

Transformation STEM Education in The Age of Artificial Intelligence: Generative Technologies, Adaptive Learning, Digital Assessment and New STEM Competencies

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Abstract

The rapid development of artificial intelligence (AI), generative models, adaptive educational systems, and digital assessment tools has begun to significantly change the content and organization of STEM education. While previously the key issue was the creation of interdisciplinary STEM tasks integrating natural sciences, technology, engineering, and mathematics, the current era is characterized by a transition to intelligently supported and personalized educational environments.

The purpose of this analytical review is to identify the main areas of transformation in STEM education under the influence of artificial intelligence and to define new requirements for the educational process and STEM competencies. This review analyzes scientific publications on the use of AI in science teaching, generative AI in STEM, personalized and adaptive learning, intelligent tutoring systems, digital assessment, and the development of teacher and student competencies. It demonstrates that AI can enhance personalization, provide dynamic feedback, and support modeling and complex problem solving. However, the educational impact depends significantly on instructional design.

Recent meta-analytic data confirm the positive effects of AI-supported instruction and GenAI, but also demonstrate high heterogeneity in the results. The changing nature of assessment is particularly significant: traditional checking of the final answer is no longer sufficient, as generative models are capable of independently generating texts, program code, mathematical solutions, and explanations. The need for a shift to assessing the process of reasoning, design, verification, critical evaluation of AI results, and the student's ability to meaningfully use AI is substantiated. A conclusion is drawn regarding the emergence of a new model of STEM education, in which artificial intelligence is not a substitute for teachers or students, but an intelligent tool for collaborative problem solving, and AI literacy, critical thinking, verification, data management, and the ethical use of technology become integral elements of modern STEM competence.

The scientific novelty of this review lies in its approach to the transformation of STEM education, which is not viewed as a standalone implementation of AI technologies, but rather as a change in the entire architecture of STEM activities—from task setting and personalization of learning to assessment and competency structure. The article proposes a conceptual model of Human-AI Integrated STEM, in which artificial intelligence is not a substitute for students or teachers, but an intellectual component of interdisciplinary problem solving. It is further substantiated that, in today's environment, independent verification, validation, and critical assessment of AI results should be considered independent components of a new STEM competency.

Keywords: STEM education, artificial intelligence, generative artificial intelligence, ChatGPT, adaptive learning, personalization, intelligent tutoring systems, digital assessment, AI literacy, STEM competencies.

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1. Introduction

In the previous decade, STEM education developed primarily around the idea of interdisciplinary integration. The primary goal was to create educational situations in which students simultaneously utilize knowledge of natural sciences, mathematics, technology, and engineering design. However, the rapid spread of artificial intelligence has fundamentally changed the technological and pedagogical context of STEM. These changes have become especially rapid with the spread of generative models capable of creating texts, program code, mathematical solutions, images, explanations, and educational materials. Therefore, AI in modern STEM is no longer simply a tool for automating individual operations. It is gradually becoming an element of the educational environment, capable of participating in problem setting, explaining complex concepts, generating hypotheses, modeling, programming, data analysis, and generating feedback [1].

A systematic review of empirical research published in 2024 found that AI is already impacting various components of science education, including teaching, assessment, learning outcomes, and teacher-student interactions [1]. In 2025, this trend was further developed by research on personalized STEM education and AI-enabled adaptive learning [2–5]. Thus, the current stage of STEM development is characterized by a shift from the question “how to integrate four disciplines?” to a more complex question: “how to organize educational activities in which humans and artificial intelligence jointly participate in the exploration, design, solution, and assessment of STEM problems?”

From the digitalization of STEM to the intellectualization of the educational environment.

The transition to AI represents a qualitatively new stage in the digital transformation of education. The use of computers, educational platforms, and digital labs primarily expanded students' access to information and tools. Artificial intelligence adds the ability to dynamically interpret the educational situation and generate a response tailored to the student's context .

A systematic review of AI in science teaching and learning, published in 2024, shows that research is now expanding beyond automated information delivery to include intelligent learning support, assessment, feedback, and analysis of learning outcomes [1]. In this regard, the function of digital technology is fundamentally changing. In a traditional digital environment, students interact primarily with pre-prepared content. In an AI environment, content can be generated dynamically. For example, a student solving a physics problem might receive not just the correct answer, but a sequence of hints tailored to the nature of their error. When learning programming, AI can analyze code, explain the error, and suggest alternative solutions. In an engineering project, a generative system can suggest several design options, which the student must then compare and test. Thus, a fundamentally new pedagogical configuration emerges:

student → AI tool → educational task → human review → solution correction.

The learner remains central. AI enhances cognitive capabilities, but does not eliminate the need for understanding, verification, and decision-making.

Generative AI as a New Component of STEM Education. The most notable technological change of recent years has been the spread of generative AI. Its importance is particularly significant for STEM education, as generative models can work not only with text but also with mathematical expressions, program code, structured data, images, and multimodal tasks.

In 2026, a systematic review and meta-analysis of the impact of generative AI on cognitive outcomes in STEM learning was published. Eighty-five studies were included in the analysis, of which 49 studies with 59 effect sizes were included in the quantitative meta-analysis. The authors found an overall positive effect of student interaction with GenAI, but simultaneously identified extremely high heterogeneity in the results. This means that the presence of generative AI alone does not guarantee improved learning [6]. This conclusion is of fundamental importance. Generative AI should be viewed not as an independent pedagogical technology, but as a component of the pedagogical process .

Its educational value is most evident in four types of activities.

The first is explanation. AI can create different explanations for the same scientific concept, adapting the level of complexity.

The second is idea generation. During project work, students can use GenAI to formulate multiple hypotheses or engineering solution options.

The third is modeling and programming. Generative systems can help create code, mathematical models, and computational procedures.

The fourth is critical validation. The most promising approach is not simply receiving an answer from the AI, but rather analyzing its correctness.

This last aspect fundamentally changes the nature of the STEM task. While previously the student had to independently generate a solution, now the educational task may involve generating an AI solution, identifying its errors, verifying its assumptions, and improving the proposed model. Consequently, generative AI shifts some of the STEM activity from directly generating an answer to its analysis, verification, and improvement.

Personalization and adaptive STEM learning. The second fundamental direction of transformation is the shift from a relatively uniform educational trajectory to personalized learning. In 2024, a meta-analysis of independent studies of AI-enabled adaptive learning showed a positive effect of adaptive systems on learning outcomes, although the magnitude of the effect depended on the characteristics of the educational context [2].

More recent research has addressed this issue specifically in relation to STEM. A meta-analysis of AI-enabled personalized STEM education in schools, published in 2025, found that the effectiveness of AI-enabled personalized learning depends, in particular, on the educational level, the type of AI application, the personalization model, and the subject area [3].

It's especially important that the adaptive system is no longer limited to choosing the next task. Modern AI systems are potentially capable of taking into account:

- the student's previous results;
- the nature and typical causes of errors;
- speed of task completion;
- the level of difficulty that is optimal for a particular student;
- the nature of interaction with educational materials;
- the need to repeat a certain concept;
- the dynamics of competence formation.

A systematic review of research on personalized adaptive learning in higher education, published in 2024, found

that improved academic outcomes were reported in 59% of the studies reviewed, and increased engagement in 36% [4].

However, personalization also has its limitations. It requires high-quality student data, reliable algorithms, and a pedagogically sound adaptation model. Moreover, excessive automation can lead to the educational trajectory being determined by an algorithm without sufficient teacher input.

Therefore, the promising model is not the “AI instead of a teacher” model, but the following model:

diagnostics → AI analysis → personalization → pedagogical solution → adapted task → feedback → re-diagnostics.

In such a system, the teacher retains the function of a pedagogical interpreter, while the AI takes on a significant portion of the analytical work.

Intelligent tutoring systems and the changing role of the teacher. Intelligent tutoring systems occupy a special place in the development of adaptive STEM. A 2025 study on adaptive intelligent tutoring systems in STEM shows the promise of systems that use machine learning and natural language processing to dynamically adjust educational trajectories and provide personalized feedback [5]. Such systems are especially important for mathematics, physics, and programming, where learning has a sequential structure: a lack of understanding of a fundamental concept can hinder the assimilation of subsequent material.

An intelligent tutor can identify such difficulties earlier than a teacher would in a traditional classroom setting. This changes the teacher's professional role. In the traditional model, a teacher simultaneously explains material, monitors assignments, diagnoses errors, and evaluates results. In an AI-enabled model, some of these operations can be automated. However, this does not diminish the teacher's role. On the contrary, the importance of functions that are more difficult to automate increases:

- setting educational goals;
- designing complex STEM tasks;
- interpretation of AI recommendations;
- development of critical thinking;
- organizing group work;
- discussion of ethical aspects;
- control of the reliability of AI results;
- development of student independence.

Thus, artificial intelligence can reduce the volume of routine activities for teachers, but at the same time

increases the demands on their pedagogical, digital, and AI competencies .

From the use of AI to the collaborative work of humans and artificial intelligence, one of the most important trends is the changing understanding of learning itself. In traditional STEM, the student had to independently:

pose a problem → collect information → build a model → get a solution → check the result.

In an AI-supported environment, a different sequence is possible:

pose a problem → formulate an AI request → obtain several options → critically check → select or modify a solution → experimentally verify → explain the result.

The second model is potentially more productive, but only if the student has the ability to control the AI's operations. Therefore, a new category of educational activity is emerging: AI-mediated problem solving .

A paradox arises here. The more sophisticated the AI tool becomes, the less direct technical work the student can perform. At the same time, the need to understand why the AI offers the solution it does and whether it can be trusted increases . Consequently, one of the most important outcomes of modern STEM is not the ability to compete with AI in computational speed or coding, but the ability to effectively use AI to solve problems that require human understanding, verification, and accountability.

Digital assessment: from answer checking to process evaluation. AI is transforming assessment most radically. Even before the spread of generative models, one of the challenges in STEM was the discrepancy between the interdisciplinary nature of educational goals and the predominantly subject-based assessment system. The spread of GenAI has exacerbated this tension.

A 2024 systematic review of the transformation of assessment under the influence of generative AI showed the need to reconsider traditional assessment models and increase the focus on student autonomy, responsibility and academic integrity [7].

Recent research on STEM assessment in the age of AI explores the emerging capabilities of machine learning and natural language processing for automated assessment, dynamic diagnostics, personalized feedback, and progress monitoring [8]. However, automated assessment also poses a fundamental challenge: what exactly should be assessed if AI can generate the correct answer?

If a student is asked to solve a math problem, write software, or prepare a textual explanation, a generative model can do much of the work. Therefore, assessing the final product is no longer a sufficient indicator of individual understanding.

As a result, there is a need to shift the center of assessment:

from product → to process;

from the correct answer → to the justification;

from reproduction → to application;

from the result → to the trajectory of its achievement.

For STEM, this means strengthening the following types of assessment:

1. explanation of the logic of the solution;
2. protection of the design solution;
3. analysis of alternatives;
4. identifying errors in the AI response;
5. testing a mathematical or scientific model;
6. experimental verification;
7. maintaining a digital project log;
8. demonstration of individual contribution;
9. reflection on the use of AI;
10. solving new problems that require knowledge transfer.

Thus, digital assessment is gradually transforming from a tool for recording the final result into a tool for analyzing the cognitive process .

A new challenge: the reliability of AI results.

Generative AI poses another unique challenge for STEM: the possibility of obtaining a convincing but erroneous result. This is especially significant for the natural sciences and engineering. AI can offer a plausible explanation for a physical phenomenon, a mathematical transformation, or program code containing a hidden error. Therefore, the traditional focus on "getting the right answer" must be complemented by the focus on "proving the answer is correct." This fundamentally changes the content of STEM literacy.

The student should be able to:

- formulate a correct request;
- recognize AI limitations;
- identify logical errors;
- check calculations;
- compare the result with scientific sources;
- conduct an experimental test;
- assess the quality of data;
- distinguish between fact and probabilistic assumption;
- to accept or reject an AI recommendation with reasons.

Thus, verification becomes an independent STEM competency .

Developing new AI competencies for teachers. STEM transformation is impossible without changing teacher competencies. In 2025, a system for assessing teachers' competencies in the field of generative AI was developed and validated, reflecting the transition from a general understanding of digital literacy to a more specific GenAI competency [9].

For STEM educators, simply knowing how to use digital educational platforms is no longer enough. Additional competencies are required:

AI instrumental competence is the ability to select and use appropriate AI systems;

Pedagogical AI competence - understanding where AI truly improves the quality of education;

AI assessment competence - the ability to design tasks that are robust to simple AI implementation;

information-analytical competence - the ability to verify the reliability of AI-generated information;

ethical competence - understanding issues of confidentiality, authorship, academic integrity and fairness;

Methodological competence is the ability to incorporate AI into a STEM project without turning it into a substitute for the student's cognitive activity.

Of particular importance is the concept of AI competence, which distinguishes simple knowledge of the principles of artificial intelligence from the ability to apply this knowledge in a specific situation [10]. Therefore, in a prospective system for training STEM teachers, AI should be considered not as a separate, optional technology module, but as a comprehensive component of professional training .

A New Framework for STEM Competencies. The development of AI requires a reconsideration of the very concept of STEM competence. In the traditional model, it included subject knowledge, mathematical thinking, research skills, engineering design, problem solving, communication, and teamwork. New components are currently being added to them.

Table 1. Transformation of the structure of STEM competencies under the influence of artificial intelligence
Traditional component New content in the AI environment

Subject knowledge	Ability to apply knowledge in conjunction with AI tools
Mathematical thinking	Validation and interpretation of AI calculations and models
Problem solving	Collaborative human-machine problem solving
Research activities	Forming hypotheses using AI and independently testing them
Information literacy	A Critical Assessment of AI-Generated Information
Programming	AI-assisted coding and verification of generated code
Modeling	Generation, comparison and verification of digital models
Creation	Generation and critical selection of alternative solutions
Communication	Formulate effective queries and explain AI-supported solutions
Independence	The ability to use AI without cognitive dependence on it
Digital literacy	AI literacy
Ethical responsibility	Responsible, transparent, and secure use of AI

Thus, modern STEM competence is becoming metacognitive. Students must not only know and be able to do something, but also understand when, why, and how to use artificial intelligence.

Key Risks of AI-Based STEM Transformation.

Despite AI's significant potential, there's no reason to view it as a universal tool for improving the quality of STEM education. There are a number of risks that must be considered when implementing AI in the educational process. The first risk is related to cognitive dependence. If a student constantly delegates analysis, calculation, and decision-making to an AI, independent thinking may be impaired.

The second is the fallibility of AI results. Even a convincingly formulated answer may contain factual, logical, or mathematical errors.

The third risk is the diminished validity of traditional assessments. If the final product is easily generated by AI, it ceases to be a reliable indicator of an individual's level of competence.

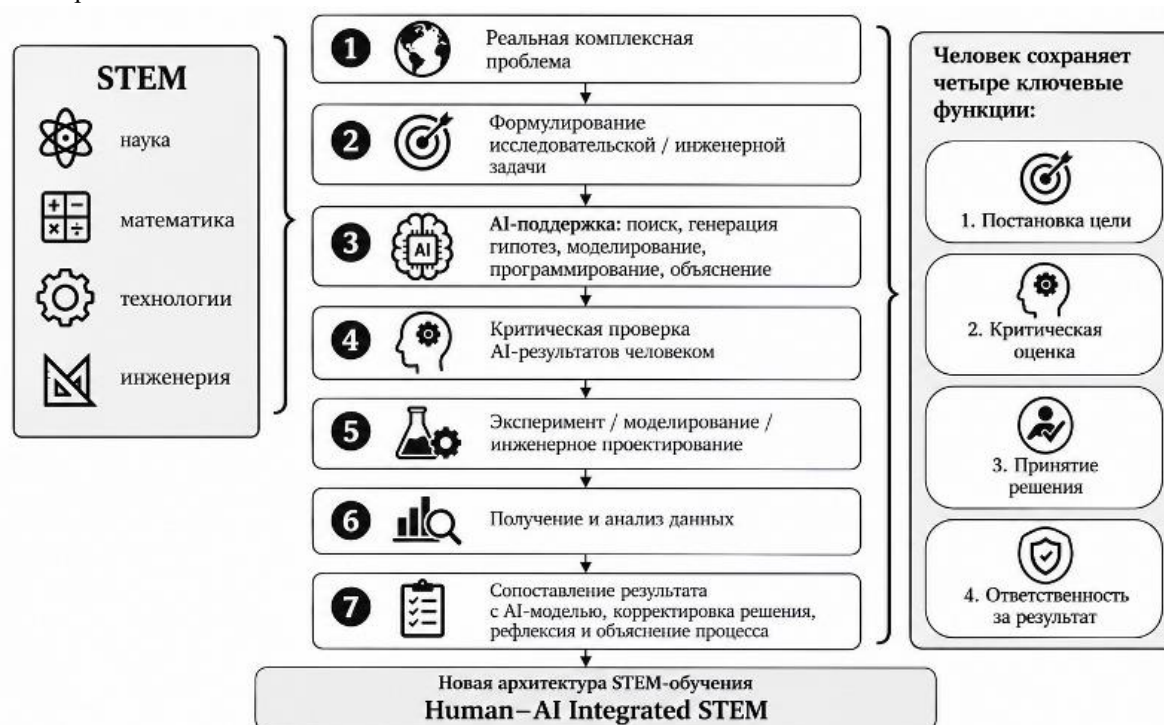
Fourth, inequality of access. Differences in access to modern models, computing resources, and high-quality digital tools can exacerbate educational inequality.

The fifth risk is the professional level of teachers. Even a high-quality AI tool can produce poor educational results if used improperly.

The sixth risk is the substitution of technological innovation for pedagogical goals. Using AI for the sake of using AI is not a STEM innovation.

Therefore, the key principle of modern transformation can be formulated as follows: AI should not determine the pedagogical model; the pedagogical goal should determine the way AI is used.

An integrated model of STEM education in the era of artificial intelligence. Based on an analysis of recent research, we propose expanding the conceptual model of STEM. The modern model can be represented as follows:



This is how a new architecture for STEM education is emerging, which can be loosely described as Human-AI Integrated STEM. Its fundamental difference from the previous model is that artificial intelligence is not added to STEM as another technological component. It becomes a tool for organizing individual cognitive operations within an interdisciplinary task. At the same time, the human retains four key functions: **goal setting** → **critical evaluation** → **decision making** → **responsibility for the outcome**.

From STEM to AI-enhanced STEM: Key Transformation Directions. A summary of the research identifies five interconnected directions. STEM content includes AI literacy, data science, algorithmic thinking, an understanding of generative model principles, and the ethics of artificial intelligence. Second, the transition occurs from a predominantly sequential transfer of knowledge to personalized, interactive, and adaptive learning. Third, the student becomes not only the performer of a task but also the operator of intelligent

tools, the analyst of AI results, and an expert in their verification. Fourth, the teacher gradually shifts from the role of the primary source of information to that of the designer of the educational environment, mentor, moderator, and expert in the interpretation of results.

Fifth, not only the final product but also the process should be assessed: problem setting, argumentation, use of AI, verification of the result, independence, and the ability to transfer acquired knowledge.

2. Conclusion

STEM education is entering a new phase of development, characterized by a shift from digital and interdisciplinary learning to an intelligently supported, adaptive, and personalized learning environment.

Artificial intelligence is simultaneously impacting STEM content, teaching methods, student and teacher activities, assessment systems, and competency frameworks. Generative models expand capabilities for explanation, programming, modeling, hypothesis generation, and design. Adaptive systems enable dynamically changing educational trajectories. Intelligent tutors provide personalized feedback. Digital assessment is shifting from monitoring the final product to analyzing the solution process and individual contribution.

However, recent scientific data does not support the notion of AI as a universal tool for improving STEM effectiveness. The resulting effect depends significantly on the educational context and the nature of human interaction with technology. The most significant transformation is occurring in the structure of STEM competencies. Traditional subject-matter, research, engineering, and cognitive skills are being supplemented by AI literacy, the ability to formulate effective queries, critically evaluate AI results, validate data and models, manage collaborative human-AI activities, and make responsible decisions.

In this regard, a promising STEM model can be formulated as follows: **pose a real problem → identify the necessary knowledge → use AI to expand research capabilities → critically examine the AI result → experimentally or logically validate the solution → improve it → explain the process → evaluate the result and the method for obtaining it.**

Thus, modern STEM is gradually transforming from a model of integrating four disciplines to a model of integrating people, interdisciplinary knowledge, and artificial intelligence. The most promising direction for further research is identifying pedagogical conditions

under which AI does not reduce student independence, but rather enhances their ability to explore, engage in engineering design, think critically, be creative, and transfer knowledge to new situations.

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