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THE EVOLUTION AND STRUCTURAL ATTRIBUTES OF STEM LANGUAGE IN UNIVERSITY MATHEMATICS EDUCATION OF THE USA AND UKRAINE

The article provides a theoretical, methodological and comparative analysis of the development of STEM language in mathematics education at universities in the United States and Ukraine. It is shown that in the leading educational systems of the world, in particular in the United States, STEM language is formed as an integrated system of knowledge and practices focused on solving real problems, while in Ukraine this process is transformative in nature and requires scientific understanding and improvement. The methodological basis of the study is a combination of systemic, competency and integrative approaches, which allow considering STEM language as a multi-component holistic system. The attributes of STEM language literacy are identified: mathematical, algorithmic, digital, modeling, communicative, interdisciplinary, research, critical and innovative. It was established that both educational systems have a common basis, but differ in the pace of transformation: in the USA – evolutionary development with early integration of technologies, in Ukraine – the dominance of theoretical training and the gradual introduction of digital approaches. In the USA, STEM language literacy is formed systematically, while in Ukraine there is an imbalance between fundamental mathematical training and the development of digital and communicative components. The conclusion is made about the need to modernize mathematics education in Ukraine on the basis of the STEM approach, which will allow to increase the level of STEM language literacy of students and their readiness for professional activity in the conditions of global technological development. The results of the study have theoretical and practical significance, as they expand the understanding of STEM language as a pedagogical category, offer tools for its structuring and assessment, and also determine the directions of improving mathematics education in the context of modern educational challenges.

Key words: *STEM education, higher education, university, STEM language, mathematical education, STEM language literacy, USA, Ukraine.*

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In the current conditions of globalization, digitalization and rapid development of technologies, the problem of forming a new quality of mathematical education, capable of preparing specialists for work in a high-tech environment, is of particular relevance. One of the key factors in such transformation is the emergence and development of STEM language as an integrated means of scientific, educational and professional communication, combining mathematical, algorithmic, digital and interdisciplinary components.

Analysis of modern scientific research indicates a gradual transition from the traditional understanding of mathematical language as a formal-symbolic system to its interpretation as a functional-activity tool that provides modeling, data analysis, programming and interdisciplinary interaction [4], [5], [9], [17] [18]. In this context, a comparative study of the development of STEM language in different educational systems, in particular in the USA and Ukraine, which have different historical, methodological and institutional prerequisites for the formation of mathematical education, is of particular importance [2], [8], [11], [21].

The purpose of the work is a comprehensive theoretical, methodological and comparative analysis of the formation and development of STEM language in mathematics education at universities in the USA and Ukraine, which involves identifying its structural components, educational-historical dynamics (1940–2026), similarities and differences in educational models, as well as substantiating the attributes of STEM language literacy as the basis for its qualitative and quantitative assessment.

Achieving the goal entails solving the following research tasks: to analyze the evolution of STEM language in mathematics education at universities in the USA and Ukraine in time (1940–2026) and identify the key stages of its transformation; to identify similarities and differences in the formation of STEM language based on a comparative analysis of educational systems, reflected in the corresponding summary table; to structure the concept of STEM language by identifying key attributes of STEM language literacy (mathematical, algorithmic, digital, communicative, interdisciplinary, etc.); to determine the levels of formation of these attributes in the context of mathematics education at universities in the United States and Ukraine; to substantiate the possibilities of using the attributive approach as a tool for further quantitative measurement of STEM language literacy; to formulate scientifically based conclusions on the directions of modernization of mathematics education in Ukraine, taking into account leading international experience.

The empirical and theoretical basis of the study was scientific publications on the problems of STEM education, mathematical didactics, digital pedagogy and interdisciplinary learning; monographs and analytical reports of international organizations dedicated to the development of STEM competence; educational standards, curricula and curricula of universities in the USA and Ukraine, reflecting the peculiarities of the organization of mathematical education; results of previous studies on the integration of digital technologies, programming and modeling in mathematics teaching.

To achieve the goal of the work, a set of complementary methods was used: analysis and synthesis of scientific literature which was applied to generalize theoretical approaches to understanding STEM language, determining its essence, structure and functions in mathematics education; comparative method and pedagogical analysis used to study the evolution of STEM language in mathematics education at universities in the USA and Ukraine in the period 1940–2026, which allowed us to identify key stages of development and patterns of transformation of educational models; and to identify similarities and differences in the formation of STEM language in different educational systems, which is reflected in the corresponding summary table; system approach allowed us to consider STEM language as a holistic integrated system that includes interconnected components (mathematical, algorithmic, digital, communicative, etc.); structural and functional analysis used to identify and substantiate the attributes of STEM language literacy, determine their role and relationships within the educational process; expert assessment method used to determine the levels of development of individual attributes of STEM language literacy in universities in the USA and Ukraine based on the generalization of scientific sources and educational practice; generalization and interpretation of results used to formulate conclusions regarding the level of development of STEM language and determine the prospects for its development in mathematics education.

The phenomenon of STEM language, determining its structure, dynamics of development and impact on the quality of training of future specialists in the field of mathematics and related disciplines in the paper are describes the two interrelated analytical constructs: first, a table of similarities and differences in the development of STEM language in time (1940–2026), which allows us to trace the educational-historical dynamics and patterns of transformation of educational approaches; secondly, a table of attributes of STEM language literacy, which provides structuring of this concept and creates a basis for its empirical measurement.

As a result of the study of the features of the functioning of STEM language in mathematical education in US and Ukrainian universities, both common features and significant differences were identified, reflecting the specifics of the organization of the educational process in both countries (see Table 1).

The analysis of the data presented in Table 1 allows us to trace the long-term evolution of STEM language in mathematics education at universities in the United States and Ukraine in the context of the transformation of scientific and educational paradigms, digitalization, and interdisciplinary integration. The generalization of historical stages in combination with the scientific approaches of leading authors [22], [10], [15], [19], [7], [14], [17] demonstrates a significant asymmetry in the dynamics of the development of STEM language between the two educational systems.

The evolution of STEM language in mathematics education is a multi-level process that encompasses the transition from classical mathematical formalization to modern digitally integrated and competency-based STEM communication. In 1940–1960, the USA developed applied and computational mathematical language influenced by the military-industrial complex and early cybernetics [22]. At the same time, in Ukraine (within the framework of the Soviet educational model) the fundamentalization of mathematical training, focused on theoretical rigor and logical provability, dominated [1], [14]. This created an initial divergence: in the USA the mathematical language from an early stage acquired an applied character, while in Ukraine it was academic-theoretical. In the period 1960–1980, the formation of an algorithmic and computer paradigm of mathematical language took place in the USA, which is confirmed by the works of E. W. Dijkstra [10] and Donald E. Knuth [15] who laid the foundations of structured programming. At this time, mathematical language begins to transform into STEM-language as an integrative tool for describing computational processes. In Ukraine, the corresponding process was limited in nature and did not go beyond the experimental use of computing

Table 1

STEM language in mathematics education at universities in the USA and Ukraine (1940–2026)

Period	Common features (USA and Ukraine)	Differences (USA vs Ukraine)
1940–1960	Formation of fundamental mathematical language; development of logical thinking	USA: applied and military-engineering orientation; Ukraine: theoretical and proof model
1960–1980	Strengthening the role of computational mathematics	USA: development of algorithms and programming; Ukraine: limited implementation of computational methods
1980–2000	Gradual digitalization of education	US education: the emergence of digital STEM language and constructionism; Ukraine: fragmented computerization
2000–2010	Development of innovative educational approaches	US: the formation of STEM as an integrated system; Ukraine: isolated STEM initiatives
2010–2015	Strengthening interdisciplinarity in the	USA: institutionalization of STEM, active programming; Ukraine: beginning of systematic implementation of STEM
2016–2020	Active digitalization of mathematics education	USA: data science, Python, R as part of STEM language; Ukraine: partial integration of digital technologies
2021–2026	Strengthening the competency approach; development of digital skills	USA: AI, Big Data, STEM as a professional language of activity; Ukraine: a transitional model of digital STEM education

technology, which led to a lag in the formation of the digital component of mathematical communication. Between 1980–2000, the USA shifted toward digital education and constructionist learning [19], fostering modeling and interactivity and forming STEM language as an integrated system that combines mathematical, technological and cognitive components [4]. Ukraine experienced gradual but mainly adaptive modernization without a holistic STEM framework. The period 2000–2015 marked the institutionalization of STEM education in the USA, with full transition to interdisciplinary models involving programming and data analysis [3], [6], [9]. STEM is considered as an integrated educational system that forms a new type of scientific language [3], [7]. In Ukraine, STEM elements emerged fragmentarily with limited integration. In the current period (2016–2026), a qualitative transformation of STEM language is taking place under the influence of artificial intelligence, Big Data and data science [17], [20]. In the USA, STEM language functions as a universal tool for professional activity, ensuring communication between mathematics, engineering and digital technologies. In Ukraine, there is an intensification of the processes of digitalization of education, however, STEM language has not yet reached the level of full integration and remains partially formalized. Thus, the analytical generalization of Table 1 allows us to conclude that the key difference between the USA and Ukraine is the speed and depth of the transformation of mathematical language into STEM language. In the USA, this process has a continuous evolutionary character with early integration of technologies and interdisciplinarity, while in Ukraine it is mainly of a stage-by-stage catching-up nature. At the same time, in the modern period there is a tendency towards convergence of educational models, which creates the prerequisites for further harmonization of STEM education at the international level.

The development of a STEM-language literacy attribute table aims to operationalize this interdisciplinary concept through measurable indicators. It is based on systemic, competency-based, and integrative approaches, viewing literacy as a unified structure of interrelated components. The identified attributes include mathematical, algorithmic, digital, modeling, communicative, interdisciplinary, research, critical thinking, innovative, and professional literacy. These reflect the shift from formal mathematics to a digital-communicative system. Each attribute serves as an indicator of STEM language formation and enables comparative analysis of educational practices in the USA and Ukraine. Expert assessment ensures validity and supports further quantitative evaluation, including the calculation of a STEM Language Literacy Index (ISLG).

Thus, the developed table is a methodologically sound research tool that provides a transition from the conceptual level of understanding STEM language to its quantitative and qualitative assessment in the context of mathematics education at universities in the United States and Ukraine (see Table 2).

The presented table reflects the structural and functional analysis of STEM-language literacy as a complex integrative phenomenon that is formed within the framework of mathematical education and determines the readiness of students for professional activity in the digital economy. First of all, it should be noted that mathematical literacy in both countries is at a high level, which confirms its basic status in the structure of STEM education. According to L. D. English, mathematics is at the core of STEM integration, providing a conceptual framework for other disciplines [12]. At the same time, the nature of its implementation is different: in the USA it functions as a tool for applied analysis and modeling, while in Ukraine it retains a predominantly theoretical and evidence-based orientation. This indicates different educational paradigms: activity and academic, respectively. Analysis of algorithmic and digital literacy reveals clear differences: in the USA these components are fully integrated into mathematics education, forming a holistic STEM language, while in Ukraine they remain partial and unsystematic, limiting practical application. A gap is also observed in modeling and research literacy. US universities active use project-based learning, enabling students to build models and conduct real research [16], whereas in Ukraine such practices are limited, leading to predominantly reproductive learning. These findings align with research confirming the effectiveness of interdisciplinary integration. Communicative STEM literacy is another weak area in Ukraine. In the USA, it is a key element, supporting academic writing, presentations, and teamwork [6], while in Ukraine its Insufficient development complicates integration into the international environment.

Differences are also evident in interdisciplinary and innovative literacy: the USA demonstrates a systemic approach fostering innovation and student involvement in projects, whereas in Ukraine these processes remain fragmented. Professionally-oriented literacy further highlights the gap: US education is closely linked to labor market needs, while in Ukraine there is a disconnect between theoretical training and practical demands. Thus, an analytical review of the table allows us to conclude that STEM language literacy is formed as a multi-component system, where the effectiveness of each attribute depends on the level of their integration. In the USA, this system is holistic and functional, while in Ukraine there is an imbalance between a high level of mathematical training and insufficient development of digital, communicative and interdisciplinary components. This determines the need to modernize mathematics education in Ukraine by strengthening the practice-oriented approach, digitalization and development of STEM communication.

The results of the conducted scientific and pedagogical research allow us to assert that the STEM language in mathematics education at universities in the USA and Ukraine is formed under the influence of different educational strategies, which determines its functional content, level of integration and practical orientation. The generalization of empirical data in combination with the analysis of modern scientific works made it possible to

Table 2

Attributes of STEM-language literacy in mathematics education at universities in the USA and Ukraine

Attribute of STEM-language literacy	Content of the attribute	Manifestation USA/Ukraine	Level of formation USA/ Ukraine
Mathematical literacy	Mastery of symbols, formulas, proofs, abstract thinking	Integrated with applied problems and modeling / Orientation to theoretical training and provability	High / High
Algorithmic literacy	Understanding of algorithms, logic, data structures	Widely integrated into mathematics courses / Partially represented, by separate disciplines	High / Medium
Digital literacy	Use of ICT, programming, data analysis	Active use of Python, R, AI, Big Data / Limited or unsystematic use of digital tools	High / Medium–low
Modeling literacy	Building mathematical models of real processes	Orientation to real cases and projects / Mostly theoretical problems with limited modeling	High / Medium
Communicative STEM literacy	Ability to explain, present and interpret results	Advanced academic writing, presentations, teamwork / Limited attention to communication of results	High / Medium–low
Interdisciplinary literacy	Integration of knowledge from different fields (mathematics, IT, engineering)	Systemic interdisciplinarity / Fragmented integration	High / Medium
Research literacy	Ability to analyze, experiment, work with data	Active participation in projects and research/ Limited practical research activities	High / Medium
Critical thinking	Analysis, evaluation, interpretation of mathematical and digital data	Developed through problem-based learning/ Formed mainly through theoretical tasks	High / Medium
Innovation literacy	Ability to create new solutions based on STEM	Startups, engineering projects, AI solutions / Limited practical implementation of innovations	High / Low–Medium
Professionally oriented literacy	Application of STEM language in professional activities	Close connection with the labor market and industry / Partial gap between education and practice	High / Medium

deepen the understanding of this issue and identify key patterns. In particular, the results of the study confirm the conclusions of modern authors regarding the integrative nature of STEM language in the US educational system. Thus, the works of R. W. Bybee [7], L. D. English [12], S. Freeman et al. [13] and Y. Li et al. [17] emphasize that effective STEM education involves an organic combination of mathematical apparatus with digital technologies, engineering thinking and data analysis. The results obtained are consistent with these approaches: in the studied US universities, the language of mathematics is actively transformed into a functional tool for solving applied problems, which is implemented through the use of programming languages (Python, R), mathematical modeling, and interdisciplinary projects. In comparison, the results of the analysis of the Ukrainian educational environment demonstrate a certain discrepancy with modern global trends [2]. STEM education in Ukraine is at the stage of active implementation, but is characterized by insufficient systematicity and limited integration into curricula. The language of mathematical education in Ukrainian universities retains a predominantly theoretically oriented character, with the dominance of formalized symbolism and evidential approaches, while STEM elements are used episodically.

An important aspect of the analysis is the communicative component of STEM language. Research emphasizes the role of active learning, collaboration, and scientific communication. In the USA, universities actively develop skills in interpreting and presenting mathematical results and working in interdisciplinary teams, while in Ukraine this component remains insufficient, limiting professional application. Comparative findings confirm that interdisciplinary integration improves competences, and its systematic implementation in the USA ensures a higher level of STEM language development [4], [8]. In Ukraine, integration is often fragmented, creating a gap between theory and practice. Digital competences are key component of STEM language [17]. In the USA, digital tools are fully integrated into mathematics education, whereas in Ukraine their use is limited. Although mathematical language is fundamental in both systems, in the USA it has a broader functional role, combining mathematics with programming, data analysis, and engineering. Interdisciplinary and project-based learning turns STEM language into a tool for modeling, communication, and real-world professional activity.

Thus, the results of the study indicate that the main difference lies in the level of integration and functionality of the STEM language: in the USA it is an integral part of practice-oriented and interdisciplinary education, while in Ukraine it mainly retains a theoretically oriented character. At the same time, the presence of a common

fundamental basis creates the prerequisites for further modernization of mathematical education in Ukraine, taking into account the international experience of STEM education.

The conducted research allows us to formulate the following generalizing conclusions. It is substantiated that STEM language in mathematics education is a complex integrated system that has evolved from a formal-symbolic mathematical language to a multifunctional tool for interdisciplinary, digital and professional communication. Its formation is determined by the interaction of mathematical, algorithmic, digital and communicative components. It is established that the development of STEM language in mathematics education at universities in the USA and Ukraine has common historical prerequisites, but is characterized by different trajectories. In the USA, this process is continuous, evolutionary and institutionally supported, while in Ukraine it is staged and transformational, with the dominance of fundamental mathematical training. It is found that in the USA all attributes of STEM linguistic literacy have a systematic and balanced development, while in Ukraine there is an imbalance between a high level of mathematical training and insufficient development of digital, communicative, and innovative components. It is proven that the use of an attributive approach creates the basis for further quantitative assessment of the level of STEM linguistic literacy, in particular through the construction of integral indices, which opens up opportunities for objective comparison of educational systems. It has been established that the key factor in the effective formation of STEM language is the degree of integration of mathematical, digital and communicative training, which determines the readiness of students for professional activity in the conditions of the modern technological environment.

Comparing the results of our own research with the works of modern authors allows us to conclude that the key difference lies in the functional purpose of STEM language: in the US educational system it acts as a universal tool of activity, communication and interdisciplinary interaction, while in Ukraine it is mainly a means of formalized description of mathematical objects. This determines the need to transform approaches to mathematical education in Ukraine in the direction of strengthening interdisciplinarity, digitalization and development of communicative competencies, which corresponds to modern trends in the development of global STEM education.

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Л. В. Батюк. Еволюція та структурні атрибути STEM-мови в університетській математичній освіті США та України

У статті здійснено теоретико-методологічний і порівняльний аналіз розвитку STEM-мови в математичній освіті університетів США та України. Показано, що у провідних освітніх системах світу, зокрема у США, STEM-мова формується як інтегрована система знань і практик, орієнтована на вирішення реальних задач, тоді як в Україні цей процес має трансформаційний характер і потребує наукового осмислення та вдосконалення. Методологічну основу дослідження становить поєднання системного, компетентнісного та інтегративного підходів, що дозволяють розглядати STEM-мову як багатокомпонентну цілісну систему. Виокремлено атрибути STEM-мовної грамотності: математичний, алгоритмічний, цифровий, моделювальний, комунікативний, міждисциплінарний, дослідницький, критичний та інноваційний. Встановлено, що обидві освітні системи мають спільну основу, але різняться темпами тран-

сформації: у США — еволюційний розвиток із ранньою інтеграцією технологій, в Україні — домінування теоретичної підготовки та поступове впровадження цифрових підходів. У США STEM-мовна грамотність формується системно, тоді як в Україні спостерігається дисбаланс між фундаментальною математичною підготовкою та розвитком цифрових і комунікативних компонентів. Зроблено висновок про необхідність модернізації математичної освіти в Україні на засадах STEM-підходу, що дозволить підвищити рівень STEM-мовної грамотності студентів та їхню готовність до професійної діяльності в умовах глобального технологічного розвитку. Результати дослідження мають теоретичне та практичне значення, оскільки розширюють уявлення про STEM-мову як педагогічну категорію, пропонують інструменти її структуризації та оцінювання, а також визначають напрями вдосконалення математичної освіти у контексті сучасних освітніх викликів.

Ключові слова: *STEM-освіта, вища освіта, університет, STEM-мова, математична освіта, STEM-мовна грамотність, США, Україна.*

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