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### **STEM education: defining the core concepts**

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**Abstract.** The article “STEM Education: Defining the Core Concepts” is devoted to a comprehensive analysis and systematisation of the terminological and conceptual field of STEM education as an innovative educational paradigm of the twenty-first century. The relevance of the study is determined by the role of STEM education in the modernisation of educational systems, its capacity to respond to global socio-economic and technological challenges, and its ability to ensure the training of competitive specialists equipped with critical thinking, creativity, innovativeness, and teamwork skills. The authors emphasise that STEM education combines integrative and pragmatic approaches, which provide an organic synthesis of theory and practice and orient the educational process toward the demands of the contemporary labour market. The article presents an in-depth review of scientific literature, which demonstrates the dynamic and interdisciplinary character of STEM discourse and highlights the asymmetry between the well-developed international research field and the domestic scholarly context. Particular attention is given to the analysis of the core components of STEM (Science, Technology, Engineering, Mathematics), which are considered as interrelated elements of an integrated educational system. Three levels of integration are identified: disciplinary, interdisciplinary, and transdisciplinary, which progressively expand the possibilities for applying knowledge and skills in the learning process and contribute to the development of learners' capacity for comprehensive problem-solving. Derivative concepts are also examined, including STEAM (integration of the arts), STREAM (integration of language activities such as reading and writing), and STEMM (integration of medicine). These extensions illustrate the dynamic evolution of the STEM terminological field and its adaptation to contemporary

educational and social challenges. The study demonstrates that STEM education is not merely an aggregation of separate disciplines but rather a multidimensional phenomenon that unites content, methodology, and pedagogical technologies, thereby ensuring the formation of key twenty-first-century competences. The systematisation of the terminological and conceptual field of STEM education is presented as a necessary condition for conceptual clarity, the harmonisation of international educational standards, and the effective implementation of educational reforms. The research contributes both to the theoretical understanding of STEM education and to the practical support of its implementation, aimed at preparing young people for successful professional activity in a rapidly changing environment.

**Keywords:** STEM education, integrative approach, pragmatic approach, STEAM, STREAM, STEMM, critical thinking, innovation, educational paradigm.

### **STEM-освіта: трактування ключових концептів**

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**Анотація.** Стаття «STEM-освіта: трактування ключових концептів» присвячена комплексному аналізу та систематизації термінологічно-поняттєвого поля STEM-освіти як інноваційної освітньої парадигми XXI століття. Актуальність дослідження визначається роллю STEM-освіти у модернізації освітніх систем, її здатністю відповідати на глобальні соціально-економічні та технологічні виклики, а також забезпечувати підготовку конкурентоспроможних фахівців, здатних до критичного мислення, креативності, інноваційності та командної співпраці. Автори підкреслюють, що STEM-освіта поєднує інтегративний та прагматичний підходи, які забезпечують органічне поєднання теорії й практики та орієнтацію на потреби сучасного ринку праці. У статті здійснено ґрунтовний огляд наукової літератури, що засвідчує динамічний і міждисциплінарний характер STEM-дискурсу, а також окреслює асиметрію між розвиненим зарубіжним та вітчизняним науковим полем. Особливу увагу приділено аналізу ключових компонентів STEM (Science, Technology, Engineering, Mathematics), які розглядаються як взаємопов'язані складники інтегрованої освітньої системи. Визначено три рівні інтеграції – дисциплінарний, міждисциплінарний та трансдисциплінарний, що

поступово розширюють можливості застосування знань і навичок у навчальному процесі та сприяють формуванню здатності учнів до комплексного розв'язання проблем. Особливо розглянуто похідні концепції – STEAM (інтеграція мистецтва), STREAM (інтеграція мовленнєвої діяльності: читання та письмо), STEMM (інтеграція медицини), які свідчать про динамічність розвитку термінологічного поля та його адаптацію до сучасних освітніх і соціальних викликів. Показано, що STEM-освіта не є простою сукупністю дисциплін, а постає як багатовимірний феномен, що поєднує зміст, методологію та педагогічні технології, забезпечуючи формування ключових компетентностей XXI століття. Систематизація термінологічно-поняттєвого поля STEM-освіти є необхідною умовою для концептуальної визначеності, узгодження міжнародних освітніх стандартів та ефективної реалізації освітніх реформ. Представлене дослідження робить внесок у теоретичне осмислення STEM-освіти та практичне забезпечення її впровадження, спрямованого на підготовку молоді до успішної професійної діяльності у швидкозмінному середовищі.

**Ключові слова:** STEM-освіта, інтегративний підхід, прагматичний підхід, STEAM, STREAM, STEMM, критичне мислення, інноваційність, освітня парадигма.

## Introduction

**Topicality of the problem.** The relevance of STEM education in the twenty-first century is determined by its role as a driver of educational innovation and as a strategic response to global social, economic, and technological transformations. STEM education equips learners with the ability to integrate knowledge from science, technology, engineering, and mathematics, thereby fostering analytical and critical thinking, creativity, collaboration, and problem-solving skills. These competences are recognised internationally as essential for effective participation in a rapidly changing professional environment and for addressing the challenges of the knowledge-based economy.

The urgency of studying STEM education lies not only in its practical orientation toward labour market needs but also in its theoretical significance as an innovative educational paradigm. Unlike traditional models that emphasise isolated disciplinary learning, STEM education is characterised by integration of content, methodologies, and pedagogical technologies, which enables learners to apply knowledge comprehensively in both academic and real-world contexts. This integrative nature differentiates STEM from conventional approaches and positions it as a multidimensional system that unites theory and practice.

At the same time, the terminological and conceptual field of STEM education is dynamic and continually expanding. The emergence of related concepts such as STEAM (integration of the arts), STREAM (integration of reading and writing), and STEMM (integration of medicine) illustrates the adaptability of the paradigm but also underscores the need for systematic clarification of its terminology. Without a coherent conceptual framework, there is a risk of inconsistency in scholarly discourse, curricular design, and practical implementation.

Furthermore, the study of STEM terminology is crucial for ensuring international comparability and academic mobility. As STEM education is increasingly embedded in global educational strategies, harmonising its conceptual field facilitates cross-cultural communication, interdisciplinary collaboration, and the exchange of best practices. It also supports the alignment of national educational systems with international standards, thereby enhancing competitiveness and innovation capacity.

**Literature review.** The analysis of the scientific literature on the terminological and conceptual field of STEM education demonstrates its dynamic and interdisciplinary character, as well as a marked asymmetry between the well-developed international discourse and the research of domestic scholars, which, however, has shown notable intensification in recent years.

The conceptual framing of STEM education as an independent scholarly construct is primarily associated with international analytical and research works of the early 2010s. J. Breiner, S. Harkness, C. Johnson, and C. Koehler systematically examined various conceptions of STEM in education and partnership models of its implementation, thereby laying the terminological foundation for subsequent studies [7]. H. Gonzalez and J. Kuenzi characterised STEM education as a strategic resource for responding to labour market challenges and ensuring national competitiveness [11]. B. Granovskiy further developed this approach, emphasising the evolution of state STEM policy [12]. C. McDonald analysed the specificity of science, technology, engineering, and mathematics as distinct yet interconnected components of an integrated educational system [17].

The integrative nature of STEM education constitutes the central theme of a substantial body of scholarly publications. The issue of integrating technology into STEM was addressed by P. Chacko, L. Zhao, S. Appelbaum, and J. Montclare, who highlighted the role of the technological component not only as a tool but also as a mode of thinking [8]. A. Khushk, L. Zhiying, X. Yi, and Z. Zengtian outlined current directions in the development of the T-component within modern educational systems [16]. The mathematical dimension of STEM education was conceptualised by I. Mierluş-Mazilu and F. Yilmaz, who presented mathematics as the universal language of science and technology, enabling the formation of abstract, logical, and critical thinking [18]. The development of students' research abilities in STEM education was investigated by Y. Dosymov, E. Ergobek, S. Ramankulov, and colleagues, who proposed a new approach to fostering these skills under contemporary educational conditions [9].

The levels of integration in STEM education constitute a distinct research direction. Disciplinary integration and the characterisation of corresponding STEM teacher training programmes were analysed by C. Rodríguez, R. González-Reyes, A. Ballen, and others [19]. Interdisciplinary approaches and integrated STEM education from the perspective of science teaching methodology were examined by C. Johnson and C. Czerniak, who emphasised the capacity of interdisciplinary integration to expand students' cognitive opportunities [13]. The transdisciplinary dimension of STEM education and the role of technology in overcoming disciplinary boundaries were explored by A. Karakaş and Ç. N. Hıdıroğlu, who characterised transdisciplinarity as the highest level of integration of knowledge, skills, and abilities [14].

The dynamic nature of the STEM terminological field is reflected in studies of derivative concepts. STEAM education, understood as the integration of the arts into the STEM system, has been examined by M. Khine and S. Areepattamannil [15]. The concept of STREAM education, which incorporates reading and writing, was studied by W. Sun and B. Zhong, who identified the positive impact of integrating language activities on students' cognitive processes [20]. STEMM education, involving the integration of medicine, has been analysed by A. Ziegler and H. Stoeger, who considered it through the lens of equity and accessibility issues in STEM policy [21].

Among domestic studies, particular attention should be given to publications on STEM education in the training of future engineers, which reveal the integration of the content and methodology of science, technology, engineering, and mathematics as a defining feature of the STEM approach [5]. Scholars also view STEM education as a means of activating individual creative potential, emphasising creativity, collaboration, and critical thinking [3]; outline its connection with the development of students' critical thinking and innovative abilities [4]; investigate STEM education as integrated learning of natural sciences, stressing that knowledge from one discipline deepens and complements understanding of another [2]; and conceptualise

STEM education as a component of the modernization of Ukraine's education system, situating it within the broader context of educational reforms [1].

Thus, the analysis of the scientific literature indicates that, despite the considerable body of research on STEM education, the issue of systematically structuring its terminological and conceptual field considering integrative and pragmatic approaches, levels of integration, and the dynamics of derivative concepts, remains insufficiently developed. This gap underscores the scholarly relevance and significance of the present study.

**The aim of the article.** The investigation of the core concepts of STEM education is both timely and necessary. It provides conceptual clarity, strengthens the theoretical foundations of STEM as an educational paradigm, and ensures its effective application in preparing young people for life and professional activity in the twenty-first century. This article seeks to contribute to this endeavour by systematising the key concepts and approaches that shape the essence of STEM education.

### Research results

In the context of our study, particular attention should be paid to the definition of the key terms, concepts, and categories that are characteristic both of the development of STEM education and of its implementation. Based on the examination of the source base of the research, it can be stated that several approaches are employed by scholars to interpret the terminological and conceptual field of STEM education. Among these, the integrative and pragmatic approaches occupy a prominent place.

In the context of our research, particular emphasis should be placed on defining the key terms, notions, and categories that are essential both for the development of STEM education and for its implementation. Given the very essence of the concept of "STEM education," the integrative approach is applied, which determines not only the substantive content of this concept but also the specific organisation of STEM learning. Scholars argue that STEM education presupposes the implementation of the integrative approach within the educational process, enabling learners to employ knowledge, skills, and abilities from different domains of scientific knowledge for the comprehensive resolution of learning tasks [6]. Accordingly, the application of this approach foregrounds integration as a defining feature of STEM education, which cannot be regarded as a mere aggregation of several academic disciplines. As noted, "...through the STEM approach to learning, integration of the content and methodology of the natural sciences, technology, engineering, mathematics, and logical thinking is realised in collaboration and research" [5, p. 131]. Researchers further demonstrate that "the use of the leading principle of STEM education – integration – makes it possible to modernise methodological foundations, the content and scope of educational material in the natural science and mathematics cycle, to technologize the learning process, and to foster: skills for solving complex practical problems, critical thinking, creativity and cognitive flexibility, organisational and communication abilities, the capacity to evaluate problems and make decisions, readiness for conscious choice and mastery of a future profession, financial literacy, a holistic scientific worldview, value orientations, general cultural, technological, communicative and social competences, mathematical and scientific literacy; comprehensive personal development through the identification of individual aptitudes and abilities; skills in mastering the means of cognitive, research, and practical activity; the cultivation of a personality striving for lifelong learning; and the formation of abilities for the practical and creative application of acquired knowledge" [1, p. 5].

The pragmatic approach to interpreting the essence of STEM education also deserves research attention. At its core lies the orientation of the educational sphere towards preparing citizens and specialists in various fields for the labour market, which demands a high level of competitiveness, readiness to overcome challenges in a constantly changing professional

environment, and the ability to adapt quickly to new conditions of social life and professional activity. The application of the pragmatic approach defines STEM education as a resource through which learners, within a practice-oriented educational environment enriched by experiential, research, and problem-based learning, are formed as specialists who not only demonstrate solid knowledge in the natural sciences, engineering, technology, and mathematics, but are also able to apply analytical and critical thinking skills and engage in interdisciplinary teamwork. Taken together, these capacities enable them to solve problems of higher complexity. From this perspective, the pragmatic approach is directly connected with the integrative one, since it foregrounds the issue of integrating theory and practice. In fact, the use of the pragmatic approach corresponds both to the needs of the labour market and to the expectations of employers, among whose primary requirements is a specialist with theoretical and practical training that allows them to function effectively in the professional environment.

In our view, the differences inherent in each of the approaches have more advantages than disadvantages, and their value lies in their complementary nature. We justify this position by noting that, in essence, STEM education, as a phenomenon that unites several academic disciplines, represents a system characterised by the integration of substantive content and the use of appropriate pedagogical technologies in the educational process. We agree that “their integration occurs in the way that knowledge from one science complements and deepens the understanding of another, while technology, engineering, and mathematics serve as instruments for the practical application of this knowledge” [2, p. 119]. The orientation towards pragmatism creates opportunities for the organic integration of theory and practice. The analysis of scholarly and pedagogical sources confirms that “STEM education belongs to innovative educational systems that fully correspond to global trends in the development of modern education. Creativity, collaboration, and critical thinking are key competences for success in the twenty-first century” [3, p. 312].

Turning to the concept of “STEM education,” it is important to emphasise the acronym “STEM,” which itself unites several academic disciplines, and an awareness of the specific features of each of them contributes to a clear definition of the essence of STEM education. “STEM education promotes interdisciplinary learning that combines theory with practice: students apply scientific, mathematical, and engineering knowledge to solve real-world problems, linking school with the needs of the community, business, and the high-tech economy. This approach is designed to develop in young people critical thinking, creativity, and innovative abilities necessary in the modern labour market” [4, pp. 21–22].

Thus, the element S (Science) denotes the natural sciences, including physics, chemistry, biology, earth sciences, and others. The specificity of teaching these subjects lies in the fact that it presupposes the use of inquiry-based learning. Indeed, the natural sciences involve not only the acquisition of a defined body of knowledge but also the formation of relevant skills and abilities necessary for problem formulation, hypothesis generation, organisation and conduct of experimental research, processing and analysis of experimental data, their interpretation, and the drawing of conclusions [9].

The element T (Technology) refers to technologies, which are understood as means and instruments for transforming the environment. In this sense, it encompasses human-made phenomena and objects, as well as the processes through which these phenomena and objects are created [16]. The emphasis here is placed not only on the final product but also on the process of developing ideas, designing, and implementing them. This requires a clear awareness of theoretical foundations and their translation into pragmatic practice, which in turn presupposes the development of initiative, innovative thinking, and readiness for communication and collaboration within a team [8].

The element E (Engineering) in the STEM acronym interprets engineering as a way of transforming the world in accordance with human needs. A crucial feature here is that knowledge of the natural sciences and mathematics must be regarded as fundamental and

indispensable for the development of engineering solutions [11]. The very process of designing engineering solutions requires the ability to apply knowledge from different disciplines in a comprehensive manner to identify the most optimal solution among many possible alternatives. This approach substantiates the need for organising learning in such a way that learners move beyond the simple reproduction of knowledge and algorithms towards a complex investigation of problems from multiple perspectives, generating a range of alternative ideas and approaches to their resolution, followed by critical analysis and evaluation of the effectiveness of the developed engineering solutions [12].

In our view, the element M (Mathematics) should be considered as the universal language of science and technology, characterised by precision of expression, structured thinking, and logical reasoning [18]. Undoubtedly, mathematics provides the foundation for the development of engineering solutions, as it is applied in modelling and forecasting processes, as well as in the analysis and processing of information and data. It is a discipline that offers effective tools for quantitative measurement, algorithm construction, and hypothesis testing. The distinctive features of this component in STEM education include the fact that mathematics enables the formation and development of abstract, logical, and critical thinking, as well as the application of modelling skills.

It should be noted that integration is fundamental to STEM education and differentiates it from the traditional teaching of separate natural and technical disciplines. The scholarly literature identifies several levels of integration: disciplinary, where each science retains its identity; interdisciplinary, which involves common themes and methods; and transdisciplinary, which entails disregarding disciplinary boundaries altogether in project-based activities.

With regard to disciplinary integration, it is understood as preserving the identity of each science and organising learning without going beyond the boundaries of a given field of knowledge [19]. At the same time, such integration in the context of STEM education presupposes the contribution of each science to the overall STEM system, encouraging learners to systematically master knowledge from each discipline, understand its methodology, recognise its role and significance, and develop the skills necessary to apply it in solving complex tasks.

Considering interdisciplinary integration, it should be emphasised that it involves identifying commonalities among different academic disciplines (content, methods, tools, approaches) and allows the application of knowledge from several disciplines simultaneously, which collectively facilitates the search for solutions to complex tasks or research problems [13]. In this context, interdisciplinary integration in STEM education contributes to the development of learners' ability to apply both knowledge and methodological tools from different domains of scientific knowledge, combining them in the process of solving complex problems.

Characterising transdisciplinary integration, it should be emphasised that it represents the highest level of integration, distinguished by going beyond the boundaries of individual academic disciplines [14]. Researchers argue that in this case, a complex of knowledge, skills, and abilities is applied in their integrated form without clear demarcation between subjects. In essence, transdisciplinary integration is grounded in the fusion of theory and practice and presupposes the development of innovative thinking, which is regarded as one of the components of professional competence of a modern specialist prepared to function in a dynamic professional environment.

It is important to emphasise that the terminological and conceptual field of STEM education is characterised by a dynamic nature of development. For instance, the term "STEAM education" is now widely used, referring to the integration of the arts (A – Arts) into the STEM framework [15]. In scholarly publications, researchers also employ the term "STREAM education," which implies that the relatively traditional STEM model incorporates additional forms of language activity such as reading and writing (R – Reading/Writing). This tendency

toward disciplinary integration of various forms of language activity within STREAM education contributes to the development of learners' cognitive processes and the formation of corresponding knowledge constructs [20]. Another term, "STEMM education," denotes the integration of medicine (M – Medicine) into the STEM system, which is actively developing in universities and research institutions in advanced countries. Such integration underscores the importance of knowledge in physics, chemistry, engineering, and mathematics for the professional competence of future healthcare specialists [21].

In addition, scholarly publications introduce the notion of "STEM literacy," which researchers interpret as a basic or elementary level of awareness across different disciplines and fields of knowledge, considered essential for full participation in everyday life regardless of profession [10]. A further concept, "scientific citizenship," is understood as the responsible and active participation of citizens in decision-making processes of societal importance, grounded in scientifically validated data [6].

### Conclusions

The results of the analysis of the terminological and conceptual field of STEM education confirm that STEM should be regarded as an innovative educational paradigm grounded in both integrative and pragmatic approaches. Integration emerges as the defining feature of STEM, as it ensures the combination of the content and methodology of the natural sciences, technology, engineering, and mathematics, enabling learners to address educational and practical tasks comprehensively. The pragmatic approach, in turn, highlights the orientation toward labour market needs and the preparation of competitive specialists capable of critical thinking, innovation, and teamwork.

The study of the essence of STEM education has revealed that integration is realised at three levels: disciplinary integration – preserves the identity of individual sciences while contributing to the overall STEM system; interdisciplinary integration – facilitates the search for common themes and methods, allowing learners to combine knowledge and approaches from several disciplines; transdisciplinary integration – transcends disciplinary boundaries, harnessing their collective potential to solve complex problems. Altogether, these levels progressively expand the possibilities for applying knowledge and skills within the educational process, positioning STEM education as a dynamic and future oriented system that responds to societal challenges and fosters twenty first century competences.

It is important to note that STEM education is continuously evolving and enriched with new concepts such as STEAM (integration of the arts), STREAM (integration of language activities: reading and writing), and STEMM (integration of medicine). This demonstrates the dynamic development of its terminological and conceptual field and its adaptation to contemporary educational and social challenges.

Thus, STEM education emerges as a multidimensional phenomenon that combines theory and practice, fosters the formation of key twenty-first-century competences (analytical and critical thinking, creativity, communication, and collaboration), and prepares young people for effective functioning in a rapidly changing professional environment.

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