to enhance student learning in STEM. Although we highlight a range of support offered by the projects using AI, we do so to focus on a specific feature of systems and their relationship to student learning. Many of the systems we identify could be categorized into several strategies or supports offered by learning partners. This exemplifies the potential GenAI systems may provide avenues to collect and combine student data in innovative ways to offer multiple supports.

As a learning partner, AI can support all learners in building integrated understanding so individuals can use what they have learned in different situations. For example, AI can provide instructional support tailored to an individual's needs and motivation. In many respects, with the support of AI, learners can develop the intellectual resources needed to independently solve challenging problems. This might sound contradictory because earlier, we argued for the importance of distributed intelligence and how the tools, the environment, and others can help support what learners can do and build integrated understanding. However, we do not see AI as a crutch but rather as a support that will adjust or calibrate over time as the learner becomes more sophisticated, knowledgeable, and independent. The model we presented in Figure 1 lists various ways AI can extend support for learners' developing understanding.

Our focus on using AI to support learning doesn't diminish the crucial role that teachers play in the classroom. Similar to the use of AI in medicine (where AI provides an initial diagnosis of clear-cut cancer cases, but a physician must decide what treatment a patient receives and make the final decisions on challenging cases), teachers must oversee the feedback and suggestions provided by the AI to ensure AI's recommendations are appropriate, particularly in challenging cases (Barnes et al., 2024; Price & Grover, 2025).

AI as a Learning Partner for Cognitive Support

Cognitive support aids learners in various cognitive processes, such as thinking, learning, remembering, explaining, and problem-solving. Learners need to develop an integrated understanding of complex ideas and scientific practices to find solutions to ill-structured problems or complex phenomena. Cognitive support should help learners analyze the elements and relationships among them in a problem to rapidly access meaningful information and scientific principles when knowledge is needed in learning tasks.

Strategies for Cognitive Support

Cognitive support can range from hints, such as sentence starters, to breaking down complex tasks into steps learners find more comprehensible. For example, to guide evidence evaluation, cognitive support can prompt learners to consider whether all relevant evidence has been accounted for when justifying an explanation.

Humans, technology, and environmental modifications can each provide various cognitive supports to foster critical thinking and comprehensive understanding. A teacher could support a learner in developing an experimental design by suggesting essential variables the learner might have overlooked. A teacher could also break down a complex task into simpler components that more easily guide a learner through a process. Such advice is rooted in 17th-century scholarship, such as Descartes' maxim from *Discourse on Method* (1637/1956): "Divide each difficulty into as many parts as is feasible and necessary to resolve it." Technology tools can provide a range of cognitive supports, from automatically giving hints to providing organizational structures (Quintana et al., 2004). Modifications in the learning environment can provide an appropriate working space for collaborative lab experiments to support learners in observing scientific phenomena that may not be visible to the naked eye. These various human, technological, or environmental supports align with the theoretical foundation of distributed cognition by integrating external prompts into the learner's cognitive process.

Current Use of AI Cognitive Support

AI provides cognitive support as a learning partner in various NSF projects, two of which we describe below.

Evaluating Effects of Student Automatic Feedback Aligned to a Learning Progression to Promote Knowledge-In-Use[3] explores the effect of an assessment system that uses AI to generate feedback based on students' open-ended responses to modeling and evidence-based scientific explanation tasks in high school physical science. The formative assessments and feedback are consistent with an empirically validated Next Generation Science Standards-aligned learning progression that describes successively more complex understandings students can develop about electrical interactions. The researchers are designing and testing an automated assessment system using machine learning, which will provide individualized feedback to students based on the responses and class summaries they submit to their teachers. The project will then examine whether such automatic formative feedback supports students' learning outcomes and their development with respect to the desired learning progression. The work supports teachers by providing actionable feedback on explanations and models for numerous students across classrooms.

[3] U.S. National Science Foundation. (2022). Award abstract # 2200757: Evaluating effects of automatic feedback aligned to a learning progression to promote knowledge-in-use. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2200757&HistoricalAwards

The Future of Nurse Training: Robotic Teaching Assistant Systems for Nursing Instructors[4] aims to develop Robotic Intelligent Teaching Assistant Systems using an interaction between virtual and embodied intelligence components to support student learning.

Virtual and augmented reality (VR and AR)—a real-time technology integrating real-world and computer-generated information—can enhance deep understanding by involving students in authentic situations with meaningful experiences (Fernández-Batanero et al., 2022). Leveraging AI in VR and AR can help support cognitive engagement while employing contexts that engage learners.

The noted project uses VR and embodied AI to support nursing students in training to learn routine nursing procedures and by helping to assess trainees' skills. The system, developed with the support of nursing instructors, will ultimately provide assessment summaries to instructors and deliver instructor-guided tutoring, thus leading to pertinent cognitive support for individual learners. AI enables immersive learning by creating virtual reproductions of real-world scenes using multimedia, simulation, and VR technologies. Multidimensional presentations of learning content engage students' vision, hearing, kinesthetic, and other senses, creating a solid sense of reality. This technology makes abstract concepts and theories more intuitive and visual and stimulates students' interest in the subject, thus enhancing their learning.

Potential Use of AI for Cognitive Support

Chatbots are AI-based applications that process and simulate conversations with users. Over the past decades, they have been applied to various educational contexts. Traditional chatbots often rely on predefined scripts, statements, or rule-based responses, which minimize the range of responses to queries and limit students' ability to respond and engage in a conversational format.

Newer approaches leveraging GenAI, such as conversational AI, enhance the capability of chatbots by making them more contextual and producing interactions that feel natural, enhancing their role as learning partners. GenAI models can respond to a broader range of sequential questions, adapt responses based on conversational context, and supply justifications for feedback. This promotes active knowledge construction, as students can ask for clarification or probe feedback, and facilitates deeper learning. These chatbots can handle complex, nuanced questions, respond with questions themselves, and allow varying levels of detail in answers through iterative prompt engineering. Such features make GenAI-powered chatbots more personalized and responsive, expanding their effectiveness as rich learning resources. We do not imagine AI *presenting* a student with information but rather *responding* in ways that will support the learner in actively engaging in the process.

In addition to its ability to process and produce text, GenAI can process and produce a wide range of media types, including static images, video, and audio, which allows for the

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[4] U.S. National Science Foundation. (2023). Award abstract # 2326390: The future of nurse training: Robotic teaching assistant systems for nursing instructors. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2326390&HistoricalAwards=false

customization of difficulty levels for various media formats embedded in simulations, games, or AR for learners. GenAI can improve simulations and AR by increasing the personalization of content based on the student. GenAI can also continually create and modify different simulation scenarios, increasing the number of possible scenarios a user may encounter while reducing the amount of coding for predefined setups. Experiencing multiple scenarios will provide learners with more opportunities to make connections among more ideas, thus developing knowledge they can apply in various situations. GenAI can create extensive and detailed virtual worlds for learners to investigate based on specific variables while varying the learning contexts. For example, students could explore tropical and temperate rainforest environments or analyze differences in terrain between regions of a country in virtual spaces.

For game-based learning, GenAI can improve adaptive difficulties or challenges students experience. Again, the increased computing power of the newer systems allows them to process more data quickly, leading to real-time interactivity. For example, rather than simply modify the content based on sporadic inputs from the learner, GenAI could produce entirely new content based on the flow of information within a game. The challenge level of the new scenarios can also be adapted to the student's proficiency level for the measured objectives. Such adaptive games and immersive experiences may prevent student frustration and increase their engagement and motivation.

AI as a Learning Partner for Metacognitive Support

Complex problems for which there is no clear solution require learners to organize and direct their cognitive endeavors in different ways and to a different degree. Learners must continually analyze and judge their learning process using metacognitive skills, such as changing strategies, modifying plans, and reevaluating goals (Kluwe & Friedrichsen, 1985). Metacognitive support guides learners in planning, monitoring, and evaluating their learning processes (Brown et al., 1983) and helps learners reflect on their knowledge to identify what they already know and what additional information they need to search for solutions (Chi et al., 1982).

Strategies for Metacognitive Support

Prompting self-reflection on their own learning strategies and outcomes can help learners develop their metacognitive skills and engage in cognitive processes. For example, after completing a task, a learning partner providing metacognitive support might ask learners to review their approach and identify areas for improvement. For checking their work, a learning partner can provide reminders and checklists to ensure learners have reviewed their work thoroughly before submission. In supporting a claim, a learning partner could prompt the learner to ensure they have sufficient and appropriate evidence. These supports foster self-regulation and continual improvement, critical components of metacognitive development.

These examples illustrate how metacognitive prompts given by a learning partner can help learners develop metacognitive abilities by encouraging them to reflect on their skills, thinking processes, and completed tasks. The prompts also encourage learners to participate further in cognitive processes related to the task.

Current Use of AI for Metacognitive Support

Researchers in the *Automated Formative Feedback of Problem-Solving Strategy Writing in Introductory Physics Using Natural Language Processing*[5] use NLP to develop an automated system to provide personalized formative feedback to students in undergraduate physics courses about their problem-solving strategies. The team examines the following two questions: (1) "How accurately can an NLP classifier score such essays, and how can it generalize across problem types?" and (2) "How well does providing students with such feedback improve their problem-solving strategies and abilities?"

Starting with a vast corpus of existing data, the investigators use supervised and unsupervised learning to train a machine-learning model to classify the problem-solving strategies. The aim is to determine the accuracy with which a machine-learning model can provide feedback on short essays written by students describing their strategy for solving a problem. The researchers also investigate how real-time formative feedback can help students refine their strategies iteratively to solve problems with increasing generality.

Potential Use of AI for Metacognitive Support

We envision several ways researchers and educators can use AI as a learning partner to support metacognition and enhance students' STEM learning. One possibility is that AI can offer interactive prompts while monitoring student learning using heterogeneous data, such as computer vision (e.g., eye tracking, body movements) and learning activity data (e.g., dialogue with classmates, written and drawn responses, log files). The AI system can analyze these data to provide various metacognitive strategies to learners at appropriate times, either at pauses in work or at the start or end of tasks. For instance, AI as a learning partner can pose such questions as "What are you thinking right now?," "What information do you need?," "How can you improve your work?," or "Have you used all the necessary information?"

AI could also help students construct a model to explain a phenomenon by prompting them to check whether all the relationships are necessary to give a causal account of the system. For example, if students are writing an argument about the importance of sustainable food, the AI system, as a learning partner, could prompt them to seek more information on how to grow food without pesticides.

AI as a Learning Partner for Motivational and Emotional Support

Cognitive engagement cannot be separated from motivational and emotional engagement, as motivational and emotional engagement is necessary for cognitive engagement. Several variables—including *affect* (an individual's positive or negative feelings about an idea or event [Voss, 1988]) and *values* (an individual's belief system)—can enhance one's motivation and emotional engagement. In addition, learners must employ their affective knowledge, including

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[5] U.S. National Science Foundation. (2024). Award abstract # 2300645: Research on automated formative feedback of problem-solving strategy writing in introductory physics using natural language processing. https://nsf.gov/awardsearch/showAward?AWD_ID=2300645

emotions, values, and beliefs (Sinnott, 1989), to evaluate possible solutions to an ill-structured problem and decide which solution is most helpful in a given context.

Strategies for Motivational and Emotional Support

Learning activities aligned with learners' interests increase emotional engagement. John Dewey (Dewey, 1913) famously coupled student interest with effort, although the complexity of this relationship has been more thoroughly documented since then (Renninger & Su, 2012). Connecting to students' interests promotes their engagement and motivation and, thus, their development as learners. Linking a task and the learning content to local issues, the community, or students' cultural backgrounds makes the task and content relevant and engaging. For instance, if a learner is interested in environmental issues, contexts focusing on relevant topics, such as water quality and air pollution, will support initial and longer-term learning efforts. These strategies leverage the principles of situated cognition, cultural foundations of learning, and motivation constructs shown in Figure 1.

Choice is a critical variable in developing positive attitudes and emotional engagement among students. When students are given choices to make, their sense of ownership and relevance fosters internal motivation and supports engagement throughout the learning process. When learners have the choice to select goals and information to modify a task, they become more motivated to complete it (Jonassen, 1997). Offering students a variety of relevant topics, activities, and information to choose from gives them a sense of control over their learning and makes the learning activities seem more valuable and applicable to their lives. This personalized approach aligns with distributed active construction and situated cognition theories, ensuring learning is relevant, and engagement is emotionally and cognitively appropriate.

Current Use of AI for Motivational and Emotional Support

As a learning partner, AI can provide various motivational and emotional support. Following, we highlight three ways AI can serve this role: personalized AI lessons; AI adaptive feedback; and supporting values, beliefs, and attitudes toward STEM learning.

Personalized AI lessons can be generated based on learners' backgrounds and characteristics to better engage their interest in learning activities. The collaborative project *A Semiconductor Curriculum and Learning Framework for High-Schoolers Using Artificial Intelligence, Game Modules, and Hands-on Experiences*[6] aims to develop high-school students' career interest in semiconductors using a game-based learning environment. To recruit more diverse students into STEM fields, the project developed a semiconductor curriculum for high-school students and coupled classroom and workshop activities with real-world industry experiences. The project will also produce a GenAI-based agent that can provide suggestions or additional materials to students based on their interests and preferences. The project's research questions address whether AI-based agents affect student awareness and interest in STEM careers.

[6] U.S. National Science Foundation. (2024). Award abstract # 2342748: A semiconductor curriculum and learning framework for high-schoolers using artificial intelligence, game modules, and hands-on experiences. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2342748

The flexibility of *AI adaptive feedback* can support learners in various emotional and motivational ways. It can provide real-time personalized feedback to help learners progressively deepen their understanding by monitoring and responding to other inputs, such as body language, facial expressions, and group discourse, instead of only submitted responses or clicks in a Web-based system. For example, *Intelligent Science Stations: Developing Adaptive Mixed-Reality Technology to Enhance Inquiry-based STEM Learning in Schools*[7] aims to develop and research Intelligent Science Stations to engage K–4 students in inquiry-based science learning opportunities to sustain their interest in science. The Intelligent Science Stations provide students with first-hand science experiences, supplemented by an intelligent agent that offers feedback based on students' actions analyzed by AI computer vision to enhance engagement. The Intelligent Science Stations incorporate scientific apparatuses such as earthquake tables or balance scales, and the intelligent agent observes and evaluates students' actions. The agent appears as an animated character on a screen and provides interactive feedback to guide students through scientific inquiry. This innovative approach offers evidence-based, personalized support and feedback while assisting teachers in integrating more inquiry-based science learning into their classrooms. By modeling such behaviors as asking questions, making predictions, and explaining scientific phenomena, the interactive AI system helps teachers enhance their classroom experiences. Through classroom observations and controlled experiments, the project will compare the use of Intelligent Science Stations, providing insights into student engagement, science conversations, and science inquiry processes.

Learners need *positive values*, *beliefs, and attitudes toward STEM learning* to evaluate and use the information AI provides for their learning activities and tasks. *The Development of a Digital Platform for Evaluating and Using AI-Generated Content for Academic Purposes*[8] developed a Web-based platform called Compose With AI, aimed at guiding students to evaluate AI-generated content and use factual information to compose common types of science-focused writing (e.g., composing arguments, claims, or solutions related to science topics). The Compose With AI platform will (1) guide students to gather and critically evaluate content produced by AI, (2) guide students on beneficial and ethical uses of content produced by AI, and (3) scaffold students' use of AI-generated content as a model and resource for composing science-focused texts. The project team will use these data to determine what critical evaluation approaches and strategies inhibit and enhance students' abilities to use and critically evaluate content generated with AI.

Potential Use of AI for Motivational and Emotional Support

The projects highlighted above use advanced AI approaches to provide motivational and emotional support to learners—for example, leveraging a broad range of data about the learner's engagement, activity, or emotion (from user input data and audio and/or visual

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[7] U.S. National Science Foundation. (2023). Award abstract # 2300734: Intelligent science stations: Developing adaptive mixed-reality technology to enhance inquiry-based STEM learning in schools. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2300734&HistoricalAwards=false

[8] U.S. National Science Foundation. (2023). Award abstract # 2337969: RAPID: DRL AI: The development of a digital platform for evaluating and using AI-generated content for academic purposes. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2337969

sources) to generate a unique user experience. Some systems use such data (e.g., eye tracking, facial expressions) to identify when student mind wandering (i.e., disengagement) occurs (Bosch & D'Mello, 2022; Hutt et al., 2019), allowing the system to re-engage students in learning tasks.

AI-customized lessons can enhance learning experiences by tailoring lessons to students, considering their personal backgrounds, interests, concerns, and learning preferences, thereby increasing their emotional engagement. For instance, if a learner is interested in environmental issues, AI can frame the learning context within environmental science, discussing pollutants in water when a class studies solubility or focusing lessons on topics such as sustainable food and pollution. AI can also connect learning content to local or cultural issues, making it more relevant and emotionally engaging. For example, in a community facing water scarcity, AI can highlight the importance of water conservation and provide tasks that focus on finding solutions to conserve water in communities.

AI agents may also create content to contextualize learning materials based on students' STEM interests. This allows students to experience personalized learning paths paced appropriately and in various contexts that provide cognitive, motivational, and emotional support. Collaborative GenAI learning partners could respond to a variety of inputs from students (e.g., text, drawing, speech) and respond to students using these same diverse modalities. Further, such agents can be developed to represent different virtual partners for the student, from a tutor who teaches and provides ideas on how to respond to questions about science to a collaborative peer in math problem-solving to a coach who can offer motivation and encouragement. In this way, AI can play various roles as a learning partner, not all of which focus on the STEM content or the cognitive aspects of learning, thus providing a more authentic and contextualized experience for each learner.

AI as a Learning Partner for Collaboration and Discourse Support

Collaboration skills—such as respectfully communicating and resolving disagreements—can facilitate effective group interactions by helping learners mediate conflicts and ensure constructive dialogue. Collaborative support should enhance the social aspects of cognition by fostering learning situations where learners interact with each other to share ideas and discuss issues.

Strategies for Collaboration and Discourse Support

To foster collaboration in and outside the classroom, teachers and other forms of scaffolding can synergistically support students by using strategies that work together to encourage students to talk with one another about important issues (MacDonald et al., 2017; Tabak, 2004). Teachers, peers, or various technology tools can facilitate collaboration by encouraging learners to consider other ideas. For instance, teachers or technology supports can use sentence starters to promote students talking with each other (e.g., "My idea is similar to your idea because . . . , but my idea is different from yours because . . .").

Current Use of AI for Collaboration and Discourse Support

Fostering of Collaborative Computer Science Learning with Intelligent Virtual Companions for Upper Elementary Students[9] provided learning experiences for upper elementary school students to learn computer science while building collaboration skills. The group learning activities included developing virtual learning companions to scaffold and support students as they interact with their learning environment. This project found specific discourse elements will increase when student pairs received structured feedback from teachers (Zakaria et al., 2022). Although this project focused on pair programming in a group as a collaborative strategy, the findings lay the groundwork for providing collaboration and learning support through a virtual AI agent.

CueLearn: Enhancing Social Problem Solving through Intelligent Support[10] aims to foster effective peer collaborations to improve mathematical problem-solving among middle school students while supporting teachers in using technology for collaborative work. This project will develop, test, and implement two strategies to enhance students' collaborative problem-solving: (1) facilitating effective student collaborations through creating effective peer groups within CueLearn, and (2) using real-time support to increase student engagement and help students persist productively. Machine-learning techniques will monitor students' engagement and detect unproductive forms of persistence to provide in-the-moment support as needed.

Potential Use of AI for Collaboration and Discourse Support

As a learning partner, AI can provide collaboration and discourse support in several ways. To foster dialogue, AI's NLP capabilities can encourage learners to consider and discuss one another's ideas. By analyzing group discourse using voice and/or speech analytics, AI as a learning partner can prompt students to ask one another questions to help clarify if a model provides a mechanism to explain a phenomenon or to prompt for a discussion if a group has appropriate and sufficient evidence to support their claim. AI could also foster group discourse by suggesting how a student can involve others in the conversation by showing how their ideas relate or providing ideas on how to build on one another's contributions to craft an artifact related to a driving question. When students discuss topics with the potential to become emotional or heated (e.g., the cause of climate change), AI can monitor conflicts or changes in tone or voice to help mediate disputes and ensure constructive dialogue by suggesting ways to resolve disagreements and promote respectful communication.

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[9] U.S. National Science Foundation. (2017). Award abstract # 1721000: Fostering collaborative computer science learning with intelligent virtual companions for upper elementary students. https://www.nsf.gov/awardsearch/showAward?AWD_ID=1721000

[10] U.S. National Science Foundation. (2023). Award abstract # 2300827: CueLearn: Enhancing social problem solving through intelligent support. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2300827&HistoricalAwards=false

Future Directions: Using AI as a Learning Partner

The examples above illustrate how AI can support students as learning partners, offering personalized assistance, adaptive learning experiences, real-time feedback, customized problems and situations, and support for collaboration during STEM learning. When thoughtfully integrated into the educational process, AI has the potential to serve as a powerful learning partner to scaffold the cognitive, metacognitive, motivational, emotional, and collaborative aspects of learning. By providing tailored support and adjusting as learners become more independent, AI has the potential to ensure learners develop the intellectual resources necessary to tackle complex STEM problems and explain compelling phenomena. This approach aligns with the theory of distributed cognition, emphasizing the interplay between internal and external cognitive resources to build learners' integrated understanding and ability to use what they have learned in new situations.

Supporting a Broad Range of Learners

GenAI can transform learning for students from various cultures by adapting the learning environment to meet learners' unique needs and supporting them in considering the value of diverse opinions to develop scholarly products. However, it is crucial to ensure that AI-driven opportunities are accessible and beneficial to all students, regardless of cultural and economic background, race, gender, or sexual orientation. It is likewise essential to ensure that the implementation of AI in education does not exacerbate existing learning gaps, inequity, and bias toward learners from different cultural and racial backgrounds. For example, personalized learning experiences based on stereotypes or biased data (e.g., Asian students are better at mathematics, boys are better at science) could inadvertently track or pigeonhole students into limiting paths. Researchers and educators need to carefully design, monitor, and refine AI systems to prevent bias and inequalities and to ensure AI responds appropriately to the wide-ranging needs of a diverse student population. AI should empower students by offering diverse learning opportunities to encourage exploration and growth for all learners (Barnes et al., 2024). However, without vigilance, these AI systems risk misdiagnosing or misclassifying students by overlooking language use, ethnicity, or prior experiences, potentially deepening existing learning gaps among learners. By prioritizing inclusivity and equity, educators and researchers need to create AI systems that recognize and address potential biases that could marginalize or disadvantage certain groups of students.

One potentially powerful utility of AI is the real-time translation of text and speech into multiple languages, thus supporting students for whom English is not their primary language. This capability could facilitate the translation of curriculum materials, assessments, and AI-based feedback within the same AI agent embedded in an adaptive system.

GenAI agents can also address issues related to disability equity for learners. As we noted earlier, newer AI systems can process and evaluate multiple data inputs, including written text, drawn images, speech, facial expressions, and eye-tracking. Similarly, these GenAI-based agents can respond to users in various formats (e.g., text, image, speech)—including those the user prefers. Importantly, these inputs and outputs could be processed and generated by the same AI agent in a system to produce multi-modal texts instead of implementing different educational technology systems or strategies—which means, for example, students with impaired speech or low vision can interact with the same AI agent in very different ways (e.g., text versus speech). Further, the same AI agent can be used by other students in the classroom, so all students are engaged with the same personalized learning partner, thus promoting equal opportunities in the classroom for all of them.

A third possible use of GenAI systems is to assist in automatically adjusting complex texts to different reading levels or to redesign STEM learning materials according to the principles of Universal Design for Learning (Rose, 2000). For example, when considering representation, the same information can be presented in multiple formats to accommodate diverse needs—for students with vision impairments, larger fonts with voice-over features, and for students with reading difficulties, visual representations, or diagrams.

Acknowledging and addressing socioeconomic disparities is another key aspect of providing inclusive educational experiences. Equal access to AI learning tools is imperative to avoid widening the gap between students from well-resourced districts and those from under-resourced ones. Without deliberate efforts to ensure equitable access, the benefits of GenAI as a learning partner could be disproportionately available to students in more affluent communities, leaving behind those who might benefit the most from these advanced tools (Crawford, 2021). Educators and researchers should ensure all students have equal access to AI-driven learning tools, particularly those from underrepresented or economically disadvantaged communities, so that all learners develop the emotional, metacognitive, and cognitive skills necessary to grapple with the challenging problems they face. This may involve educational systems and community libraries providing schools and families with the necessary technology, training, and support to implement AI as a learning partner.

Although we acknowledge there is still much more to consider in providing equity for diverse learners, GenAI systems will likely be a key support in these efforts. To ensure AI tools are culturally responsive and sensitive to the needs of learners from diverse communities, researchers, educational technologists, and/or education technology developers must develop AI systems with input from diverse stakeholders, including educators, students, and community leaders from various cultural and demographic backgrounds. By addressing these considerations, AI can become a powerful learning partner, providing cognitive, metacognitive, motivational, emotional, and collaborative support to create a more equitable and inclusive educational experience where every student—regardless of background, race, gender, culture, and socioeconomic status—has opportunities to learn challenging content and practices.

The Role of Teachers in AI-Enhanced Learning Environments

Implementing GenAI in education requires not only physical resources but also significant human resources. The intent is not to replace teachers but to enhance their capabilities, helping them perform their jobs more effectively by providing suggestions to tailor lessons to local contexts and also actionable and constructive feedback on open-ended tasks (Barnes et al., 2024; Price & Grover, 2025). This shift will necessitate a change in the perception of what a teacher does. Just as AI assists doctors in diagnosing patients, GenAI can support teachers in facilitating and enhancing student learning. This partnership can allow teachers to focus more on personalized quality instruction and mentoring, leveraging AI to handle routine tasks and provide targeted interventions.

Need for Future Research

Many current NSF-funded *Division of Research on Learning in Formal and Informal Settings* (DRL) projects relating to AI and student learning are supported through programs outside the DRK-12 portfolio (e.g., ITEST, Research on Innovative Technologies for Enhanced Learning). In this work, we have highlighted various ways STEM educators and researchers can incorporate AI into educational experiences to act as a learning partner, hoping to inspire the DRK-12 community to see ways to enact and study AI applications to support student learning. We also hope that the DRK–12 program continues to support and expand research on student learning with AI, as this is critical to evaluating AI's impact on student learning and motivation in STEM classrooms. Below, we suggest three areas for future research.

Scaffolding Integrated Understanding for All Students

Although we have presented a vision of how GenAI can support students' learning beyond traditional AI (e.g., data-driven machine learning) by providing various cognitive, metacognitive, motivational, emotional, and collaborative supports, it is crucial to conduct extensive research to determine whether GenAI can indeed promote integrated understanding or if it risks becoming a crutch for students in the learning process. As noted above, the potential for GenAI agents to draw from different theoretic foundations to supply different kinds of learning supports at relevant times is an area for further investigation. Further research on using AI as a scaffold and when and how to fade this scaffold over time is likewise needed.

Promoting Inclusivity in STEM Education Addressing Biases and Inequity

A critical aspect of integrating GenAI into education is ensuring AI systems do not perpetuate existing gaps in learning or introduce biases against any racial or cultural group. AI systems are only as good as the research-driven data on which they are trained and the algorithms that power them. For example, a GenAI model such as Retrieval-Augmented Generation (Chu et al., 2024; Yang et al., 2024), which uses data gathered from targeted external sources, will provide more accurate and reliable information than one of the large language models available to the public (e.g., ChatGPT), which use data on the Internet as their corpus. Thus, it is essential to diligently identify and mitigate potential biases. This involves continually monitoring and updating AI systems to ensure fairness and inclusivity to foster integrated understanding in educational environments where all learners have equal opportunities to learn challenging content and practices. This research should involve carefully tracking students from various backgrounds on the depth of learning they achieve over time. By examining how different demographics interact with GenAI, we can assess the tool's effectiveness and impact on long-term educational outcomes.

Transferring Learning Experiences with AI Between Informal and Formal Settings

As GenAI-enabled applications become more common, students will likely encounter and learn how to use AI, especially AI agents, in various informal settings. Because students will have a broad range of experiences and interactions with AI outside of the classroom, research should consider how to monitor and address these potentially disparate student experiences. This could lead to several interesting questions, for example: (1) "How do students apply their outside-classroom knowledge about AI and virtual agents or their skills with such in formal classroom settings?" and (2) "What learning partners best support knowledge transfer between informal and formal educational settings?" These questions are critical to explore as integrating home, informal, and formal learning along with cultural resources can foster more inclusive and meaningful learning in STEM education (Coleman & Davis, 2020).

When and How to Use GenAI Supports

As presented above, GenAI-based applications may have the ability to act as learning partners to provide multiple types of support for students' science learning. This opens the possibility of studying what specific supports promote learning and at what point to use these different supports to best enhance students' learning. This research may draw from and integrate various theoretical perspectives in developing new GenAI-based applications and supports.

Researchers need to consider privacy issues when collecting and using sensitive student data (e.g., personal discourse interactions, facial expressions, and body movements) to create personalized adaptive learning environments. These data are personal information, and we need to protect students' privacy. Educators and researchers should limit AI usage to situations where it is essential to support motivation and learning (i.e. when current resources and technologies are insufficient for providing these needed supports).

Conclusion: A Bright but Challenging Future

The future of AI as a learning partner in education looks promising. AI has the potential to revolutionize learning experiences and outcomes for students from all backgrounds, cultures, and races so that they can solve challenging or ill-structured problems and make sense of compelling and complex phenomena. This partnership involves the exchange of ideas, knowledge, and perspectives. As a learning partner, AI can challenge students' thinking, offer critical feedback, help refine ideas, suggest ways to approach problems, and aid in making informed decisions.

AI can also support the necessary conditions to build integrated understanding so all learners can use what they have learned. Based on Vygotsky's social constructivism, this idea is built on Pea's (1993) seminal work in which intelligence is not confined to individual minds but instead distributed across people, artifacts, and environments. Knowledge and reasoning are often socially constructed through collaboration and the use of designed artifacts, such as tools, diagrams, and computer interfaces. Humans use tools to augment their capabilities in many areas (Engelbart, 1962). AI is one such tool that can work alongside students as a learning partner to promote deep, usable knowledge.

The future of GenAI is not additive but rather transformative, creating learning environments where students actively participate in knowledge creation. Integrating AI into STEM education as a learning partner shifts how STEM students engage with content, enabling them to explore real-world phenomena, solve complex and ill-structured problems, and make informed decisions more effectively. However, as we have also noted, there is a learning gap between more privileged students and students from marginalized racial groups, those with disabilities, or those from lower socioeconomic backgrounds. As educators, we must ensure the equitable and inclusive use of AI and provide opportunities for all learners to access AI tools. Likewise, we must ensure GenAI is not biased for or against certain groups.

As AI continues to evolve, its impact on education will grow, offering new ways to support learners and educators. This CADRE brief highlights the progress and potential for future advancements driven by NSF's commitment to educational innovation. However, significant work remains to ensure this promise is realized equitably and effectively. By conducting rigorous research, addressing disparities, leveraging human resources, and preventing biases, we can ensure the light of AI in education does not dim but continues to shine brightly, illuminating the path to a more inclusive and effective educational system.

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Community for Advancing Discovery Research in Education

CADRE is a network for STEM education researchers funded by the National Science Foundation's Discovery Research PreK-12 (DRK-12) program. Through in-person meetings, a website, common interest groups, newsletters, and more, CADRE connects these researchers who are endeavoring to improve education in science, technology, engineering, and mathematics in, and outside of, our schools.

CADRE helps DRK-12 researchers share their methods, findings, results, and products inside the research and development community and with the greater public so that we are:

- **Better informed** about the work that is being done,
- **Continually building** on what we have collectively learned,
- **Working with our schools, communities, and policy-makers** to make our findings and products accessible and usable, and
- **Progressively able to address new and more challenging issues—**including those issues that extend beyond the limits of what any singular research project can impact.

Together, we can make a larger impact on policy, research, and education.

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