International Academy of Applied Sciences in Lomza

Institute of Pedagogy of NAES of Ukraine

DIGITAL TRANSFORMATION OF EDUCATION: CHALLENGES AND PROSPECTS

Monograph

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Lomza – Kyiv

Wydawnictwo: MANS w Łomży – 2025

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The monograph has been prepared based on the results of the International Scientific and Practical Conference held in April at the Dragomanov Ukrainian State University, in cooperation with scholars from the Institute of Pedagogy of the National Academy of Educational Sciences of Ukraine and the International Academy of Applied Sciences in Lomza.

The first chapter provides a detailed overview of modern digital technologies applied in educational and communication processes. The second chapter, devoted to digital and informatics education, skillfully combines the analysis of domestic and international experience, thereby contributing to the search for new ways of effectively integrating digital tools into the educational process. The third chapter describes contemporary aspects of STEAM education and educational robotics. The fourth chapter focuses on the use of artificial intelligence in education, highlighting not only the current state of technological development but also outlining potential ethical and methodological challenges that bring forward further academic discussion.

The systematization of examples and the analysis of their practical significance make this material valuable for researchers, university lecturers, and educators. The presented content is practice-oriented, thus opening broad prospects for its application in the educational process at institutions of various levels

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1.1. PEDAGOGICAL CONDITIONS FOR IMPLEMENTING THE PROCESS OF DIGITALIZATION OF THE EDUCATIONAL ENVIRONMENT OF A GENERAL SECONDARY EDUCATION INSTITUTION DURING MARTIAL LAW

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The process of digitalization of education has its own history, which began in the 60s – 80s of the last century, and consisted in the gradual introduction of computer technologies into the educational sphere. This process was aimed not only to improve the quality of education, but also to form the necessary digital skills in young people. The gradual spread of computers and increasing their accessibility contributed to developments related to the automation of administrative processes in education and the implementation of educational programs. Further expansion of digital technologies in education took place in the field related to the development of electronic textbooks and educational resources. With the development of the Internet in the 90s, new opportunities appeared for the development of distance learning, communication and obtaining information. Developers in the IT sector created further conditions for the digitalization of education through educational platforms and online courses, and the use of multimedia tools (video, audio, interactive games) in the educational process increased.

The COVID-19 pandemic and martial law in Ukraine have significantly affected the digitalization of education, transforming it from an innovation into a means of preserving the educational process, while opening up new opportunities for pedagogical technologies in teaching and the accelerated introduction of the digital component to the educational environment. The need to use digital resources has contributed to increasing the basic level of digital literacy of educational subjects and increasing the efficieThe COVID-19 pandemic and martial law in Ukraine have significantly affected the digitalization of education, transforming it from an innovation into a means of preserving the educational process. At the same time, this has opened up new opportunities for pedagogical technologies in teaching and the accelerated introduction of the digital component to the educational environment. The need to use digital resources has contributed to increasing the basic level of digital literacy of educational subjects and increasing the efficiency of the educational process. The digitalization of education has received all the necessary prerequisites for rapid development, in particular through the development of its educational and methodological support. This factor has become a catalyst for the transition of the digital component of the educational process to alternative educational formats such as: distance learning, blended learning, online learning.

One of the current directions of development of the digitalization process in education today is the digitalization of the educational environment. It consists in using digital technologies to improve the quality of the educational process and involves the development of digital competence of subjects of the educational environment. The creation of an effective learning environment is facilitated by the use of online tools, electronic resources and interactive teaching methods.

The organizational and pedagogical conditions for the effective implementation of the process of digitalization of the educational environment include:

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- expansion of computer equipment, free access to the Internet in educational institutions;
- creation of programs, computer educational games;
- updating and replenishing information resources of the educational process, use of licensed multimedia resources;
- increasing IT competence of teachers in the field of information technologies;
- taking into account the basics of age psychology;
- compliance with ergonomic and pedagogical requirements;
- compliance with hygiene and safety requirements for conducting classes (Trubacheva, Alekseenko, 2025).

Currently, due to the need to streamline digital education and digital technologies, determine their role and status, the issues of standards, norms and rules of digital transformations that are taking place and should take place in the future in the process of education development should be implemented. Solving this task can be considered a priority condition for the further systematic expansion of the digitalization process in education and the designation of promising strategies for the development of the digital component of education.

In general, to form standards for the functioning of the digital educational environment, it is necessary to develop educational strategies at the official state level. This is especially important in the context of constant reform of education, caused by transformations and processes of innovation that meet the civilizational norms of progress. Therefore, this process requires new methodological approaches to standardization, effective in the education system and the development of norms and rules relevant in the modern socio-cultural environment.

Today, the positioning of the principles of digitalization can already be partially traced both in educational standards, which are defined in the strategies for the development of the educational sphere at the professional, local, state or global international levels, and in practically-oriented norms and rules, which are implemented directly in educational institutions by participants in the educational process. The digitalization of education in Ukraine is based on the principles of openness, accessibility, inclusiveness, security and orientation to the needs of education seekers. It is also advisable to emphasize the principle of integrativity, which assumes the interconnection of all elements of the digital educational environment in view of the need to ensure the integrity of the educational process. The closely related principle of systematicity requires the construction of a digital educational environment as a complex formation from many different elements - information resources, tools for organizing learning, and means of managing it. The principle of distribution or modularity, in turn, involves structuring the content of the digital educational environment primarily in accordance with the functional capabilities provided by all components of the educational process (Storonska, 2024).

One of the most important problems of digitalization of education is that innovations in the digital educational space are not only technical and technological innovations, but also changes in the content and organization of educational content, in the structure and organizational principles of educational institutions. Key aspects include the introduction of digital technologies, the development of digital competencies among teachers, the creation of a modern digital educational environment, as well as ensuring the quality and transparency of educational processes (Sysoeva, 2021).

During 2020–2023, the MES team, together with educators, scientists, methodologists, colleagues from other departments, and international partners, achieved significant results in this area. First of all, it is worth mentioning the "All-Ukrainian Online School", the order on the procedure for filling the distance learning web platform was signed in October 2021.

With the support of the United Nations Children's Fund in Ukraine (UNICEF), the All-Ukrainian School Online platform is constantly updated with educational courses. Specialists from the Ministry of Education and Science, institutes of the National Academy of Pedagogical Sciences of Ukraine, professional public organizations, as well as international partners are working on the implementation of this project. The platform is administered by the Ukrainian Institute for the Development of Education.

The digitalization of education in Ukraine is reflected in several key legislative acts, in particular, in the Law of Ukraine "On Education" and the Law of Ukraine "On Amendments to Certain Laws of Ukraine Regarding the Functioning of Integrated Information Systems in the Sphere of Education". These laws provide for the creation of an Automated Information Complex for Educational Management (AICOM) to ensure proper digital interaction in the education system between state authorities, local governments, educational institutions and organizations, participants in the educational process, and other legal and physical persons. These documents define the legal principles and mechanisms for introducing digital technologies into the educational process.

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AICOM is a single digital environment for general secondary education institutions. It ensures interaction between other key state information and communication systems and public electronic registers in the field of education, in particular, the Unified State Electronic Database on Education, the Unified State Demographic Register, the Unified State Register of Legal Entities, Individual Entrepreneurs and Public Organizations, the State Register of Civil Status Acts of Citizens, the State Register of Compulsory State Social Insurance, etc.

Currently, the Ministry of Digital Transformation has implemented the Educational Mriya application in school practice. Now any school can become part of the educational ecosystem, which provides access to such digital services as: daily plan, journals, grade constructor, achievement dynamics, chats, personalized content library Mriya ID. Services for children and parents and AI-based functionality – an automatic test generator – will also be included.

The strategy for digitalization of education in state documents includes a wide range of measures aimed at improving the educational process using digital technologies. The main areas are ensuring access to digital education, implementing innovative digital solutions and developing digital literacy.

It is advisable to take into account the approach of the European Union countries. Thus, the EU has developed a number of strategic documents, programs and initiatives to support and implement digital technologies in education. For example, the European Union has developed framework documents that are mandatory for implementation in all education systems of countries. Such documents include: The European Digital Education Action Plan, which was developed by the European Commission and is the main document that defines the directions of digitalization of education in the EU. Its main goals are to increase the digital literacy of citizens, integrate digital technologies into educational processes, and develop infrastructure for online learning. The EU's Digital Europe Strategy covers the development of digital technologies in various sectors, including education. The strategy aims to provide broadband internet in all educational institutions, create a safe cyberspace and implement innovative digital solutions. The European Skills Agenda envisages the development of digital skills among EU citizens at all levels, starting from school. It calls on Member States to adapt curricula to ensure digital literacy among young people. The European Digital Certificate, introduced for the mutual recognition of online learning and digital qualifications among Member States (Noskova, Korets, 2024).

When developing standards for the digitalization of education, it is worth considering that these digital mechanisms will relate to the content, educational and methodological components of the educational environment, and will influence the formation of organizational and managerial, socio-pedagogical and technological components (Trubacheva, Alekseenko, 2025).

Standards for electronic textbooks, educational and methodological materials should be developed in close cooperation between educators, IT specialists and representatives of the publishing industry. At the same time, technological feasibility, unity of procedures for creating digital educational products and educational quality of educational materials should be ensured, which will allow for further scaling and constant updating of the project.

The direction of digitalization of the educational process and its educational and methodological support should be aimed at its diversification, increasing the effectiveness of learning, student interest and the development of their critical and creative skills. The implementation of this process is ensured by a set of software and hardware tools and educational content necessary for the implementation of educational programs. A significant role is played by the use of e-learning, distance education technologies, which provide access to educational services and services in electronic form.

An important condition for the development of the process of digitalization of the educational environment is the standardization of forms of organizing the educational process, which provide for the mandatory use of digital tools and learning technologies, such as: distance learning, blended and online learning (Topuzov, 2021).

For example, designing an educational environment in a blended learning environment involves adhering to a number of pedagogical conditions:

1. Blended learning should be based on three elements: distance learning, classroom learning, and online learning.

2. The main task that the teacher must solve is to correctly compose the training course and distribute the training material. It is necessary to clearly distribute the material for independent study, for individual lessons, and for group work on the project.

3. The distance part must necessarily include projects for group work, creative, laboratory and practical tasks, reference materials and links to additional materials on the global network, intermediate tests to test knowledge of various levels and complexity. Testing of knowledge should be carried out not only online or on the platform, but also in the classroom.

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4. It is assumed that there is a high level of development of digital competencies of the teacher in the e-learning environment.

5. During martial law, specific conditions for ensuring the safety of the educational environment are added to the basic design conditions, which are related to the presence and size of the school shelter. Thus, educational institutions combine rotational and flexible models: for example, the first, second and fifth grades study in person every day, while other parallels join them for two weeks, alternating with each other.

Specific conditions during martial law include taking into account the peculiarities of education of children who study only remotely from abroad. The education of such students is carried out mainly through the use of individual educational trajectories.

The class schedule is usually structured so that education takes place in two shifts: in the morning, face-to-face education at school and remote education for students in Ukraine, and in the afternoon, remote education for children abroad.

To study special subjects in parallel with full-time study, schools often organize dynamic groups in which students rotate internally between classes.

6. One of the important conditions for effective design of blended learning is conducting a survey. The results of a survey among parents and teachers will help the administration to more clearly understand the wishes regarding the form of education, expectations, concerns and capabilities of the participants in the educational process. During such a survey, it is worth offering all possible options: full-time, blended, distance, family form or external.

In conditions of quarantine and martial law, it is digital technologies that make it possible not to stop learning, but to continue it safely in a distance or blended format. Specific conditions can also include the following: a) a modern teacher must have a certain level of information and digital competence. This includes the ability to use educational technology tools, as well as the ability to effectively integrate digital technologies into teaching methods and lesson plans; b) a teacher must know and be able to use various means of digital communication and collaboration; c) use digital technologies for professional development; d) manage and organize the work and learning process using digital technologies and use digital technologies to assess students and expand their learning opportunities; e) create conditions for the development of students' digital competence (Trubacheva et al., 2022b).

The effectiveness of implementing various forms of learning also depends on the technical level of equipment that its participants have, as well as a connection to a stable high-speed Internet. If possible, it is advisable to use online platforms, interactive technologies, electronic textbooks, digital laboratories and multimedia content. The means of increasing the effectiveness of distance, blended and online learning are: video conferencing systems, electronic diaries, online communication tools, which will help organize a comfortable educational environment for all participants in the educational process in any conditions. In addition, it is necessary to develop personalized learning using adaptive educational technologies that take into account the individual needs of students.

This process should be facilitated by the introduction and use of modern digital technologies in educational activities, in particular network services, which allow creating an appropriate pedagogical and technological basis for supporting modern information systems for educational purposes. With the help of various interactive and digital tools, it is easier for a teacher to implement innovative approaches, such as educational games, video presentations, laboratory and practical classes, cases and various project technologies. A modern teacher must learn to use and create interactive content. Currently, the following are actively used in lessons: constructors and robotics, virtual laboratories, scribing presentations, game learning, mobile learning and knowledge testing, cloud technologies. Modern classrooms are now equipped with a variety of digital equipment: interactive complexes, laptops, computers, digital cameras, educational tablets, multimedia projectors, printers, e-books, document cameras, MFPs. Their use has such didactic possibilities as: the learning process becomes more mobile with the ability to transfer information to other computers; promotes students' motivation to learn through the use of bright pictures, clear diagrams and educational videos; formation of a scientific approach in students during practical work; stimulates creative and cognitive activity, develops skills in searching, systematizing and analyzing information; allows you to control and evaluate students' knowledge in a more convenient form and process the results of such an assessment much faster; saves the teacher's time in preparing for the lesson (Trubacheva et al., 2022a).

The use of smartphones plays a significant role in the educational process. They are always at hand, providing access to information. Smartphones allow teachers to create and share video and audio materials for teaching. Students can view and listen to these materials to learn new material. The smartphone can be used for interactive lessons and activities, such as virtual tours, voice and text discussions, virtual research.

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Currently, significant funds are allocated for the computerization of schools with a focus on high modern characteristics so that the equipment has a long-term reserve of relevance to current educational needs and software requirements. Computer classes that are not computer science rooms must be prepared to use such equipment properly. It is necessary to think about natural and artificial lighting, the location of equipment and its power supply, safety standards and other sanitary and hygienic standards. It is desirable that the workplace be placed so that the light falls on the monitor from the left, and artificial lighting is distributed throughout the class depending on the location of the workplaces. The classroom should be aired often, because the positively charged ions formed by computers are harmful: they cause fatigue, headaches, but do not forget about the norm of working time at the PC. The school should have a local Internet network for exchanging information, and access to certain sites on the global Internet should be limited.

Along with digital educational content, a key role in the modern educational process should be played by digital educational services – as well as properly standardized and approved means and tools for organizing the educational process and using modern multimedia content in it. First of all, these are means of interaction for teachers and students and students among themselves, which include various exercises, tests and projects. Specialized digital tools for teachers' work should occupy a proper place among digital educational services, from electronic document management tools to "constructors" of lessons, curricula and individual and group educational trajectories.

Also, important pedagogical conditions for designing an educational environment include the implementation of the ideas of individualization and differentiation of student learning. Diagnostics of general and special abilities of students, their educational characteristics, aptitudes and psychological and pedagogical support for their development are built on the basis of the attitude towards the student as a subject of his own development and self-development. For example, the effectiveness of the formation of general educational competencies of students, in primary school in particular, depends on taking into account such individual and typological characteristics of students as the level of formation of the student's educational motivation, the level of formation of knowledge about the methods of cognitive activity, past experience of independent learning, the ability to communicative and reflective activities. Considerable attention is paid to the level of formation of the student's educational motivation.

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Designing an individual technology for teaching students in an educational institution includes the following components: pedagogical conditions as a special type of pedagogical practice for providing education to children with different learning abilities; organizational and pedagogical conditions for studying and taking into account the individual characteristics of students, implementing a personally oriented approach, forming the subjective position of students as the basis for their successful socialization; humanistically oriented content, functions and forms of professional activity of the teaching staff; openness of the school as a local educational system; appropriate scientific and methodological support for the educational process (Trubacheva et al., 2022a).

The formation of motivation is an important qualitative indicator of the effectiveness of the educational process, its personal orientation. In this regard, the organization of psychological and pedagogical support for the process of forming and developing cognitive motives and interests of students and ensuring diagnostics of the level of independence of their educational activities at different stages of learning can be attributed to the essential didactic conditions. Thus, the use of the Quizizz network provides opportunities for creating interactive interesting quizzes that promote active learning and assessment of knowledge in a few minutes. The DALL-E application allows students to generate images in lessons according to certain conditions. Teachers can create cases and choose neural networks that can be effectively used in their lesson.

Recommendations for the implementation of the digitalization process in the organizational and managerial component of the educational environment acquire the status of requirements and rules. This direction should be focused on simplifying document flow, improving control over the educational process and promptly obtaining the necessary data. It includes maintaining and storing documentation in electronic form, automating the movement of education seekers and recording their success, drawing up and adjusting the class schedule. It should also provide for the use of electronic services for interaction between the administration, teachers, students and parents. The integration of information systems for monitoring the quality of education, reporting and making management decisions will contribute to increasing the efficiency of managing an educational institution. One of the main conditions for the effective functioning of this aspect is the ability of managers to organize work on the digitalization of the educational environment of a general secondary education institution (Trubacheva, Alekseenko, 2025).

The electronic journal Unified School provides opportunities for performing administrative processes, interacting with parents, implementing analysis and forecasting processes for management analytics, and creates conditions for technical support. Important here is the development of tools and resources that help teachers in preparing and conducting lessons. Also effective is an interactive assistant - a planning assistant, which reminds of important events, helps in finding the necessary information, and automatically analyzes reviews about the school in social networks and on websites.

The school administration must ensure the organization of the activities of the educational institution in terms of distance, blended and online learning, manage the distance education web environment, coordinate the rules and schedule of interactions of all participants in the educational process to implement the educational programs of the institution. The task of the head of the educational institution is to discuss the change in forms of education with the teaching staff, choose an online platform, organize and implement training using distance technologies. In addition, the following are specific features of organizing distance education of students in the process of designing the educational environment: it requires the creation of an information base for storing and adapting educational materials to the web environment and posting them on web resources; special equipment for full functioning; provides for specialized organization of students' work using this educational technology; requires taking into account the specifics of developing, building and publishing materials in a virtual environment.

Digitalization in terms of the socio-pedagogical component includes, firstly, promoting inclusion and accessibility issues. In particular, ensuring equal opportunities for all participants in the educational process, in particular for people with special educational needs. It may include the introduction of adaptive digital tools, software for alternative communication, audiobooks, subtitled video lessons and other technological solutions that contribute to the creation of an inclusive environment. It is also important to provide technical support and accessibility of digital resources regardless of the social status or place of residence of students, which will help eliminate the digital divide and promote equal access to quality education. Secondly, it should be focused on ensuring interaction with parents and the public. Digital technologies are aimed at improving communication between the educational institution, parents and the community. In this case, social networks and online platforms are used that allow users to create profiles, establish connections with others, exchange information and content. The most popular today are: Facebook, Instagram, Twitter (X), YouTube, TikTok, LinkedIn, Telegram, WhatsApp and others.

This also includes: electronic diaries, chats, mobile applications for feedback, which contribute to greater awareness of parents about the educational process of their children.

It is also worth implementing open online resources where parents and the public can familiarize themselves with the achievements of students, plans for the development of the institution and take an active part in the life of the school through online voting, forums and consultations.

There should be no significant complications in terms of standardization of the technological component, since digital tools function synchronously with technological innovations. An important direction for ensuring the digital development of the technological component is to address cybersecurity issues. The introduction of a privacy policy, the use of modern antivirus programs and training all participants in the educational process in cybersecurity rules will help minimize the risks of online threats. Therefore, it is worth developing and implementing a privacy policy, creating data backups, using modern antivirus programs and information protection systems, as well as conducting regular training activities to raise awareness of students, teachers and administration about the basics of cybersecurity. An important aspect is controlling access to confidential information, using strong passwords, two-factor authentication and regularly updating software.

Also, one of the important tasks of this component of the educational environment is the integration of digital technologies into the educational process: the use of innovative educational technologies, the integration of artificial intelligence tools and the creation of educational content aimed at the development of digital competencies.

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As we can see, two normative and regulatory paradigms are being formed for the digital educational environment: the norms and rules of using digital resources in the educational process and the level of digital literacy of its participants.

The development of a digitalized educational environment often requires resolving issues related to the discrepancy between its demand and the lack of proper digital support for the educational and methodological component of the educational process and the insufficient formation of digital competencies of its subjects. Sometimes their low motivation in this process is due to the fact that they are not always familiar with the prospects that digital skills provide, especially in combination with fundamental knowledge of educational subjects.

The development of digital competence of subjects of the educational environment is the process of improving skills, knowledge and abilities to use digital technologies in teaching and professional activities (Bykov, et al., 2022). It includes the confident, critical and responsible use of digital tools for learning, work and participation in public life. The main conditions for increasing the level of digital competence include the following: the use of digital technologies in the learning process (use of online platforms, educational programs, electronic educational resources). Regarding the training of teachers (Ovcharuk, 2019), this primarily concerns processes that activate their professional involvement aimed at using digital technologies in professional interaction with colleagues, students, parents and other interested persons and at their own individual professional development. This process includes the use and creation of electronic educational resources for learning needs; teaching and learning using digital technologies to empower students and ensure the development of their digital competence. The effective implementation of this process is facilitated by taking into account such needs as: critical analysis of the action, studying the indicators of reliability and impact of the information data used, as well as an ethical, safe and responsible approach to the use of these tools by educators.

This process should also include regular training and professional development of teachers in the field of digital technologies. The solution to this issue is impossible without students acquiring technical and functional knowledge of digital tools. This involves not only learning how to work with software, but also understanding the principles of digital systems, their capabilities and limitations. It is important that knowledge and skills are sufficient to ensure a high-quality educational process, as well as to perform professional tasks in the future.

The formation of digital competence also involves the development of the ability to work in a virtual environment, in particular, by cooperating with other participants in the educational process, effectively using tools for collaboration, such as video conferencing, cloud services, LMS platforms and messengers. It is important to develop skills in digital etiquette, critical thinking and effective interaction with various participants in the educational process. Master classes, trainings, online courses and webinars will help improve teaching efficiency, increase the digital competence of teachers and support students in developing their digital skills. It is also worth creating an internal network for exchanging experience between teachers, introducing mentoring and supporting participation in international educational programs related to digital technologies. This will contribute to the continuous improvement of teaching methods and the effective use of modern digital resources.

As we can see, in complex variable educational models, the development of a digital educational environment comes to the rescue, which allows each student to have access to education at any time and build an individual learning trajectory.

To achieve these goals, the education system needs to solve the following tasks: develop uniform requirements for the structure and content of the digital educational environment; within the framework of each educational program, determine the level of application of digital education in the educational process and for each specific discipline; determine the possibilities of using existing resources and ensure, if necessary, improving their quality; form an algorithm for the digital transformation of the educational process; develop and, subject to successful testing, implement a model for organizing the educational process using a digital educational environment.

The educational process within the framework of the digital transformation of education should be based on a mandatory combination of active forms and remote classes: conducting webinars, virtual discussions in forums, role-playing and business games in the format of webquests, round tables in chats, blogs, project activities based on wiki technologies, and independent work of students.

The main advantages of the digital transformation of the educational environment are as follows: a flexible work schedule is created for the performance of educational work by education seekers and, accordingly, the ability to choose an individual pace of movement according to the curriculum; conditions are created for the implementation of inclusive education. The structure of the teacher's activity is changing, the main functions that occupy most of his time are: designing educational work, preparing educational tasks for independent work on the entire content of the

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discipline, control tasks with degrees of protection of the reliability of the results, individual counseling in remote mode, monitoring and evaluation of the results of educational work.

The organization of learning and management of the educational process is changing. The organization of training for independent work of education seekers and coordination of their activities using distance learning tools are coming to the fore. The main efforts are directed to the organization of the educational process taking into account the characteristics, intentions and abilities of each education seeker.

Academic mobility in the context of digitalization of the educational environment provides students with the opportunity to change the trajectory of their education at any time with minimal loss of time and maximum preservation of academic achievements obtained at previous stages of education.

Digitalization makes the educational process more mobile, flexible, personalized and differentiated, significantly affects the content of education, methods, means and technologies of learning, organizational forms of learning and management of educational activities, which significantly increases the efficiency of the functioning of the educational environment of general secondary education institutions.

Thus, digitalization is a relevant and promising direction for the development of the domestic education system. In the course of Ukraine's post-war reconstruction, it is also expected that the process of digitalization in education will continue. The Ministry of Education and Science has presented a draft of the Plan for the Restoration of Ukraine in the Field of Education. This orients the preparation for numerous changes.

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1.2. SOCIAL EFFECT OF DIGITAL TRANSFORMATIONS OF THE EDUCATIONAL ENVIRONMENT ON THE TYPOLOGICAL CHARACTERISTICS OF STUDENTS OF THE "NETWORK" GENERATIONS

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In the conditions of dynamic development of the information society and the latest technologies, digitalization has become a new reality, and it is with it that the immediate future of humanity is associated. Under its influence, knowledge and the boundaries of consciousness expand, new ways of thinking, communicating, professional activity, solving everyday problems and gaining experience are formed.

The process of personal socialization is also taking on the characteristics of digitalization. This is especially noticeable among the younger generations, whose entry into society is carried out in close connection with digital technologies and network communications, which not only shape the digital space of life, but also improve the ways of involving children and youth in it, their digital socialization.

Given that the process of digitalization of society and the education system is developing quite dynamically, it is relevant for pedagogical science and practice to analyze the social effects of digitalization of the educational environment and digital socialization of the personality of a modern schoolchild as a resource of the future –

this will allow not only to optimize the conditions of the educational environment and the educational process, to introduce methods and technologies of socio-pedagogical support adequate to the situation and individual needs for those who find themselves in situations of risk, but also to predict the further development of human capital and related socio-economic issues.

The problem of digital socialization of the personality of modern students in the works of scientists of the National Academy of Pedagogical Sciences of Ukraine is considered in several contexts:

- digitalization of the educational environment, informational, methodological and scientific-methodical support for the digitalization of education in Ukraine (Bykov, Kremen, Litvinova, Lugovyi, Lyashenko, Malovany, Pinchuk, Topuzov 2022; Tverdokhlib, 2024);
- modernization of the educational environment, state and overcoming educational losses during martial law (Topuzov, Golovko, Lokshina, 2022; 2023; Alieksieienko, 2024; Zhuk, 2024);
- analysis of classified threats on the Internet and opportunities for training in security in the virtual world (Bykov, Zholdak, Chepeleva, 2010);
- the relationship between the risks of the Internet space and the social development of the individual (Alieksieienko, 2018, 2019; Hrytsenko, Burlay, 2020) and others.

Based on our previous experience as an author in the study of socialization as a process and a gradual result of the social maturation of an individual (Alieksieienko, 2007; 2008; 2009; 2017; 2023) and the specifics of the course of digitalization, we offer the following definition of the concept Digital Socialization: Digital Socialization – this is the process of an individual's appropriation of social values and acquisition of social experience of interaction, behavior, communication, competencies, development of digital identity through available information and communication technologies and online contexts, their reproduction in specific slang, real and Internet communication, digital competence, features of environmental perception in virtual, augmented and mixed reality and behavior (Author T.A.).

We base our analysis of the features of digital socialization of modern students as representatives of network generations, the creation of appropriate typological characteristics for them, and the determination of the social effects of digital socialization based on the proposed author's definition, observation of personality development in a digital educational environment, and the results of a survey of focus groups of teachers of general secondary education institutions.

In disclosing the research topic, we adhere to several fundamental positions:

- network generations are defined based on the Theory of Generations (Verfasser, Strauss, William (1992);

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- the analysis of the features of the digital socialization of the student's personality is carried out in the context of transformational changes in education in Ukraine, in particular during the Russian-Ukrainian war;
- the social effects of the digital socialization of the personality are interpreted using the term challenges, thereby emphasizing their dynamic nature.

Digital socialization of the individual as a scientific problem and the social effects associated with it are of interest for consideration in the context of the development features of children of new generations - "networked" - children of the early 21st century.

In our analysis, their isolation is carried out based on the classification proposed by American scientists Neil Howe and William Strauss in the Theory of Generations (Verfasser, Strauss, William (1992), the interpretation of its provisions in the context of psychological features of personality development (Mitchell D., 2008; Shaw Brown G., 2010), conflict of values between parents and children (Alieksieienko, 2018) and the features of the transformation of education in Ukraine (Kremen, 2020-2024; Topuzov 2020-2024; M. Horvat, M. Kuzma-Kachur, 2021; A. Polishchuk, 2021) and others.

We are talking about children of Generation Z ("Zomers") and A (Gen Alpha), who are involved in the process of transforming modern education, have become the main users of digital technologies, are shaping a new Internet culture and new trends in learning, consumption, communication, and social interaction.

Generation Z ("Zoomers") - children born between 1995 and 2010 (there are also other dates of birth of Generation Z (Hawkins - 1991; Schmidt - 2001; Walker - everyone born after 1995). These time differences are largely related to the level of industrial and digital development of different countries, and therefore do not cause debate. The buzzwords were formed during the period of intensive development of the information society, the Internet and future technologies, in the era of globalization. At the everyday level, they are also called the generation "born with a gadget in their hands". The definition of the "buzzer" generation is synonymous with the concept of "digital person." Taking into account the various manifestations, the buzzer generation also has other names, although less common: "Silent Generation," "Internet Generation," "Google Generation" and others.

Generation Z is characterized by: independence and freedom-loving, the ability to quickly accumulate a large amount of knowledge and the need to share it with others, the need to recognize and receive an assessment of themselves and their actions, the absence of complexes, protest against inequality, denial of authority, a tendency to quickly change moods and interests, expressiveness, skepticism, a certain immersion and dependence (phubbing), organizational simplicity of the learning process and other aspects of life, impatience, and a focus on quickly achieving results.

In the educational process such children do not perceive coercion and learning as a duty. For them, interest is important, that is, for it to be interesting. This increases the requirements for the teacher's competence and pedagogical skills, his erudition, as well as the ability not to be authoritarian, but to build a dialogue with the student as a full-fledged subject of the educational process, who must be unobtrusively directed to a certain choice and activity, directly involved in it, making him interested in innovations.

Currently, Generation A (Alpha), born after 2010, is at school. The name was suggested by Australian demographer Mark McCrindle, author of the book for parents and teachers, Generation Alpha. Understanding our children and helping them thrive (2021). Mark McCrindle perceives this generation "as the most materially gifted and technologically literate," and "the first generation of distance learning," which has received complex life experiences, and therefore parents and teachers need to know it in order to best guide, educate and teach and get the best result from them. The author defines the boundaries of Generation Alpha from 2010 to 2024 (MccRindle M., Fell A., Buckerfield S., 2021). However, we do not find an author's explanation of this duration for a generation. In our opinion, a period of 15 years is insufficient for the reproduction of a generation. In sociology, the generally accepted period for the change of generations is 20-25 years.

In literary sources, the abbreviated name Generation A is also used to refer to "Generation Alpha", "Google Babies", "Zen Generation", "Smartphone Children", "Glass Generation" (the name emphasizes the simultaneity with the appearance of Instagram and iPad), "Millennial Children".

According to Mark McCrindle's book, as well as the author's own observations, a social portrait of the generation is already emerging among alpha children, who are now teenagers, in which properties and traits are manifested to varying degrees, but give an idea of the collective image, its potential, and in which direction the organization of an educational and developmental environment for them can be most appropriate and effective.

This generation is characterized by a high level of purposefulness and digital literacy, a desire for self-affirmation, including economically, from adolescence. They strive and know how to achieve their own goals, earn their own money in order to

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freely dispose of it and provide for their needs. Therefore, they are already set on their own business projects, which they are trying to implement, including using network platforms and an active presence in them, acting as bloggers and not only, shooting short videos for TikTok, building a personalized online space. There are numerous examples of the success of such creative and business activities, in which they are attracted by the opportunity to be independent, creative, not only to earn money for their own needs, but also to be recognizable and popular.

Marketers, media, advertisers, and the gaming and non-gaming industries are focused on the business abilities and inclinations of the Alpha generation, as well as the development of a unique consumer identity in their environment, including in relation to digital brands. As a result, children early, and according to some parents from the age of 2-3, already establish associations, and over time, quite naturally identify themselves with digital brands - brands of the media space, that is, brands that are "promoted" using digital technologies. Representatives of the Alpha generation are distinguished by a simplified spectrum of emotions or by reluctance or difficulty in expressing and describing them - in part, this gives the impression of frustration - an emotional state that arises from the inability to satisfy a need or achieve a desired goal (Social Pedagogy: Dictionary-Reference, 2009, p. 499) or existential frustration - a psycho-emotional state characterized by an emotional vacuum (reminiscent of indifference or emptiness), experiencing boredom, apathy, loss of meaning in one's own life, in cynical attitudes and statements. Under the influence of media violence and manipulation, in particular manipulative online games, adolescents show a tendency to suicide. This was clearly observed in the results of the coordinated teenage game "Blue Whale" (also known as "Silent House", "Wake Me Up at 4:20", "Sea of Whales", "U19", 'F57" and other names), which was distributed mainly in Russian-language social networks and ultimately led the player to suicide. It caused the spread of suicide cases among Ukrainian teenagers in the so-called "groups of death'. That is why modern children need socio-emotional support and support in understanding the value of life and realizing life values, in forming resilience to manipulation, social stability, a sense of belonging to their family, household, school, country, and culture.

Like the Zoomers, the Alpha generation is driven to merge the real and virtual worlds in their own way of life, embedding one into the other and blurring the boundaries between them through the Internet, exposing themselves to digital risks and anxieties associated with social media, including cyberbullying, cybermobbing, cyberfraud, sexting, and phishing (Alieksieienko, 2021, p. 7). They actively share their life stories in chat rooms and blogs, and in TikTok videos, preferring virtual communication in chat rooms over face-to-face contact.

They actively and freely communicate and find common interests with their peers remotely, including from other countries, since, for the most part, they do not have a sense of social and geographical boundaries and language barriers. This is facilitated by the opportunity to travel to different regions and different countries in real life, knowledge of English and other languages of international communication. As a result, compared to previous generations, they feel freer and more independent, open to the perception of the diversity of life, show tolerance for otherness, and adapt quite quickly to new living and learning conditions. This is confirmed by the examples of school-age children from among the internally displaced persons and children - refugees from war to safer regions of Ukraine and host communities of foreign countries.

In learning, children of the buzzer and alpha type mostly show the speed of perception and processing of a large amount of information, readiness for continuous learning in conditions of formal and informal education, for self-education and self-development. They are mobile in movement and decision-making. In decision-making, they try to adhere to a certain algorithm developed in previous experience, and are focused on applying the least effort for this, “in one click”. At the same time, they do not avoid problems and prepare themselves for multifunctionality, for cooperation with others, for teamwork, for which the social demand and their interest are growing. However, we note that in teamwork, leadership roles are more attractive to them, rather than performers. And yet, due to long periods of interrupted learning during the covid-19 pandemic, instability in the organization of the educational process, and military threats and associated emotional states, Alpha children from Ukraine have significant educational losses (PISA-2022 (2023); Alieksieienko (2023 b); Official Portal of Kyiv, 2023).

However, the brightest representatives of the generation even improved their academic results, as they received a new impetus in motivation to study as self-affirmation in difficult life circumstances and understanding of education as a reliable prospect for self-realization, future career development and achieving decent living conditions. In general, Alpha children have largely adapted to the new way of life, obtaining education and spending leisure time. And this is a sign of their resilience.

The Alpha Generation has had to fully immerse itself in the technologies of the digital society and subordinate its life to its challenges and opportunities. They are associated with social expectations for the restructuring, renewal of the world in various aspects: ecological, economic, technological, cultural. They already take responsibility for the state of the planet and its future, showing initiative in solving issues related to the environment, in particular, they call for their protection and themselves join the volunteer movement or actions to preserve nature and its resources, including by developing and implementing student projects of scientific, social, ecological and cultural content. Which, in the face of the threat of possible ecological and man-made disasters of the planet, becomes extremely relevant.

Representatives of the Zoomer and Alpha generations have much in common, as they are the closest in time by birth and life activity, and at the same time, they are unique, associated with the reassessment of values and past social experience and the experience of older generations, the exacerbation of social problems, intergenerational conflicts and social confrontation, and the formation of civil society. Therefore, their uniqueness is due to both different conditions of social maturation, acquired social experience (in particular, during a pandemic, war, military threats to life and distance learning), and to a certain extent, different social values dominant in a society that has been dynamically developing and changing in recent decades.

Life values have set the conditions for the growth of ecological and social awareness in generations Z and A. Both try to be in trend, keep up with the times, determine consumption trends, including in the field of educational services. They like the use of game technologies in educational and creative activities, gamification.

They are focused on preserving their own boundaries, a narrow circle of social contacts, love solitude and have significant influence on their parents, deny subordination, are impatient, are determined to aggressively defend their needs and their rights. They are also interested in artificial intelligence and are already involving it in their learning process, including with the aim of facilitating it and violating academic integrity. They are less concerned about grades than representatives of previous generations. However, it is difficult for them to impose someone else's vision and someone else's choice.

According to observations and statements of practicing teachers, students from Generation Z and A have a short attention span and do not perceive information well by ear due to long messages. They have a dominant visual memory. Therefore, during a lesson based on verbal teaching methods and resembling a lecture, their level of concentration deteriorates. They perceive video information better - presentations, videos, trailers, pictures, etc., than words. They also easily learn the algorithm for finding the necessary information on devices, rather than the information itself. At the same time, they are curious, like to find answers to various questions themselves and learn independently, if they understand why they may need this knowledge in life. They impress with their pragmatic thinking.

As individuals, representatives of generations Z and A are formed during the period of intensive development of the entertainment industry, to which they are involved from early childhood through modern toys, various games and gaming devices. That is why, if there is an opportunity to combine entertainment and learning in the learning process, they like it. Otherwise, they consider lessons uninteresting, and during lessons they delve into the programs and content of their gadgets. According to the survey in focus groups, the motivation for learning in such children is increased by gamification and creative tasks, in which they can demonstrate their achievements, including the skills and abilities of users, gamers, as well as the ability to use computer programs to solve specific tasks, apply knowledge and skills in information processes and the ability to use the necessary computer software products in educational and leisure activities.

There are also challenges in the digital socialization of schoolchildren and in the formation of the class team. The predominance of virtual communication with peers through gadgets, which is welcomed and supported in the modern digitalized environment, leads to the fact that they lose the need to be a member of a real community and do not know how to build relationships with classmates. Or they gather in small groups based on interests related to computers or phones. And even in such small groups, communication using gadgets is dominant.

In communication with teachers and in learning, as indicated in the responses to our online survey of students in grades 5-9, network systems Viber, Skype, Telegram, Discord; Classroom applications, electronic diary; educational platforms Zoom and Google Meet are used. In communication with peers, there are network systems, most often Instagram and TikTok, which reach wide audiences and where there is an active exchange of photos, sharing of various stories, their distribution on their own services and other social networks.

As the survey data revealed, modern teenagers also practically do not think about the fact that they leave a digital trace of themselves as a network user in virtual space, using the electronic environment, in particular:

- registering on various sites and platforms, where they provide their personal information (name, age, gender, phone, place of residence, etc., upon request);
- making purchases in an online store;
- using electronic applications for various purposes.

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So, with all the possibilities of self-presentation through digital technologies, digital identification also contains many risks associated with fraud and cyberbullying. Cyberbullying is a type of bullying (bullying by one person) and cybermobbing (group bullying) in the Internet space with the aim of harassing, harming, and degrading the dignity of another by spreading compromising or inaccurate information about them. Such circumstances exacerbate the need to pay increased attention to the safety of children on the Internet, in particular safe behavior. We draw your attention to the fact that both outsiders of groups and the brightest, strongest personalities – their otherness and identity – become victims of cyberbullying. The main mechanisms of its development are, as a rule, "jealousy and competition, fear, rejection of otherness, the desire to subordinate someone to one's own will (to assert oneself as strong and authoritative), to oust someone from the group (collective), to humiliate" (Alieksieienko, 2012).

Isolation or alienation from classmates over time leads to marginalization or conflict both in the educational environment and among peers. As a result, it is difficult for the teacher and other students in the class to interest these children in common activities and involve them in them.

Marginalization, uncontrolled curiosity and behavior of schoolchildren on the Internet, their anonymity (under fictitious nicknames) create favorable prerequisites and conditions for the development of computer addiction (which manifests itself in an obsessive fascination with computer games), cyberaddiction (characteristic manifestations of which are immersion in virtual life and communication, devaluation of reality and real contacts, change in the hierarchy of values, virtualization of consciousness, cyber-risky behavior).

The marginality of individual students or small groups of students usually leaves their behavior and interests beyond control. However, children may also be beyond control for other reasons – personality traits and independent behavior, excessive trust in adults, including teachers, parents' self-removal from control functions and some supervision over how children spend their free time. This applies especially to which websites a child visits, what content interests them most, what and with whom they communicate in blogs and chats.

Natural curiosity, trustworthiness and the pursuit of adulthood/independent choices during adolescence can lead to them becoming victims of sexting, being drawn into the web of drug dealers, extremist groups, or, as already noted, suicidal games.

In the context of the Russian-Ukrainian war, manipulative technologies of a subversive nature are actively spreading among the audience of Ukrainian teenagers in order to involve them in subversive activities, using their interest in pocket money and social immaturity. The specificity of manipulation is that it is not only latent, but also merges in the consciousness and self-awareness with the own interests of those who fall under its influence.

There are known facts when, during the current Russian-Ukrainian war, teenagers from Ukraine were recruited through social networks, under the pretext of participating in various quests, or possibly earning their own money, to photograph critical infrastructure facilities, send these photos and geodata to the aggressor, as well as to manufacture or deliver explosive devices to specified addresses. Then such facilities were subjected to missile attacks and destruction. There are also known facts about the destruction of such couriers by the enemy.

The existing problems of cyberbullying and manipulation using digital technologies actualize the task of developing not only digital literacy, but also humanistic consciousness among representatives of network generations, as well as increasing the school's attention to the formation of social competence, social stability and civic position in students, the need to increase attention to the safety of children on the Internet, in particular safe behavior.

In determining approaches to the formation of safe behavior of schoolchildren on the Internet, it is important to understand safe behavior not only as a set of actions, but also as a complex structural formation characterized by adolescents' knowledge of risks and rules of behavior in society, the environment, and the leisure sector, their ability to behave adequately and respond optimally in risky situations, control emotions, and be responsible for their own activities and behavior. In particular, in the challenges of the time, the issue of digital identity identification - identifying oneself with what is about everyone in the virtual space (as a process of acquiring it) and digital identity - an already formed digital representation of oneself, another specific person with their unique qualities and other characteristics (as a result of digital identity identification) is becoming increasingly important and requires special attention. It is an important step in the process of digital socialization (Fig. 1).

Fig. 1. The structure of a person's digital literacy and its effectiveness in the information and technological environment of developmental content (Author T.A.).

Digital identity consists of a set of electronic records on a digital footprint that stores a set of information about a user's visits and actions while online - everything he/she leaves about himself/herself in virtual space, registering on various sites and platforms, where he/she provides his/her personal information (name, age, gender, phone, place of residence, etc., upon request), making purchases in an online store or other financial transactions, in general, using the electronic environment where he/she identifies himself/herself while online.

The issues of safety/cybersecurity of the educational environment, security of the school network, and use of various educational platforms and services are also and will remain important. It is also necessary to understand that over time, as AI develops, along with opportunities, new challenges will emerge in the digital socialization of schoolchildren.

Already now, a certain challenge of the digital socialization of a schoolchild is the level of computer literacy of a modern teacher, his ability to operate multimedia computer programs, the latest information and communication technologies, interact with media information flows in the global information space, and have the skills to interact with educational platforms and web services in the process of educational activities, including to meet the ever-growing educational demands of children of generations Z and A for their development and in the process of studying educational programs.

Thus, in the context of the digitalization of society and education, there is a growing demand for the use of innovative methods and technologies aimed at both taking into account the individual needs of the education seeker and activating cognitive activity, acquiring competencies for functioning in an information-rich technological society. This determines the quality of the educational process in the context of its course and the prospects for the professional development of the education seeker.

Also, in the modern educational process, there is a growing demand for such teaching methods and technologies that would facilitate the perception of educational information, the accumulation of which has all the signs of overloading schoolchildren, which arose as a result of disruptions and gaps in their education during quarantine restrictions due to the covid-19 pandemic, which has affected most countries in the world.

In Ukraine, this was added to the disruption of stable and comfortable learning conditions, forced breaks, changes in the format of learning, and in some cases, even the usual educational environments due to their destruction or destruction, forced change of residence due to threats to life and health, as well as prolonged stress, anxiety, chronic sleep deprivation of schoolchildren and young students in connection with the military invasion of Russia and the systematic shelling of Ukrainian territories with ballistics and other types of weapons. This tragic situation for Ukraine caused not only educational losses, including educational losses among schoolchildren, but also significantly affected their motivation to study. This is confirmed by the results of our research (Alieksieienko, 2023 b).

Scientists and educators of Ukraine were faced with the task of not only organizing the educational process in the changed conditions of social life and a disrupted education system, overcoming educational gaps, but also taking into account the needs of schoolchildren in cognitive and socio-emotional development, in a positive atmosphere for carrying out the educational process.

According to the focus group survey, the use of a game approach to the learning process, along with other methods and technologies aimed at the sensory sphere of the personality, increases the motivation for learning of such children, making it innovative and emotionally rich. Thanks to gamification, as well as the appropriate use of video games and specially designed educational applications, animated videos during learning, learning occurs through play, relieving stress, immersion in positive emotions and the creative process, involving schoolchildren in design and experimentation, developing their analytical and spatial thinking, and the ability to interact and cooperate without conflict.

The gaming approach is based on gaming technologies and gaming practices using various videos, cartoons, quests, creative tasks, etc. Given their potential, provided there is no oversaturation, they can be used to simultaneously solve educational and educational tasks (in terms of their idea and moral content), expand the understanding of the possibilities of creative solutions, promote the development of emotional perception, create a positive mood, thereby performing a certain therapeutic function, which is extremely necessary for relieving emotional tension and stress, especially during distance learning, war, and will be useful during the period of post-war reconstruction of the country.

Along with other methods and technologies that are already being implemented for this purpose during war, gamification helps optimize the educational process. Thanks to it, as well as the appropriate use of video games and specially designed educational applications, animated videos during training, learning occurs through play, relieving stress, immersion in positive emotions and the creative process, involving students in design and experimentation, developing their analytical and spatial thinking, and the ability to interact and cooperate without conflict.

Knowledge, skills and abilities acquired in the process of game learning serve as the basis for the development of cognitive and social activity of the student's personality, his ability to withstand stress and cooperate in a team, gaining experience in moral behavior, successful self-presentation and self-realization in educational activities and social life, their multitasking and preparation for being a simultaneous performer of various social roles. Such potential of gamification and its emotional contagion creates conditions for increasing motivation in students to study, and for teachers - for further development of creative teaching of educational subjects, which students always appreciate.

Conclusions. Given the above, in direct interaction with modern students in the educational and developmental environment of an educational institution, it is necessary to:

- perceive the uniqueness of representatives of network generations, and direct and use their abilities and inclinations as a resource for development and success;
- build the educational process taking into account the peculiarities of perception, attention and concentration of modern students, diversifying teaching methods and tools;
- involve the most prepared children in the educational process as subjects of relaying digital literacy;
- strengthen educational work at school/in the educational space regarding manipulative technologies and methods of protection against them;
- adhere to the priority of creating safe conditions and cybersecurity in the educational environment and in the educational space for all participants in the educational process.

The digital socialization of representatives of network generations requires monitoring in order not only to optimize the conditions of the educational environment, but also to carry out certain preventive work to prevent negative social effects in its development.

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1.3. DIGITAL SKILLS AND ABILITIES AS AN INDICATOR OF CERTIFICATION ASSESSMENT OF THE PROFESSIONAL ACTIVITY OF TEACHING STAFF

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Nowadays, digital technologies are an integral part of social life. They are widely used in everyday life, education, medicine, transport, business, etc. They also play an important role in the personal and professional development of individuals.

The transition of educational institutions of Ukraine, in particular general secondary education institutions, to mixed and distance learning in 2020 (initially due to the COVID-19 pandemic, and since 2022 – due to the introduction of martial law in the country, which is still in force) has stimulated teachers to develop their digital literacy.

Thus, digital skills and abilities are an important component of the professional competence of a modern teacher of a general secondary education institution. According to the professional standard "Teacher of a General Secondary Education Institution" (2024), information and digital competence is one of the three competences (along with subject-methodological and language-communicative) that a teacher of a general secondary education institution must possess in order to perform one of five of his/her labor functions – teaching subjects (integrated courses) to students (Profesiinyi standart «Vchytel zakladu zahalnoi serednoi osvity», 2024). At the same time, the information and digital competence of a teacher is manifested in his/her ability to: 1) navigate in the information space, search for and critically evaluate information, as well use it in their professional activities; 2) effectively use existing and create new electronic (digital) resources; 3) use digital technologies in the educational process (Profesiinyi standart «Vchytel zakladu zahalnoi serednoi osvity», 2024, pp. 12-16).

Since 2019, Ukraine has introduced external assessment (certification of teaching staff) alongside with internal assessment of the professional activities of teaching staff (teacher certification). Since 2019, primary school teachers have been participating in the certification of teaching staff. In 2023, they were joined by teachers of Ukrainian language and literature and mathematics, and in 2024 – teachers of subjects (integrated courses) in the civic and historical educational field and/or the educational field “Social Studies”, and from 2025 – foreign language teachers (English). This means that, at present, not all subject teachers can participate in certification.

The purpose of certification is to identify and stimulate teachers who have a high level of professional skill and who is proficient in competency-based teaching methods and new educational technologies to promote their dissemination (Sertyfikatsiia pedahohichnykh pratsivnykiv. Zahalna informatsiia, n.d.).

Teachers’ participation in certification is voluntary, so they can opt out at any stage of the process.

Certification consists of three stages, which take place sequentially one after the other. The first stage is an independent testing of the professional knowledge and skills of teaching staff, which is organized and conducted by the Ukrainian Centre for Educational Quality Assessment and its regional centers. The other two stages of certification are self-assessment of one’s own teaching skills and study of the teacher’s practical work experience, which are organized and conducted by the State Service for Education Quality of Ukraine and its territorial bodies.

According to the Program for Independent Testing of Professional Knowledge and Skills of Primary School Teachers (2019), one of the components of professional knowledge and skills of primary school teachers is the digital environment (Prohrama nezalezhnoho testuvannia fakhovykh znan ta umin uchyteliv pochatkovoi shkoly, 2019, p. 2). In other words, independent testing assesses primary school teachers’ knowledge of the requirements for the use of computer technology in educational institutions to ensure the educational process, safety rules and sanitary and hygienic standards when using computer technology and digital devices, the ability to ensure the information security of students, including cybersecurity, and their ability to organize the educational process in a digital learning environment, including selecting appropriate software, digital educational environment resources, and information products to solve educational process tasks (Prohrama nezalezhnoho testuvannia fakhovykh znan ta umin uchyteliv pochatkovoi shkoly, 2019, p. 17).

However, it was only in 2022 that a component such as “Information Technology Education and Digital Educational Environment” was added to the test characteristics for primary school teachers, accounting for 6% of the total number of test tasks, i.e. 6 tasks (Pro zatverdzhennia Zahalnoi kharakterystyky testu nezalezhnoho testuvannia fakhovykh znan ta umin uchyteliv pochatkovykh klasiv..., 2022).

The Program for Independent Testing of Professional Knowledge and Skills of Primary School Teachers in General Secondary Education Institutions (2022) separately put the content of the material and the professional knowledge and skills that constitute the professional competence of primary school teachers’ in general secondary education institutions for each section. Thus, the component “Information Technology Education and Digital Educational Environment” contains material on: “Information. Data. Objects”, “Algorithms”, “Professional Communication and Cooperation in the Digital Space”, “Electronic (Digital) Educational Resources”, “Digital devices and their software” (Prohrama nezalezhnoho testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv zakladiv zahalnoi serednoi osvity, 2022, pp. 18-20). In other words, this component covers issues related to the Internet and Internet safety, including the security of websites, responsibility for one’s activities on the Internet, and the risks of non-compliance with security policies; search engines (searching for information, saving it and assessing its relevance), age restrictions on viewing certain pages and creating accounts; sources of information and their reliability and authenticity; methods of presenting algorithms and rules for constructing block diagrams; creating software projects in the Scratch environment and correcting errors in them; the purpose and capabilities of software; digital tools and resources; electronic (digital) educational resources; capabilities of cloud services; purpose, capabilities and limitations of digital devices; network etiquette; rules and norms of academic integrity and copyright while working with electronic educational resources; responsibility for unauthorized access to private data; rules for operating digital devices, safety rules, sanitary and hygienic requirements for using computer equipment; recognizing basic malfunctions of digital devices and programs

(Prohrama nezalezhnoho testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv zakladiv zahalnoi serednoi osvity, 2022, pp. 18-20).

One of the components of “teaching students subjects (integrated courses)” in the Programs for Independent Testing of Professional Knowledge and Skills of Teachers of Ukrainian Language and Literature (2023), Mathematics (2023), Subjects (Integrated Courses) in the Field of Civic and Historical Education and/or the Field of Education “Social Studies” (2024) and Foreign Languages (English) (2024), is the creation and maintenance of a digital environment for the effective teaching of the relevant subject/subjects or integrated courses in a specific educational field (language and literature, mathematics, civics and history, “Social Studies”). At the same time, for teachers of Ukrainian language and literature, subjects (integrated courses) in the field of civic and historical education and/or the field of “Social Studies” and teachers of foreign languages (English), this component includes issues related to the digital equipment of the classroom, electronic (digital) educational resources for organizing lessons and safety in the digital educational environment, and for mathematics teachers – “Basic concepts that are necessary for creating and maintaining a digital educational environment”, “Algorithms”, “Digital equipment for the classroom”, “Electronic (digital) educational resources for organizing educational activities (lessons)”, “Safety in the digital educational environment” (Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv inozemnoi movy (anhliiska mova) zakladiv zahalnoi serednoi osvity, 2024, pp. 15-16; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv (intehrovanykh kursiv) hromadianskoi ta istorychnoi osvitnoi haluzi ta/abo osvitnoi haluzi «Suspilstvoznavstvo» zakladiv zahalnoi serednoi osvity, 2024, pp. 17-18; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv ukrainskoi movy ta literatury zakladiv zahalnoi serednoi osvity, 2023, pp. 16-18; Prohrama nezalezhnoho testuvannia fakhovykh znan ta vmin uchyteliv matematyky zakladiv zahalnoi serednoi osvity, 2023, pp. 14-17).

In particular, for teachers of Ukrainian language and literature, subjects (integrated courses) in the field of civic and historical education and/or the field of “social studies”, and foreign languages (English), the component “creation and maintenance of a digital environment for effective teaching of the relevant subject/subjects or integrated courses” covers issues related to the purpose and rules of operation of digital devices, including safety rules and sanitary and hygienic requirements for the use of computer equipment; operating systems and application software objects

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and operations with them; computer network components; types and purposes of electronic (digital) educational resources; the capabilities of cloud services; recognition of basic malfunctions of computer systems (devices and programs); rules of network etiquette; rules and norms of academic integrity and copyright while working with electronic educational resources; dangers and risks in the digital space; cybersecurity; rules for safe behavior in the digital space; age restrictions on viewing pages and creating accounts; assessing the reliability of Internet sites; identifying risks of non-compliance with security policies; creating strong passwords, recognizing manipulative influences and fraudulent information sources (Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv inozemnoi movy (anhliiska mova) zakladiv zahalnoi serednoi osvity, 2024, pp. 15-16; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv (intehrovanykh kursiv) hromadianskoi ta istorychnoi osvitnoi haluzi ta/abo osvitnoi haluzi «Suspilstvoznavstvo» zakladiv zahalnoi serednoi osvity, 2024, pp. 17-18; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv ukrainskoi movy ta literatury zakladiv zahalnoi serednoi osvity, 2023, pp. 16-18).

For mathematics teachers, the component "creation and maintenance of a digital environment for effective teaching of the relevant subject/subjects or integrated courses" is supplemented by questions about the essence of the concepts of information, data, object, model; coding and decoding; creating mathematical models and implementing them in spreadsheets; using mathematical models in spreadsheets to conduct experiments and research; linear, branched and cyclic algorithms, identifying and eliminating various types of errors in algorithms; drawing block diagrams using various basic structures to solve mathematical problems (Prohrama nezalezhnoho testuvannia fakhovykh znan ta vmin uchyteliv matematyky zakladiv zahalnoi serednoi osvity, 2023, pp. 14-17).

In 2025, new programs for independent testing of the professional knowledge and skills of teachers of primary school, Ukrainian language and literature, mathematics, and subjects (integrated courses) in the civic and historical education field were approved (Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv matematyky zakladiv zahalnoi serednoi osvity, 2025; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv (intehrovanykh kursiv) hromadianskoi ta istorychnoi osvitnoi haluzi ta/abo osvitnoi haluzi «Suspilstvoznavstvo» zakladiv zahalnoi serednoi osvity, 2025; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv pochatkovykh klasiv zakladiv zahalnoi serednoi osvity, 2025; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv ukrainskoi movy ta literatury zakladiv zahalnoi serednoi osvity, 2025). In particular, the programs for all certification participants were standardized with regard to the component "creation and maintenance of a digital environment for effective teaching of subjects (integrated courses)". The programs for independent testing of the professional knowledge and skills of teachers of the Ukrainian language and literature (2023) and subjects (integrated courses) in the field of civic and historical education and/or the field of education "Social Studies"' (2024) were taken as a basis (Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv (intehrovanykh kursiv) hromadianskoi ta istorychnoi osvitnoi haluzi ta/abo osvitnoi haluzi «Suspilstvoznavstvo» zakladiv zahalnoi serednoi osvity, 2024; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv ukrainskoi movy ta literatury zakladiv zahalnoi serednoi osvity, 2023). Thus, for all certification participants, the component "creation and maintenance of a digital environment for effective teaching of subjects (integrated courses)" includes information about digital support for the educational process, electronic (digital) educational resources for organizing educational activities, and security in the digital educational environment. However, compared to the 2023-2024 programs, the 2025 programs have been supplemented with information on the implementation of artificial intelligence systems in the educational process, in particular it relates to the understanding the possibilities of using digital educational platforms, online services and artificial intelligence systems in the educational process and the ability to choose them during their teaching activities, as well the knowledge of the rules of network etiquette (Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv matematyky zakladiv zahalnoi serednoi osvity, 2025, pp. 20-22; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv (intehrovanykh kursiv) hromadianskoi ta istorychnoi osvitnoi haluzi ta/abo osvitnoi haluzi «Suspilstvoznavstvo» zakladiv zahalnoi serednoi osvity, 2025, pp. 24-26; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv pochatkovykh klasiv zakladiv zahalnoi serednoi osvity, 2025, pp. 26-28; Prohrama nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv ukrainskoi movy ta literatury zakladiv zahalnoi serednoi osvity, 2025, pp. 25-28).

Table 1 shows the percentage and number of tasks related to computer science education and the digital educational environment contained in independent testing for different categories of teachers in 2022-2025.

*Table 1**

Percentage and number of tasks on computer science education and the digital educational environment contained in independent testing for different categories of teachers in 2022–2025

	Teacher categories:									
	Primary school teachers		**Ukrainian language and literature teachers**		**Mathematics teachers**			**Teachers of subjects (integrated courses) in the field of civic and historical education and/or the field of "social studies"**		**Foreign lan-guage teach-ers (English)**
	2022-2023	**2024-2025**	**2023-2024**	**2025**	**2023**	**2024**	**2025**	**2024**	**2025**	**2025**
% of tasks in the test	6%	6%	6%	7%	6%	7%	7%	6%	6%	5%
Number of tasks in the test	6	5	5	5	5	5	5	5	5	4-5**

* The table was created using data from (Nezalezhne testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv hromadianskoi ta istorychnoi osvitnoi haluzi. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2024, 2025; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv matematyky. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2023, 2024, 2025; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2022, 2023, 2024, 2025; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv ukrainskoi movy ta literatury. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2023, 2024, 2025; Pro zatverdzhennia Zahalnoi kharakterystyky testu nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv (intehrovanykh kursiv) hromadianskoi ta istorychnoi osvitnoi haluzi ta/abo osvitnoi haluzi «Suspilstvoznavstvo»..., 2024; Pro zatverdzhennia Zahalnoi kharakterystyky testu nezalezhnoho testuvannia fakhovykh znan ta umin uchyteliv pochatkovykh klasiv..., 2022, 2023; Pro zatverdzhennia Zahalnoi kharakterystyky testu nezalezhnoho testuvannia fakhovykh znan ta vmin uchyteliv inozemnoi movy (anhliiska mova)..., 2025; Pro zatverdzhennia Zahalnykh kharakterystyk testiv nezalezhnoho testuvannia fakhovykh znan i vmin uchyteliv ukrainskoi movy ta literatury y uchyteliv matematyky..., 2023; Pro zatverdzhennia Zahalnykh kharakterystyk testiv nezalezhnoho testuvannia fakhovykh znan ta umin uchyteliv pochatkovykh klasiv, uchyteliv ukrainskoi movy ta literatury y uchyteliv matematyky..., 2023; Pro zatverdzhennia Zahalnykh kharakterystyk testiv nezalezhnoho testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv, uchyteliv ukrainskoi movy ta literatury, uchyteliv matematyky ta uchyteliv navchalnykh predmetiv (intehrovanykh kursiv) hromadianskoi ta istorychnoi osvitnoi haluzi ta/abo osvitnoi haluzi «Suspilstvoznavstvo»..., 2024).

** Approximate number of tasks in the test.

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According to Table 1, it can be concluded that each independent testing test contains 5-6 tasks on information technology education and the digital educational environment.

Let us briefly analyze these tasks.

For example, the test for primary school teachers in 2022 contained tasks on: selecting from the given names of internal memory devices; identifying an error in an algorithm created by a student for drawing a square in the Scratch environment; knowledge of the norms (rules) that must be followed when sharing someone else's video on your Facebook profile; identifying actions that can be implemented using the Google Forms tool; identifying a service that can be used to organize joint activities for students and post information on a virtual board in text or graphic form; knowledge of the characteristics of a secure email (choosing such an email from four emails) (Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2022, pp. 30-32); 2023 – knowledge of the age at which children in Ukraine are allowed to independently create a Google account outside the Google Workspace of Education domains; ability to create a software project in the Scratch environment – draw a triangle; knowing the norms of academic integrity standards when sharing a colleague's methodological work on social media; identifying statements about the organization of the educational process in Google Classroom; determining the types and functions of software; choosing a service for creating a quiz (Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2023, pp. 30-32).

The tests for teachers of Ukrainian language and literature and mathematics in 2023 included tasks on: the ability to assess emails for their safety for the recipient (choosing a safe email from four emails); choosing a problem that is the cause of a computer malfunction; knowledge of keys when working in a Microsoft Word document; choosing a service for creating a words cloud; choosing an action that cannot be performed using the Google Docs tool (Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv matematyky. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2023, pp. 11-13; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv ukrainskoi movy ta literatury. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2023, pp. 11-13).

In 2024, tests for primary school teachers and teachers of Ukrainian language and literature and mathematics included tasks on: knowledge of the characteristics of safe and unsafe websites (choosing an unsafe website from four options); knowl-

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edge of the purpose of a specific panel button; choosing a service that is not suitable for organizing group work for students on a virtual board; identifying actions that can be performed in Google Docs; resolving a specific problem when working with a PC (personal computer) (Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv matematyky. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2024, pp. 11-12; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2024, pp. 11-12; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv ukrainskoi movy ta literatury. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2024, pp. 11-12).

The test for teachers of academic subjects (integrated courses) in the field of civic and historical education and/or the field of “Social Studies” in 2024 included tasks related to: choosing what to do when receiving an email that looks like spam; solving a problem with a personal computer by taking certain actions; choosing the key used to exit the main window program and cancel certain actions; choosing the level of access for colleagues under certain conditions in Google Docs; defining what Google Drive is (Nezalezhne testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv hromadianskoi ta istorychnoi osvitnoi haluzi. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2024, pp. 12-13).

In 2025, tests for teachers of primary school, Ukrainian language and literature, mathematics, and subjects (integrated courses) of the civics and history educational field and/or the educational field “Social Studies” included tasks on: choosing a secure password for a personal Google account from four options; choosing names for devices that can only be used to enter information into a computer; choosing a Microsoft program for designing and laying out pages, creating business cards, invitations, etc.; knowing the safety rules when making a purchase in an online store; determining what Google Keep is (Nezalezhne testuvannia fakhovykh znan i vmin uchyteliv navchalnykh predmetiv hromadianskoi ta istorychnoi osvitnoi haluzi. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2025, pp. 9-10; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv matematyky. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2025, pp. 9-10; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv pochatkovykh klasiv. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2025, pp. 11-12; Nezalezhne testuvannia fakhovykh znan ta vmin uchyteliv ukrainskoi movy ta literatury. Sertyfikatsiia pedahohichnykh pratsivnykiv, 2025, pp. 9-10).

So, since 2019, certification system (external assessment) for teaching staff in general secondary education institutions has implemented in Ukraine. This is an important tool for improving the quality of education and the professional development of teaching staff in general secondary education institutions. Unfortunately, not all subject teachers are yet eligible to participate in the certification process.

Independent testing of the professional knowledge and skills of teaching staff is the first of three stages of certification. One of the components of the external assessment tests of the professional activities of teaching staff in general secondary education institutions is "information technology education and digital educational environment". Each year, each test contains 5-6 tasks on this component, one of which is on the use of electronic (digital) educational resources for organizing the educational process in general secondary education institutions and one on safety rules in the digital educational environment. The tests also pay great attention to issues of academic integrity. In our opinion, the format of the test tasks – choosing one correct answer from the options provided – does not always allow for an adequate assessment of the practical skills of teachers of a general secondary education institution, i.e. the application of knowledge and skills related to information technology education and the digital educational environment in the real educational process. We hope that the introduction from September 1, 2025 independent testing of teachers' professional knowledge and skills in the form of computer-based testing (along with paper-based testing) (Pro vnesennia zmin do Polozhennia pro sertyfikatsiiu pedahohichnykh pratsivnykiv, 2025) will lead to certain changes in the form and content of test tasks.

In our opinion, it is desirable to supplement the tests for independent testing of teachers' professional knowledge and skills with situational tasks and open-ended tasks in which teachers would solve problem situations related to the use of digital technologies in the classroom and/or during the organization of the educational process, demonstrate their skills in working with digital platforms, software, etc., justify their choice of certain digital tools for specific educational tasks, etc. Indeed, in the context of modern digital education, one of the main indicators of the certification assessment of the professional activity of a teacher in a general secondary education institution is their digital competence, and certification assessment should not be a test of teachers' knowledge and skills, but an incentive for their professional development and learning.

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1.4. DIGITAL TOOLS FOR SUPPORTING DISTANCE AND BLENDED LEARNING OF PHYSICS

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The issue of widespread implementation of distance learning in the European and international educational space gained momentum during the prolonged quarantine restrictions on the operation of educational institutions caused by the COVID-19 pandemic. In Ukraine, this issue became even more urgent and intensified during wartime conditions, when security factors have led to forced interruptions in face-to-face learning. Distance learning, implemented through modern digital tools, has become a vital (and sometimes the only) form of organizing the educational process, ensuring access for secondary and higher education students to quality educational services.

The deployment of distance learning has made it possible to accumulate intellectual, personnel, organizational and technical educational resources educational resources and ensure effective interaction between subjects of the educational process using safe locations within the country, as well as fully involve Ukrainian

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students and young people abroad in the educational environment of a particular institution.

A unique feature of the national education system is its ability not only to demonstrate remarkable resilience and maintain stable functioning under challenging and unpredictable conditions, but also to ensure consistent development. This has largely been made possible through the effective use of distance learning technologies, methods, and tools that are on par with — and in some cases surpass – those of the European Education Area. As one of the key priorities of Ukraine's educational sector is to engage as many learners as possible in face-to-face education across all levels, the organic integration of distance and blended learning technologies is particularly relevant in the short term. This approach will make it possible to bring students back to classrooms and lecture halls while emphasizing the development of key and professional competencies. These competencies are grounded in the ability to solve real-life problems encountered in daily life and are essential for future professional activity, socialization, and interaction with nature and the community (Holovko, Kryzhanovskyi, & Matsyuk, 2024b).

The deployment of blended learning is one of the key trends in global and European education. In the works of foreign researchers, blended learning is defined as a combination of traditional classroom-based instruction and learning through digital online resources and media. From an organizational and technological perspective, blended learning differs from both face-to-face and distance learning in terms of location, distance, and the technologies used for interaction between participants in the educational process.

Blended learning is viewed as a type of hybrid learning that is based on the deep integration of distance and face-to-face instruction, subordinated to a clear didactic concept. In this context, blended learning is not merely the addition of digital technologies to traditional in-person education for the sake of online learning. It involves the modernization of the educational process through new organizational and pedagogical approaches, as well as the creation of an educational environment where information and communication technologies are organically combined with pedagogical methods. This integration makes it possible to create and use didactic materials with interactive functionality, provides learners with access to them both in real time and asynchronously, supports different learning styles, and enables an optimal pace for each student.

The emergence of distance and blended learning has been driven by the rapid development of information and communication digital technologies, social networks, and modern pedagogical approaches such as activity-based, learner-centered, competence-oriented, project-based, and e-learning methodologies, as well as the development of critical thinking. The core tools of distance and blended learning include Google Classroom, YouTube, Zoom, Microsoft Teams, Skype, Moodle, and Blackboard.

These platforms and environments enable the organization of the educational process in such a way that learners, for instance, complete tasks together in the classroom and then refine and submit them to the teacher using digital tools. At the same time, students can combine taking online courses with face-to-face instruction or pursue individual learning remotely [The Definition of Blended Learning, 2021).

The most popular model of education abroad today is the hybrid learning model known as the Innosight model ("online driver" or "flipped learning").It combines the advantages of both in-person and distance learning. Typically, in purely distance learning, teachers deliver lectures during online sessions in a way similar to classroom settings, and students then submit completed assignments to the class. The downside of this approach is that teachers are not always able to review these assignments promptly and thoroughly, due to the volume and the individual characteristics of each student's learning activity, as well as delays in submitting assignments.

In contrast, in a "flipped" classroom, teachers present the educational material using online media, and students work through it individually. In the classroom, the priority is placed on activities aimed at developing practical skills (such as problem-based discussions, educational debates, and research projects). This blended learning approach ensures individualization and a learner-centered educational process: transmissive (reproductive) learning transforms into interactive learning.

Blended learning is viewed as an organic combination, an integration of different methods for organizing students' educational and cognitive activities, particularly those focused on independent learning within a digital educational environment, as well as individual or group activities under the guidance of an instructor.

At the same time, this model allows for the combination of the benefits of both in-person and distance learning, the use of specific technological solutions from distance learning in traditional educational settings, and the utilization of a system of didactic materials that includes both printed textbooks and educational manuals as well as electronic educational resources.

The most functional models of blended learning today include the following: the rotational model (involves the alternating change of key characteristics of the educational process, such as location and types of learning activities); the personalized model (features parallel face-to-face learning and the use of online resources tailored to individual learning paths); the enriched virtual model (primarily focuses on working with online courses, with the option of in-person sessions (both individual and group) for reinforcing learned material, discussing academic challenges, and reviewing completed tasks and projects) (Blended Learning, 2022).

The high effectiveness of blended learning is demonstrated, in particular, in the higher education process due to the development of students' self-education competence and their readiness to interact with instructors through educational process and resource management systems during online learning (for example, Blackboard and Moodle).

While the approaches to blended learning in Ukraine's educational system require thorough development, the legal and regulatory framework for the implementation of distance learning as one of the forms of obtaining education–either independently or in combination with full-time (daytime or evening), part-time, or network-based learning–is defined by the Law of Ukraine "On Education", which defines distance learning as an individualized process that takes place in a specialized environment combining modern psychological-pedagogical and information-communication technologies, and is characterized primarily by mediated interaction between participants in the educational process who are physically separated from one another (On Higher Education, 2014).

Since distance education involves a combination of various methods, forms, and technologies for organizing the educational process–including blended learning–it becomes particularly important in situations where safety factors must be taken into account.

General approaches to the organization of distance learning in secondary education institutions are defined by the "Regulations on the distance form of obtaining complete secondary education".

According to it, one of the important factors for the effective implementation of distance learning is its educational, methodological and system-technical support.

The first component includes methodological recommendations for organizing distance learning, as well as the content, dialectical and methodological apparatus of electronic educational resources for specific subjects (integrated courses) studied in educational institutions.

The second component includes: hardware, i.e. equipment for creating and using electronic educational resources, organizing interaction between subjects of the educational process in both synchronous and asynchronous modes, managing the educational process (computer equipment, network equipment, power supplies, servers, etc.); digital means of continuous access of subjects of distance learning to electronic educational resources and services for the purpose of organizing the educational process; specialized software for developing and supporting distance learning systems; digital educational resources in specific subjects that ensure the implementation of the content of education in distance education (Regulations on the distance form of obtaining complete general secondary education, 2020).

The types and main functions of digital educational resources are specified in the Regulation on Electronic Educational Resources (On approval of the Regulation on electronic educational resources, 2012).

According to it, digital educational resources are learning tools stored on digital media (in information and telecommunication systems) and can be reproduced using digital technologies.

These may include both digital versions of printed publications—preserving not only the content but also the page structure—and specially developed digital tools (electronic textbooks, electronic reference books, electronic laboratory workshops, electronic teaching aids, electronic educational game resources, electronic textbooks, electronic workshops, electronic workbooks, electronic dictionaries, electronic didactic demonstration materials (static and dynamic), electronic methodological recommendations for teachers on the features of distance learning of subjects and the organization of control and evaluation, electronic development of educational activities, simulators for the formation and development of practical skills in students, systems for monitoring and evaluating learning outcomes with a set of test tasks and the function of automated verification of their performance, virtual simulators with methodological recommendations for their use, etc.). They may contain theoretical and practical components in accordance with the curriculum, competency-based systems of educational tasks, differentiated by levels of complexity, interactive and game elements, tasks in test form.

General requirements for modern digital educational resources are their safety, functionality, reliability, user-friendliness, multi-platform, compliance with international standards and principles of digital development of society and domestic legislation.

A special role is assigned to the electronic textbook – a digital educational publication that presents a structured exposition of subject content in accordance with the curriculum, combined with interactive integration of digital objects in various formats. The structure and methodological apparatus of a digital textbook should provide a clearly structured, consistent and logical presentation of the educational material, in accordance with the age characteristics of the students for whom it is created, and maintain a balanced proportion of multimedia and other content (On approval of the Regulation on the electronic textbook, 2018).

Particular attention is paid to the requirements for the interface and design of a digital textbook (principles of integrity and intuitive understanding, modularity, proximity and similarity of elements, uniqueness of interface elements used for specific functions and actions, neutrality of the background and concentration of attention on key points, creation of a friendly learning environment and adaptability to the needs and requests of a specific user (settings and feedback tools, video and audio information, clear instructions, content scaling, etc.).

An important advantage of a digital textbook is the ability to use it on at least three operating systems, at least two of which are supported by mobile devices, as well as the availability of functional navigation tools and tools for working with test and multimedia educational content.

Thus, even before the COVID-19 pandemic began, a regulatory and organizational foundation had been established in Ukraine for the implementation of distance learning and the creation of its didactic support.

Blended learning becomes especially important when studying subjects and disciplines that require the development of practical skills and abilities, as well as working with real instruments and equipment in the laboratory. Systematic work on the development of electronic educational tools in physics began in the early 2000s. Through the efforts of methodologists and programmers, unique pedagogical software tools in physics were created for mass use in schools: electronic textbooks "Physics, 7th grade." and "Physics, 8th grade"; libraries of electronic visual aids for grades 7-9 and 10-11; virtual physics laboratories for grades 7-9 and 10-11 of secondary education institutions (2004-2005). These tools are still widely used in educational practice and have played an important role in the implementation of distance learning in physics.

A significant step in the development of fully functional distance learning was the implementation of the idea to supplement textbooks used in general secondary education institutions with interactive electronic applications. These applications are a mandatory component of the didactic set along with paper textbooks and are aligned with their content, goals, and learning objectives of specific school subjects.

The electronic applications are aimed at individualizing the educational process and include competency-oriented learning tasks of varying difficulty levels that ensure the formation and assessment of key competencies, tasks for self-assessment and determining the achievement of expected learning outcomes according to state education standards, as well as tasks for independent and group work, research, and creative assignments.

Important requirements for electronic applications include that they must be free of charge for users, compatible with the most common operating systems (Windows, Android, iOS, ChromeOS) and computer devices (personal computer, laptop, tablet, or smartphone), use free browsers, have interactive content, include multimedia elements (images, video and audio materials, 3D models and scenes), provide tools for interactive interaction between teachers and students (trainers, process simulations, testing, management of students' educational and cognitive activities), integration with external online resources, and more (On approval of the Requirements for an interactive electronic application to a textbook, 2024).

For example, the electronic application for the 8th-grade physics textbook of the New Ukrainian School (authors T.M. Zasiekina and M.S. Hvozdetskyi) supplements the material of the traditional paper textbook by the same authors with videos and animations, links to web pages with additional educational information and simulations, and contains tools for self-assessment, a system of interactive exercises, and testing. Its key modules are "Educational Video," "Interactive Tasks and Tests," and "Worksheets." These ensure the implementation of an activity-based approach, broad opportunities for individualizing physics education, and strengthening its practice-oriented focus. Feedback and management of students' educational and cognitive activities in the physics learning process are carried out through web tools, and for independent work, educational materials with a printing function for paper worksheets are available in the application [E-Application, 2025).

At the level of higher professional education, the organizational and methodological conditions for the effective implementation of distance learning are determined by each institution, taking advantage of their broad autonomy and ability to respond quickly to emerging challenges. Typically, each higher education institution develops its own regulation on organizing distance learning, which takes into account specific contextual factors—such as the security situation during wartime, the specifics of educational-professional or educational-scientific programs, and more.

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For instance, at Ternopil Volodymyr Hnatiuk National Pedagogical University, the key components of the distance learning system include: an electronic educational and methodological complex for each academic discipline; a distance course, implemented as an electronic system of educational content and methodological tools, accessible to students via the Internet or local network; technologies for creating, accumulating, and storing educational content, as well as providing student access to electronic courses and materials; software support technologies for managing the educational process; tools for achieving educational goals, including psychological and pedagogical technologies; synchronous tools (chats, video conferencing, social media); asynchronous tools (delayed interaction via email, forums, social media, etc.) (Ishchenko, Horbunovych, 2021).

At the same time, distance learning is implemented as an independent form of organizing the educational process, as well as a component of ensuring continuous access to high-quality educational services for people with special needs, gifted higher education students who are able to work independently, students of the preparatory department, students who cannot constantly study in person due to family circumstances or health conditions, students from remote locations within the country and forcibly displaced abroad. In addition, individual disciplines are taught in distance mode for students of full-time and part-time forms of study.

The foundation of the university's distance learning system is a specially designed digital educational environment on the Moodle platform, which supports interaction between instructors and students through modern information and communication technologies and corresponding software tools. It provides authorized access to the distance learning management system, electronic educational resources and didactic materials, digital tools, and functional instruments.

An important feature of Moodle is its ability to be used by participants in the educational process without requiring installation on the user's device or additional software. Any changes, as well as the results of work on the platform, are stored on the server, which provides an automated management process. Effective means of organizing distance and blended learning in the Moodle system are a forum, chat, e-mail, a communication service for education seekers, a file exchange, a testing system, a course management system, a system for organizing the submission of educational material, systems for organizing educational activities, planning (calendar), search, working with groups, help, tools for developing educational courses, etc. (Habrusiev, 2006).

These tools support server interaction, provide a user-friendly web interface, and offer capabilities for creating educational courses and related documentation, supporting both synchronous and asynchronous online learning, as well as organizing meetings and conferences. The system includes different modes for user groups with appropriate access rights, such as guest access (with or without identification), student learning, course uploading by authors, teaching and editing by instructors, and educational process management and administration. Moodle is also integrated with cloud services like Google Workspace and Microsoft 365, which expands its functionality in organizing distance and blended learning.

Such a system enables the remote delivery of various types of educational activities (lectures, seminars, practical and laboratory sessions, consultations) in both synchronous and asynchronous modes, supports the organization of students' independent work, and facilitates ongoing and final assessments. To ensure objectivity in assessment, remote identification of participants in the educational process is provided through web tools and digital video recording, with the recordings being stored in a cloud repository of results.

An important component is an electronic training course as a dynamic system that regulates the procedures for forming the content of specific disciplines, its updating and additions, adjustment and features of implementation in the educational process. It organically combines the means and tools for developing, editing, saving, transporting didactic materials, organizing educational and cognitive activities, as well as monitoring and evaluating learning outcomes. The teacher can independently design a training course based on given templates (structure, calendar, forum) and change them in the process of working on the course.

The system provides automatic generation of reports on the registration of students, the features of their use of resources, task completion and activity in discussing the results obtained, which allows teachers to manage the educational process quite effectively.

An important functional tool of the system is the testing module. It is possible to create test tasks of different types (with the choice of one correct answer, with multiple choice, logical choice (true/false), to establish correspondence, to open the task (to complete, insert the missing word, numerical answer).

The teacher can set the number of testing attempts and the method of evaluating its results (by the first or last attempts, as the arithmetic average of all attempts), view the test results both in general and in the context of a specific task, save them, analyze statistical data and detailed reports on various aspects of testing in the context of the student's individual educational trajectory (Habrusiev, Hrod, & Kulianda, 2020).

The system makes it possible to organize online classes ZOOM, Google Meet, consultations and discussions of educational problems in chat, blog and forum mode, maintain an electronic journal of control and evaluation of the learning outcomes of higher education applicants, carry out continuous monitoring of individual student performance and academic group performance, generate relevant reports and view sessions.

The functional modules of the electronic distance learning system are "Online classes", "Seminar", "Laboratory work", "Consultations (chat)", "Group assessment journal (google drive)", "Exam", "Independent work", "Modular control", "Laboratory work", "Discussion forum", "Reports", "Session review", "Grade review", "Curriculum plans", "Didactic materials", "Pedagogical practice", "Creative tasks", "Final test", "Individual learning tasks", etc.

The individual teacher profile provides access to current and archived courses, as well as the ability to create new courses and plan their use in the future, organize educational communications with students, analyze the effectiveness of the implementation of courses taking into account the wishes of applicants, etc.

For example, the author's course "Physics Teaching Methods" is presented by syllabi and work programs by semester, didactic materials on the content modules "General issues of physics teaching methodology", "Physics teaching methodology in primary school", "Physics teaching methodology in high school", which contain: short lecture notes on the main issues of the course, methodological recommendations and tasks for practical classes and independent work of students, plans-recommendations for scientific and methodological analysis of the main sections and topics of the school physics course, examples of physics lesson notes, advice to students on pedagogical practice, additional headings "Physics in crosswords", "Physics quiz", "Physics dictations", "What physics studies", individual tasks for students, tests for modular and final control, descriptions of laboratory work on the methodology and technique of school physics experiments and recommendations for their implementation, individual research tasks and tasks for independent work of students, etc.

For organizing distance and blended learning of physics, as well as other natural science subjects, the use of virtual simulators is provided, along with the possibility to perform laboratory and practical work in the university's laboratories. An important component of distance and blended learning of physics and physics methodology is the digital laboratory, which operates at The Department of Physics and Methods of Its Teaching at Volodymyr Hnatiuk National Pedagogical University. The functional elements of the laboratory include digital sensors and a data logger, which are integrated with a personal computer through specialized software.

The didactic potential of the digital laboratory is utilized in both in-person and online formats—such as lectures, practical classes, and consultations—through the use of specialized digital technologies in various disciplines within the fundamental and professional training cycles for future physics teachers, as well as in specialized elective courses. For example, within the elective course "Using Digital Laboratories in Physics Education", students acquire both general and specific competencies. General topics include the methodology and techniques for conducting school-level demonstration and laboratory experiments using digital laboratories, the use of cloud-based digital tools, and the role of digital laboratories in distance education and in organizing independent learning in physics. Specific topics cover the use of Fourier and Vernier digital laboratories (Fig. 1.), modern methods for measuring physical quantities, and the structure and principles of operation of devices such as counters, comparators, analog-to-digital and digital-to-analog converters, and measurement sensors used in digital labs. This training equips future teachers with the knowledge and practical skills necessary for the effective integration of digital laboratories into the educational process.

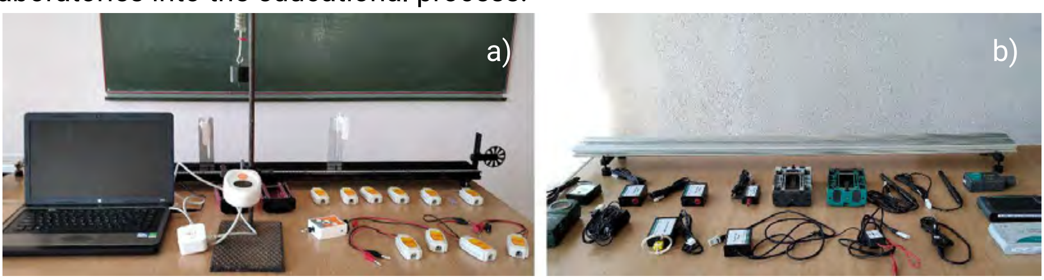

Fig. 1. a) digital laboratory «Fourier»; b) digital laboratory «Vernier».

The available equipment and software enable students to improve the methodology and technique of school physics experiments in such sections of the physics course as «Mechanics. Molecular Physics. Thermodynamics» (determining the acceleration of a body during accelerated motion, studying the law of conservation of mechanical energy, studying the oscillations of a body on a spring, checking the Boyle-Mariotte law, checking the Charles law) and «Electricity and Magnetism. Optics. Quantum Physics» (measuring the capacitance of a capacitor, determining the electromotive force and internal resistance of a current source, studying a semiconductor diode,

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determining the temperature coefficient of resistance of a metal and studying the dependence of the resistance of a semiconductor on temperature, determining the efficiency of an electric heater).

One of the trends in modern digital education is the integration of distance learning systems with cloud tools, which provides such advantages as free, unlimited in time and location access to electronic courses, continuous monitoring of the status of task completion and individual progress of each student, operational control of learning outcomes, their processing, storage and use for correction of the educational process, effective communication between its subjects, etc. (The Definition of Blended Learning, 2021).

One of the key factors in the successful implementation of distance and blended learning of physics is the didactically sound use of modern digital tools and cloud-based services that support these technologies. These tools provide educators with the ability to establish effective communication among participants in the educational process—both synchronously within the educational institution and asynchronously in remote settings. They also enable teachers to design original, author-developed methodological systems based on carefully collected, systematized, and structured educational content; to create functional subsystems for organizing learners' independent work; and to implement objective systems for monitoring and assessing learning outcomes.

While taking this course, higher education students develop practical skills that are the basis for the formation of methodological competence of a physics teacher, skills in using cloud tools to obtain and process the results of physical research, their presentation and use in the future to create didactic support for distance learning and independent work in physics.

In view of this, cloud services and specialized tools are used to organize blended learning in physics and physics methodology, which make it possible to conduct lectures, laboratory and practical classes in face-to-face and online formats. An effective means of organizing distance learning in synchronous mode are cloud video conferencing tools Google Meet and Zoom, which have been widely used by teachers since the beginning of quarantine restrictions.

Cloud services are used for storage and synchronization, which eliminates the need for users to transfer backup copies of files to different devices, and provides wide opportunities for collaborative work on documents. Therefore, they are an effective means of improving the management of the educational process and administration. For example, the “Group Assessment Journal (Google Drive)” module allows the teacher to quickly assess and record the results of students, and students to receive information about their performance in real time.

The technology of collaborative work with documents stored in the cloud is effectively used by department instructors for filling out reports and preparing informational and analytical materials, as it eliminates the need to review and compile a large number of individual documents.

To create didactic materials for theoretical and practical classes and presentations of the results of educational classes, teachers and students successfully use the Google Workspace or Microsoft Office 365 cloud tools.

Since the experimental component is a key element of the educational process in physics, one of the priority tasks in organizing distance and blended learning is the didactically justified balance between virtual and real physical experiments. (Holovko, Matsiuk, & Rudnytska, 2023).

While recognizing the undeniable importance of real (hands-on) physical experiments—and thus the appropriateness of extensively using all their forms in the educational process (demonstration, laboratory work, and specialized physics practicums)—it should be noted that under current conditions, particularly due to security concerns, virtual experiments are at times the only feasible means of providing experimental instruction in physics. Today, this virtual component is represented by virtual demonstrations, simulation software, virtual physics laboratories, and specialized tools for numerical modeling, among others.

One of the ways to maintain such a balance in the absence of access to the laboratories of an educational institution is video libraries of real physical experiments. Recordings of full-scale demonstration and laboratory experiments can be taken ready-made, but it is advisable to perform them together with students in specialized laboratories if possible. As our practice shows, this not only ensures maximum consideration of the specifics of a particular academic discipline, but also contributes to the involvement of students in active educational, cognitive and research activities. Video clips of a physical experiment can be stored and demonstrated using YouTube video hosting.

In order to better visualize the spatiotemporal features of the course of physical phenomena and processes that are studied from video recordings during distance learning, it is quite effective to use the video analysis tool Tracker. This program, for example, automatically tracks the characteristics of the mechanical motion of objects

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(speed, acceleration) and analyzes the relationships between them. At the same time, as a representative of the class of cloud services, it can process data remotely and does not require installation. To demonstrate the conditions for the course of physical phenomena and processes, libraries of digital interactive models of the PhET Interactive Simulations resource are used. Virtual physics laboratories simulate the experimental educational activities of students in the laboratory, and thanks to cloud technologies, access to them is quite simple, and their use does not require installation on the user's device. As practice shows, virtual laboratories can be effectively used during blended learning. In particular, while preparing for laboratory work, students independently study and explore virtual models of physical phenomena and processes in asynchronous mode and learn to use appropriate instruments and installations, record measurement results, etc. Working in the laboratory, they use the acquired knowledge and develop experimental skills without wasting time on familiarization with the equipment, experimental methodology and organizational aspects.

By implementing distance and blended learning of physics using cloud technologies and services, it is possible not only to significantly diversify the educational process in institutions of general secondary and higher education but also to optimize it in light of safety requirements, combining group work in the classroom with online learning. Its success depends on many factors, one of the most significant being the level of digital competence of teachers, pupils, and students. At the same time, the didactically justified use of cloud technology tools, on the one hand, requires educators and learners to possess appropriate digital skills and abilities, and on the other hand, it stimulates the development of digital competence, particularly during independent work on tasks that require its practical application (Holovko, Kryzhanovskyi, & Matsyuk, 2024b).

In the context of distance and blended learning, the problem of creating multifunctional didactic sets in physics and physics teaching methods that integrate educational and methodological materials on paper and electronic media, as well as digital educational resources, libraries of electronic visuals and video materials, virtual physics laboratories, simulators for solving physical problems, etc. Modern digital tools and cloud technology services (augmented reality tools, QR code technology) make it possible for students to organically combine work with paper and digital didactic materials.

The issue of organizing control and assessment of learning outcomes in physics is becoming increasingly relevant. The significant increase in the weight of independent work, the asynchronous mode of operation, and the physical distance between the subjects of the educational process raise concerns about the objectivity of control and assessment activities, the independence of task completion for current and final assessments, and the identification of learners. There is a need to develop a system of competency-based tasks and exercises for ongoing and final assessments, aimed at applying acquired knowledge and skills in practical situations.

Cloud tools make it possible to create such means of objective control as multi-level tests of closed and open type, with single and multiple choice, for correspondence, ordered choice, etc. They can include a variety of illustrative materials, which makes it possible to create original test tasks for the analysis of physical phenomena and processes, methodological systems for teaching physics and didactic materials.

Cloud services are a powerful auxiliary tool in the development of experimental skills in future teachers. With their help, students can join not only in contemplating a demonstration physical or methodological experiment but also take direct part in it even under the conditions of distance learning. A promising direction is the creation of interactive experimental work in simulator environments that can be performed online. In this case, the assessment will not be based on a formalized result (a report in paper and electronic format, partly based on ready-made results, or watching a video fragment), but on the application of experimental research skills. In combination with work in a physical and methodological laboratory, this will ensure the formation of experimental skills and skills in blended learning in future teachers.

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1.5. IMPLEMENTATION OF DIGITAL TOOLS FOR THE DEVELOPMENT OF STUDENTS' FOREIGN LANGUAGE COMMUNICATIVE COMPETENCE IN THE VIRTUAL LEARNING ENVIRONMENT OF A UNIVERSITY

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The need to improve the quality of vocational education is one of the primary tasks in the professional training of students enrolled in higher vocational education programs. One of the main directions that ensures the effectively implementing this task is the formation of a competent and competitive specialist's personality, one who possesses the ability to transfer knowledge to new production conditions and the skills for independently acquiring professional competencies (Stankic, Jovanović Gavrilović, & Soldic Aleksic, 2018, p. 61-64).

In the context of globalization, skills of communication in a foreign language represent an essential component of the future professional activity of specialists in the field of vocational education across various subject areas. The rapid development of international business contacts, the advancement of new technologies, and the intensification of foreign language communication in professional activities, in close cooperation with foreign specialists, greatly increase the importance of the processes involved in the formation and development of foreign language communicative competence in future vocational education specialists (Marsh, 2012).

The field of vocational education is a dynamic, complex, and multidisciplinary sphere of training for specialists with a clearly defined graduate profile (engineering educators). It is evolving within the context of the knowledge society, being directly linked to globalization processes and closely interconnected with technological progress and innovative technological solutions. All key processes within the sectoral pedagogical activity are based on effective communication and encompass both educational and techno-technological components.

Accordingly, within the field of vocational education, foreign language communicative competence becomes an integral part of professional communication. The key general professional competencies of a specialist in the field of "Vocational Education" include readiness for oral and written communication in Ukrainian and in a foreign language for the purpose of solving professional tasks. Thus, graduates of this educational field must possess a level of foreign language communicative competence defined by the "Vocational Education" standard and be able to apply it in practice, both through their native language and through the international language of communication, which is English.

Given the above, the aim of our study is to examine the impact and implementation methods of digital tools in the process of foreign language training of students within the virtual university learning environment, in order to increase the efficiency of foreign language communicative competence development.

As noted by H.D. Brown and H. Lee, communication is one of the most important tools for a vocational education specialist, as the effectiveness of their professional activity largely depends on interaction with other specialists and on the level of their communicative competence (Brown, Lee, 2015, p. 68).

Consequently, the primary objective in training students within the field of knowledge "A - Education," majoring in "A5 - Vocational Education," is not merely the development of communicative language skills in a foreign (English) language, but also the readiness and ability to interact effectively in a virtual educational environment with representatives of the international community, using the foreign language as a means of communication (Canale, Swain, 1980).

Unfortunately, it has to be acknowledged that the insufficient development of essential qualities related to business communication, and the mismatch between their level of formation and the requirements of professional activity, often result in a prolonged period of professional adaptation for future specialists in real-world production contexts. Therefore, at various stages of the educational process and professional training of future vocational education specialists, increased attention should be given to the development of students' foreign language communicative competence.

The methodological literature offers numerous definitions of foreign language communicative competence. According to domestic scholars such as O.Ye. Kravets, O.A. Kucheriuk, V.V. Osadchyi, I.M. Sviridenko, S.V. Stoiko, O.B. Tarnopolskyi, and A.O. Shchehlova, foreign language communicative competence is understood as a set of foreign language knowledge, skills, and abilities necessary for effective communication in a foreign language.

M. Byram defines foreign language professional communicative competence as a student's ability to function as a secondary linguistic personality in professionally oriented communication with specialists from other countries, as well as their readiness for intercultural professional interaction in a multicultural environment and under conditions of international mobility (Byram, 1997, p. 36).

Foreign language communicative competence comprises a number of components, including: oral and written foreign language communication; dialogue and monologue; text production and comprehension; knowledge and observance of traditions, rituals, and etiquette; intercultural communication; business correspondence and documentation; the ability to solve a range of communicative tasks; readiness for interaction in various communicative situations; and the skills to initiate, direct, control, and regulate the communication process (Lapteva, Projoga, & Pakhmutova, 2019, p. 104-106). Thus, the development of specific skills related to mastering the fundamentals of communication during university studies is a necessary condition for improving the quality of professional training for vocational education specialists. Forming communication skills in this domain becomes the basis for the successful application of graduates' abilities and creative potential.

According to H.D. Brown and H. Lee, the successful development of communicative competence in future professionals can be achieved through the implementation of the following tasks (Brown, Lee, 2015, p. 68):

- formation of a motivational and value-based attitude toward communication;
- acquisition of knowledge about the main functions and strategies of language communication and communicative activity;
- development of communicative competencies.

However, it should be noted that today a number of factors complicate the process of foreign language learning, negatively affecting the effectiveness of developing students' foreign language communicative competence. This primarily concerns the challenges of organizing effective independent language study and the "non-core" status of the discipline (British Council, 2025). In addition, other problems

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arise during foreign language instruction, such as varying initial levels of language proficiency among students, limited instructional hours, and so forth. Taken together, these factors make the task of effectively forming foreign language communicative competence through traditional approaches difficult to achieve.

We see a solution to this problem in the application of various innovative methods and educational technologies based on digital tools within the framework of the university's virtual learning environment. In this context, foreign language instruction involves productive and creative educational activity from both instructors and students at all stages of the educational process. It fosters inquiry-based learning, the development of the ability to construct and adapt one's own model of action, and promotes continuous growth.

It should be emphasized that the success of a student's foreign language training in a modern university directly depends on both internal conditions: ensuring the quality of education and future employability, and external factors, such as the public representation of educational processes and their outcomes at the regional and national levels. The university's virtual learning environment, in this regard, functions as a systemic integrator of all these components. Under the conditions of rapid technological development, open-access resources, and advanced information management, it becomes one of the key instruments for the university's activity aimed at successfully developing students' foreign language communicative competence.

Thus, under this approach, the virtual learning environment of the university becomes the main tool for developing students' foreign language communicative competence. According to generalized definitions, competence encompasses knowledge, skills, and personal characteristics, including innate abilities, emotional traits, and volitional dispositions that manifest in behavior. The current structure and content of foreign language instruction aim to develop the foreign language communicative competence defined by educational standards. However, this process often unfolds in a disorganized and spontaneous manner, heavily dependent on the personal qualities of both instructors and students. This occurs because a comprehensive system for developing foreign language communicative competence in future vocational education specialists has not yet been fully established. In our view, this is due to the insufficient utilization of available methods for intensifying foreign language training through the expanded capabilities of the virtual learning environment.

The methodological foundation for foreign language education of future professionals in the field of "Vocational Education" in the virtual space lies in an integrative approach that combines the principles of communicative, interactive, and practice-oriented learning. This approach best supports the achievement of the primary objective-effective development of foreign language communicative competence within the context of professional activity. We emphasize that we adhere to a broad understanding of the communicative approach in foreign language instruction within the virtual environment. In our view, foreign language training should include not only the acquisition of linguistic skills and abilities but also the development of general communication culture, familiarity with the basic strategies and tactics of intercultural communication, and mastery of various accommodation strategies that facilitate mutual understanding among speakers of different languages (Dyshkant, 2025).

The implementation of competence-based principles within a virtual learning environment assumes that the modern university instructor should not merely transmit ready-made knowledge but should instead manage student activity throughout the process of acquiring new knowledge. As a result, the roles of knowledge, values, and actions in foreign language instruction within the virtual environment undergo significant transformation. In traditional instruction, the pedagogical distribution is typically as follows: lecture – knowledge; seminar – values; laboratory/practical session – actions. In contrast, in the virtual learning environment, the distribution changes like so: knowledge – virtual learning environment; other forms and independent student work – values and actions.

The virtual learning environment, which provides 24/7 access to information and enables monitoring and analysis of resource usage, offers a much more productive and convenient means of storing and managing large volumes of up-to-date learning content. Based on this, the process of foreign language training for future vocational education specialists becomes qualitatively different. All static educational content and interim assessments are transferred entirely into the virtual learning environment and are used by students independently, following their individual learning schedules (Diaz Redondo et al, 2020, p. 3124). All instructional messages serve as a propaedeutic stage for the topics studied in the classroom, where value- and action-oriented approaches are then activated through in-person interaction. At the same time, when the educational process is supported by virtual tools, instructors are granted greater opportunities for pedagogical creativity, which, in turn, fosters their own professional growth.

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Thus, the virtual learning environment for foreign language training is currently capable of supporting every form of instructor activity by providing access to electronic learning courses, point-based rating systems, electronic libraries, primary sources, scientific databases, project-based resources, virtual laboratories, automated workspaces for academic advisors, and interactive formats for engaging with students. Therefore, the adaptation, implementation, and use of digital technologies in the teaching of foreign languages within the field of "Vocational Education" is extremely necessary.

Blended learning (b-learning) is a methodology that combines both face-to-face instruction and virtual learning, allowing for the integration of the strengths of each while narrowing the gap between traditional and digital approaches to education. This format enables instructors to act as mentors in the virtual environment while still maintaining face-to-face interaction and personal communication (Melhem, 2020, p. 518). In this way, it addresses the needs of students whose learning styles are social, as well as those who prefer auditory, visual, kinesthetic, or metacognitive modalities. Consequently, foreign language training within a virtual learning environment implies the use of blended learning technologies, as they enable the educational process to be organized in a way that emphasizes the advantages of different methods, tools, and formats, while partially compensating for their shortcomings.

It is important to note that when discussing blended language learning, i.e., the integration of face-to-face and online instruction within a virtual learning environment, four widely recognized models are usually mentioned: the "flipped classroom", "station rotation", "lab rotation", and "individual rotation" (Karabulut, Jaramillo Cherrez, & Jahren, 2017, p. 398-401).

Each of these models has its own unique characteristics, but the key feature they all share is the mandatory use of digital learning tools and online resources in both online and offline modes. Within the university's virtual environment, the combination of traditional face-to-face methods for teaching foreign languages with e-learning and distance technologies, based on the principle of complementarity, allows for maximum utilization of the benefits of each approach while significantly minimizing their limitations (Hodges, Moore, Lockee, Trust, & Bond, 2020). Thus, while preserving the advantages of face-to-face instruction,such as direct personal communication between students and instructors, as well as among students themselves, and the clear structure of the learning process, we enhance them with the benefits of virtual learning, including individualization, flexibility, interactivity, automated assessment,

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and structured organization of students' independent work (including extracurricular learning).

It should be noted that many domestic universities have already developed, to varying degrees, virtual learning environments that lay the foundation for implementing blended learning. According to American researchers, in a blended learning model, between 30% and 79% of the educational content should be delivered using online technologies. If less than 30% is delivered online, such a case can be classified merely as web-supported traditional learning. This is the stage where many domestic universities currently stand (Bredow, Roehling, Knorp, & Sweet, 2021).

At the same time, we highlight the following arguments indicating the need to implement blended learning technology in foreign language training:

- it allows students to work through complex material at a slower pace and increases the time allocated to active, student-centered learning methods;
- it enhances motivation, as the support provided to students encourages them to take responsibility for their own learning;
- it fosters an active attitude toward the development of the components of foreign language communicative competence as outlined by the relevant educational standards;
- it promotes the development of autonomous foreign language learning skills, which are particularly important for the effectiveness of communicative competence formation at later stages;
- it supports individualized learning paces, taking into account students' preferred cognitive styles and learning needs;
- it facilitates "deep" rather than "surface" learning, aimed at critically evaluating the degree of material comprehension, influencing independent mastery of an individually chosen foreign language learning path, group-based self-directed learning, and the development of cross-disciplinary competences (Karabulut, Jaramillo Cherrez, & Jahren, 2017, p. 402).

The use of modern educational technologies incorporating digital resources makes it possible to emphasize the dominant cognitive style of each student, stimulate their interest in the material being studied, develop their communicative abilities, and thereby improve the quality of foreign language training of future professionals.

It should be noted that the implementation of digital tools is significantly influenced by the alignment of the approaches, methods, and strategies used by instructors in foreign language training with the capabilities of the relevant technologies, tools, and resources. The effectiveness of forming students' foreign language communicative competence within the university's virtual learning environment largely depends on the pedagogically sound, coherent, and purposeful use of these tools.

When implementing digital tools, we emphasize that the development of a modern virtual educational environment with extensive use of digital technologies creates new opportunities for both instructors and students. Learners studying foreign languages for professional purposes have specific needs that can be addressed through the possibilities provided by various digital technologies. Unlimited access to a variety of digital tools and sources allows instructors to diversify their teaching methodologies, develop engaging instructional materials using various digital instruments, and more (Xenofontos, Hovardas, Zacharia, & Jong, 2019, p. 27).

The most up-to-date methods and formats used in foreign language instruction and the integration of language material within the university's virtual educational environment include:

- the global e-learning system (which encompasses electronic educational platforms, modules, and distance learning courses);
- the use of social media platforms;
- the use of cross-platform instant messaging applications;
- the use of video conferencing, teleconferencing, and live or recorded video broadcasts;
- the use of cloud storage systems and software clients;
- podcasts, educational channels, and video hosting platforms;
- mobile apps: development of unique cross-platform learning applications, and integration of pre-existing courses hosted on educational portals into mobile environments;
- using simulators;
- training in virtual reality environments using digital tools such as wireless smartphone headsets, VR glasses, and other devices that create immersive environments and support AR (augmented reality);
- artificial intelligence technologies.

For the creation of digital learning texts with embedded tasks, platforms such as LearningApps, Google Forms, and Google Docs can be employed. This is due to the fact that a significant portion of the learning materials to be implemented in the virtual educational environment combine various coding formats: traditional linear text with hypertext, multimedia elements, and links to other types of content. This approach allows users to select non-linear reading paths, navigate between texts and materials presenting diverse types of information, and engage with content at their own pace.

Digital learning texts designed using these tools make it possible to create numerous hints that account for students' different levels of prior knowledge. For example, if a student does not understand a word in the text, they simply need to click on it to receive an instant translation. Thus, such electronic texts facilitate a personalized learning experience based on the individual's proficiency level (Walder, & Anne Mai, 2014, p. 197). Students prefer working with such materials, as they are drawn to the multidimensional nature of digital learning texts.

Hyperlinks embedded within the electronic texts include a variety of tasks focused on grammar, vocabulary, listening comprehension, and the development of dialogic and monologic speech, among others. Upon completing an exercise, the student immediately receives feedback. This is especially convenient and efficient given the limited instructional time allocated for foreign language learning. Such digital learning texts are characterized by hypertextuality, multimedia integration, and interactivity (Warschauer, & Healey, 1998).

Hypertextuality currently connects informational units within electronic texts in a networked format through links, organizing them in a non-linear or multi-linear structure. Therefore, hypertextuality should be understood as semantic multidirectionality and multi-discursivity, which simplifies information retrieval and broadens the scope of the text.

Multimediality of the text involves supplementing the text with other types of information: photographs, images, infographics, audio and video materials. In essence, multimodality makes it possible to replace part of the text with visual elements, which helps to capture and retain the attention of today's students with shorter attention span, and significantly assists with the perception of the material (De Jong, Lazonder, Pedaste, & Zacharia, 2018, p. 259). In addition, the visualization of textual information greatly simplifies the understanding of a foreign language digital text, making it more attractive and engaging.

Interactivity is also characteristic of printed texts, but in the digital environment it is implemented more broadly, as it allows for a digital dialogue between teacher and student. Thus, the interpersonal aspect of interactivity in the electronic text is manifested in the evaluation system that uses the semiotics of emoji (the language of ideograms and emoticons), through which students can evaluate the digital text and leave emotionally expressive judgments (Bradbury, Tahini, & Dadykin, 2018, p. 769). The possibility to express evaluative opinions and leave comments on the digital educational text allows students to bring an informal aspect to the process of learning a foreign language, which, according to many students, is a positive feature, as they are already accustomed to commenting on various situations in the Internet space.

Therefore, our experience in the use of digital educational texts allows us to state that placing such materials in the virtual educational environment significantly increases the educational potential of foreign language classes. It is multilayered, universal, and contains many exercises that are offered according to the student's level of knowledge, since each student works through the digital educational text in full. Moreover, the teacher immediately receives a general and objective picture of the students' work with the text and sees the percentage of successfully completed exercises. Based on the practical application of digital texts in English language classes, it can be noted that due to the visualization of textual material and the availability of prompts aimed at understanding the main approaches to text processing, the process itself causes fewer difficulties for students while enabling them to absorb a larger volume of educational content.

The use of modern digital resources in English language instruction is of great importance, as it enables the implementation of a learner-centered, communicative-cognitive, and sociocultural activity-based approach to foreign language teaching. These tools are among the most widely used means that directly facilitate the process of improving foreign language training. They enrich the methodological toolkit and techniques employed by English language instructors and contribute to more diverse forms of educational activities, making classes more engaging for students.

Particular attention is currently being given to the development of electronic educational resources, which are increasingly used by the English language instructors alongside traditional teaching methods and allow the learning process to be elevated to a new level. With the help of such tools, instructors can perform the following tasks in English language classes: present new learning material, review and reinforce previously learned lexical items and grammatical structures, conduct both formative and summative assessments of knowledge acquisition, and create game-based learning scenarios that closely simulate real-life conditions.

Electronic educational resources for foreign language learning, particularly English, can be categorized into the following groups based on their content and functional purpose: informational and reference materials; internet-based resources;

integrated digital learning tools such as educational software and electronic textbooks; and instructional software designed to support foreign language classes, including demonstration materials, project-based content, computer-generated lesson plans, presentations, and other resource categories (Azevedo, & Gašević, 2019, p. 208).

These types of electronic educational resources offer a wide range of options for different groups of potential users. When Internet resources are used in English language classes, students learn to work with texts in an exploratory format, handle digital and graphical information, analyze it, and create their own ideas, projects, and messages based on it. Thus, the integration of Internet-based informational resources into the educational process allows instructors to address the following didactic tasks during classes:

- formation of students' skills and abilities to confidently use a foreign language for solving communicative language tasks in various professional communication contexts;
- development of students' ability to exchange business information in a foreign language, both orally and in written form;
- independent search for, accumulation, and expansion of professionally relevant knowledge through natural communication with native speakers of the foreign language;
- formation of reading skills by directly using online materials of varying complexity levels;
- improvement of listening comprehension skills based on authentic online audio texts;
- enhancement of monologic and dialogic speaking skills through problem-based discussions of materials presented by the teacher or fellow students online;
- advancement of correspondence skills, including the ability to independently compose written responses to partners, participate in the preparation of essays and other epistolary products of collaborative activity;
- expansion of students' vocabulary, both active and passive, with modern foreign language lexicon reflecting a specific stage in the cultural and socio-political development of society;
- acquaintance with cultural studies knowledge, including language etiquette, features of communicative behavior among different nations, cultural peculiarities, and traditions of the studied language;

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- formation of a stable motivation for foreign language activity in class based on the systematic use of “live” materials, discussing not only textbook questions but also current and engaging issues of interest to all students.
- It should be noted that effective learning of a modern foreign language in a university’s virtual educational environment is possible with the usage when materials derived from the real-life experiences of native speakers. The use of such authentic and pedagogically adapted materials enables the intensification of all types of language activities, simulates immersion into a natural linguistic environment during foreign language classes, and contributes to increased motivation for foreign language learning (Battro, 2004).
- In this regard, a pressing issue remains the variety of materials selected for foreign language classes, as these constitute an important element in the design of the content of electronic educational resources (EERs) used in virtual learning environments. Such resources, for instance, facilitate work with materials from open university courses in a way similar to home reading or working with a digital instructional text. In these cases, students may discuss both linguistic and content-related aspects of the course during classes, including lectures, noteworthy ideas from participants and moderators, useful vocabulary, and terminology (Dyshkant, 2025).

The results of our rapid survey among future professionals in the field of vocational education across various subject specialties indicate that most students identify the following advantages of enhancing their language proficiency in a university’s virtual educational environment: clarity of presented materials (57.2%), a flexible schedule for working with applications (79.3%), and the possibility for systematic repetition and memorization of language material relevant to their interests (59.7%). Among the advantages of using open university resources, students highlight the broad professional scope of the content, its authenticity, the availability of integrated audio and video materials, glossaries, discussion forums where they complete assignments alongside students from around the world, and online access to course materials that allows each individual to independently choose the time, volume, and pace of task completion. They also emphasize the availability of mobile applications for gadgets. Furthermore, students note that working with digital foreign language resources from open universities fosters increased interest in professional self-development through their direct engagement in research activities that involve communication in a foreign language.

Thus, the use of materials from open university courses partially addresses the issue of selecting authentic and professionally oriented content for foreign language instruction aimed at future specialists in the field of vocational education across various subject areas. Working with subject-specific electronic educational resources (EERs) in a foreign language is also positively perceived by the student audience (68.4%), which in turn increases motivation for further use of such resources in professional activities. Despite certain limitations in the use of open university courses, the application of their materials remains a highly promising approach.

As tools for developing the foreign language communicative competence of students in the field of vocational education within a virtual learning environment, we made extensive use of over 50 English-language online resources. These were used to teach both oral and written language skills (reading, writing, speaking, and listening), as well as grammar, in accordance with the aforementioned didactic objectives. Among them were the British Broadcasting Corporation's language learning website (www.bbc.co.uk/learningenglish), which offers free English learning resources; the ESL Writing and Reading website (https://learnenglishteens.britishcouncil.org/skills), which provides materials for developing writing and reading skills; and Best Websites for Independent Reading (https://www.commonsense.org/education/lists/best-websites-for-independent-reading), which includes online books and exercises for improving reading and writing skills, categorized by language proficiency level, along with other widely used language learning platforms.

Our practical experience shows that the aforementioned foreign-language resources for learning English significantly contribute to the development of various language skills and can be effectively used both during classroom instruction and in independent learning. Their multifaceted features allow for consideration of students' language proficiency levels, interests, age, and psychological characteristics, which attests to the high quality of these resources. They enable both students and English language instructors to achieve the objectives of specific lessons as well as the overall goal of language instruction, namely, the development of foreign language communicative competence.

It should be noted that foreign-language Internet resources offer students and instructors not only virtually unlimited opportunities for intercultural and international communication in a foreign language, but also excellent prospects for self-education and personal development, as well as for organically enhancing their overall level of language competence. Undoubtedly, online resources serve as a powerful tool for

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increasing the effectiveness of the entire foreign language learning process, enabling educators to make their work more efficient and to achieve the set educational goals within the virtual learning environment of foreign language training for future professionals in the field of vocational education.

Undoubtedly, improving the quality of foreign language instruction does not lie in the mere use of Internet resources, digital technologies, and social media platforms, as the novelty of such technologies often leads to their inappropriate application. For instance, transferring traditional teaching materials online without adapting them to the new environment merely changes the learning setting without taking advantage of the technology's potential. Therefore, effective use of new technologies requires additional effort, increased preparation time, and deliberate planning of communicative processes through the use of diverse tools and channels.

The use of authentic texts from the Internet or specialized texts tailored to the students' field of study, along with supplementary materials such as parallel texts, reference information, bibliographies, specialized websites, and glossaries, has become standard practice for working with language material in the virtual university learning environment. This approach reflects our understanding of digital tools not only as means of delivering content, but also as instruments of procedural learning. Among these tools, we include quizzes, chats, wikis, forums, glossaries, seminars, and working groups.

It is commonly assumed that quizzes with closed or open-ended responses are used solely to assess knowledge acquisition. However, we believe that they can also serve as effective tools for enhancing language skills within the university's virtual learning environment. For example, when choosing among suggested options, students may be required to review fragments of incorrect translations and compare them with the original text. These fragments can be continuous text segments but are presented within a translation memory interface. In this context, errors must be clearly identified by the student as either linguistic and/or cultural. The complexity of the exercise can be increased by drawing attention to stylistic or grammatical aspects.

Since students are given the opportunity to make multiple attempts, this type of exercise is well-suited for independent practice within a virtual learning environment, where automatic comparison of incorrect student responses with correct ones is available. A variation of this exercise involves offering several alternative translations, from which the student must select the one they consider the most appropriate. In this case, the primary focus is on developing the skill of critically

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evaluating corrections during the revision of specialized texts. These activities can also be implemented with time constraints by configuring appropriate parameters. Such an approach contributes to the development of stress management skills in time-limited conditions during the learning process.

It should also be noted that in a virtual learning environment, students construct their worldview through a foreign language by selecting appropriate subject-related educational topics. This process fosters the development of a critical approach to information retrieval. The need to identify a problem in a foreign-language text, to select and justify an appropriate argument, to evaluate, and to promptly respond to the opinions of others - all these activities create an atmosphere of moral engagement, promote foreign language competence, and support the development of students' academic and professional mobility.

Chat is a synchronous tool that enables communication between people located in different places. It is usually used as a virtual forum, but since chat allows the preservation of participants' conversations, we use it as a foreign language learning tool in the following way. Groups of no more than five students translate a short text, with each participant communicating with the rest of the group via the chat utility to explain their choice or suggest exploring the text in terms of terminology. Thus, students are compelled to carefully reflect on and become aware of the different stages of the translation process. Moreover, instructors can monitor the translation process, assuming that its outcome may be somewhat distorted at certain points because students lack the spontaneity typical of the usual translation process. The instructor can also participate in the chat to provide feedback or introduce new ideas (Lapteva, Projoga, & Pakhmutova, 2019, p. 107).

Wikis represent collaborative workspaces (webpages) where students write and edit the same text. A key feature of using this tool in foreign language training is that previous versions of the wiki are saved and can be restored if desired. Within the virtual educational environment, we have successfully used wikis in conjunction with chat during educational projects, where student groups discuss solutions for specialized translation, solve problems through chat communication, and then record subsequent versions on the wiki. This allows the instructor to track the translation processes of each group, which is crucial for addressing issues related to specialized translation. Wikis and chats function as supplementary digital tools. Through them, students learn about the specifics of the specialized translation process in general and their own implementation of this process in particular. It should be noted

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that later on, they can read not only their own wikis and chat debates in which they participated but also those of other project participants.

Another way we have implemented wikis in classes is through electronic portfolios (Mgarbi, Chkouri, & Tahiri, 2022, p. 37). As an assessment tool for instructors and a self-assessment tool for students, it is increasingly used by us in the teaching/learning process. This digital resource provides examples of personal professional development as a gradual achievement of one or several learning goals, serving as an assessment instrument in the form of biographical data, academic achievements, and many other components of foreign language training. For this purpose, students attach documents of various formats (text, audio, graphic, and video files, etc.) from their current work. Thus, they select what they want to assess and consider the best example of their academic work. Examples of such wiki implementation included the best of students' works and research projects.

The advantage of using portfolios in the process of developing students' foreign language communicative competence within the university's virtual educational environment lies in the fact that students personally observe their progress and critically assess their ability to perform professional tasks, thereby becoming more self-confident and motivated for further foreign language development. At the same time, students develop skills in using a tool that they can employ to reflect their learning progress throughout their lives and professional careers.

Forums are also successfully used by us as instructional tools in foreign language training, where instructors take on the roles of moderators and motivators to facilitate interaction and organize debates. Essentially, a forum is a tool connected to social interactions and relationships (Camilleri, & Camilleri, 2017, p. 67). For this reason, we use it as an element of collaborative learning, where foreign language training on the forum can develop in various ways. Typically, the instructor provides a source text that highlights certain problems or contains an imperfect translation that needs correction. Alternatively, students review and correct each other's work. Unlike chats, forums give students significantly more time to work through the text proposed for translation, allowing for deeper reflection and a more substantial personal contribution to solving the assigned tasks.

The purpose of a tool such as a glossary is to create a list of equivalences and/or definitions functioning as a dictionary within the virtual educational environment. The instructor can configure settings so that certain terms are marked with hyperlinks leading to glossary entries, even if the term does not appear in the texts used within the virtual campus. Requirements for glossary entries depend on the instructor's decisions. They may include sources such as dictionaries, corpora, and websites, as well as grammar and other linguistic information, visual illustrations, and more. The glossary facilitates the development of deep competence that determines the quality of professional translation, as it standardizes terminology and ensures its consistency.

The implementation of the aforementioned approaches to using this group of digital tools stimulates the development of complex, nonlinear linguistic thinking in future specialists within the field of vocational education, eliminates language barriers in professional activities, fosters multitasking abilities, and enables students to independently create a linguistic environment that corresponds to their professional level. This, in turn, ensures effective formation of foreign language communicative competence and increases comfort in foreign language communication.

A seminar conducted in a virtual educational environment facilitates foreign language training by enabling the completion of a wide range of diverse group tasks. This teamwork may simulate an authentic project-based translation process, in which seminar participants perform various roles such as preliminary thematic and terminological research of texts, verification of content accuracy, terminology, and so forth.

This approach is implemented as follows. Reading or listening texts on professional topics of interest to students that relevant to their English proficiency level, are selected from online resources. These texts are provided to students for preliminary familiarization, and during the practical session, they are offered the following types of activities aimed at developing and applying integrated skills in foreign language communicative competence.

At the first stage, the topic of the article is discussed with the students in general terms. For example, for an article titled "Seven Advances in Technology That We're Likely to See in 2025" by Lewis Endlar (https://theconversation.com/seven-advances-in-technology-that-were-likely-to-see-in-2025-245203), this task might take the following form:

- "Discuss the following questions: "
- "What technological advancements were you dreaming about as a child? How has technology changed your daily routine over the past five years?"

At the next stage, students are offered a set of exercises designed to acquire and consolidate new vocabulary. These may include tasks under the heading "Expand

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Your Vocabulary”: Write down new words with their definitions and create your own sentences using these words.

- “Match the words and phrases from one column with their Ukrainian equivalents in the other.”
- “Do the crossword puzzle.”

Students are assigned profession-oriented translation tasks involving individual phrases, idioms (with the selection of appropriate Ukrainian equivalents), as well as entire sentences.

- “Translate the highlighted phrases/sentences into Ukrainian.”

Subsequently, the most appropriate translation among those proposed by the students is selected. After completing the vocabulary tasks, the direct discussion of the article begins in the form of answering questions. If time permits, it is advisable to hear the opinions of all students involved in the discussion, not only the active members of the group.

- “Which of the seven technological advances mentioned do you think will have the biggest impact on society? Why? “
- “Would you feel comfortable being treated by a doctor who uses AI agents to help with diagnosis? Explain your reasoning. “
- “How could personalized AI education (mentioned in point 2) change the way we learn languages?”

As a task on forming one more skill – writing(within the framework of integrated skills), one of the following can be offered:

- “Write an essay on one of the following topics…”
- “Write your own prognosis on the upcoming technological advancements … Use as many words/ phrases given below as you can.”

At the end of the session, if the learned content allows for it, students may be given a test with subsequent scoring and commentary, for example:

- “How stressed are you?“
- “Do you have a healthy lifestyle?“
- “Do you love your body?“
- “Are you a spender or a saver?”

Such tasks consistently spark lively interest among students and help relieve tension and relax after the intense intellectual workload of the lesson. Since several types of language activity, like reading, listening, speaking, and writing, are simultaneously engaged during such classes, students develop the ability to perceive and process information from various sources. This leads to a deeper assimilation of authentic educational materials, increases cognitive interest and creative activity, and ultimately ensures the effective formation and development of foreign language communicative competence.

Communicatively meaningful tasks and projects in foreign language training help to shape a creative personality and stimulate exploratory activity. The motivational element is a key advantage of learning a language through projects and communicative tasks that reflect real life in the classroom, i.e., incorporate elements of real-life communicative situations. Unlike the conventional study of vocabulary and grammar rules, this contributes to the development of higher-order thinking skills, which is also one of the components of human mobility in a knowledge-based society.

The implementation of task-based learning, which involves learning a foreign language through communicatively significant tasks, and project-based learning,which focuses on project-based instruction, has a considerable impact on the following components of students' foreign language communicative competence: the ability to independently apply foreign language knowledge in practical activities; confident navigation of the foreign-language digital environment; the ability to develop lifelong learning skills and critical and creative thinking in the context of language activity; and the capacity to identify, formulate, and solve problems based on existing foreign language knowledge and skills (Stanley, 2013).

It should be noted that the educational field of "Vocational Education" is still undergoing a stage of institutional development and the formation of intersectoral connections. However, the large volume of accumulated educational and methodological material, as well as digital technologies, already make it possible to build an effective system of foreign language training in the virtual educational environment of the university and to train sectoral professionals with a high level of competitiveness in the educational market. However, for the effective formation of students' foreign language communicative competence, it is necessary to implement new formats for delivering educational content through a pedagogically balanced integration of digital tools into the process of foreign language training, ensuring continuous self-education and the professional development of teachers of professional disciplines in the field of foreign languages, and of foreign language teachers – in the field of digital technologies (Coyle, Hood, & Marsh, 2014).

The implementation of these requirements for increasing motivation to study foreign languages and for the effective formation of foreign language communica-

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tive competence is possible in the context of forming professional competences through the use of Content and Language Integrated Learning (CLIL) technology (Mehisto, Marsh, & Frigols, 2008). The dual objective applied by this method ensures the comprehensive and simultaneous development of professional skills and the successful and dynamic formation of foreign language communicative competence through the use of both the native and the foreign language (Coyle, 2007 p. 546). The term CLIL was first introduced by David Marsh in 1994.

In the process of foreign language learning based on the CLIL methodology, the teacher acts as an effective leader and role model for students. This addresses the issue of motivation and enables a comprehensive construction of synergy (interdisciplinarity) between subject-specific and language disciplines. This, in turn, ensures the development of components of both professional and foreign language competences that correspond to the types (specializations) of professional activity (digital technologies, tourism, food technologies, and other vocational education fields).

An example of the application of content and language integrated learning (CLIL) in a virtual educational environment for students of vocational education in the subject specialty "Digital Technologies" is the simultaneous use, in the course "Modernization and Repair of Computer Equipment," of authentic texts in foreign language instruction. These texts are based on the works of a well-known expert in the field, Scott M. Mueller, particularly his book Upgrading and Repairing PCs. It is worth noting that the results of implementing the CLIL methodology (provided the teacher is adequately prepared both professionally and linguistically) demonstrate a consistently high level of student motivation and indicate significant progress in the development of foreign language communicative competence.

Another example can be students specializing in "Tourism" within the field of vocational education. These students tend to acquire language skills more readily and effectively after practical exposure to international activities (e.g., internships, temporary employment, work at international exhibition booths, participation in international conferences and seminars). Even the successful completion of elementary tasks vividly illustrates the role and importance of intercultural communication in professional activity. Such practices provide a tangible understanding of real conditions for the application of foreign language communicative competence in professional contexts, which, in turn, influences student motivation in relation to professional competitiveness and self-actualization.

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Many researchers emphasize the urgent need for qualitative modernization and renewal of current teaching methodologies. In this regard, the use of mobile applications is considered one of the effective and accessible ways to enhance motivation among both educators and students. Numerous studies highlight the significant potential of mobile technologies, which can make the process of foreign language training more engaging for the younger generation, as most modern students are both technically and psychologically prepared to use mobile technologies in the learning process. This justifies considering this segment of digital tools as offering new opportunities for the more effective application of their potential in foreign language learning (Keegan, 2002; Kuznekoff, & Titsworth, 2013; Lin, Liu, Fan, Tuunainen, & Deng, 2021).

In our opinion, the practical use of mobile applications indeed carries great potential; however, the integration of working with applications into the structure of a practical lesson presents certain challenges and may be used rather limitedly. At the same time, the implementation of interactive technologies in the learning process for the purpose of organizing and intensifying students' independent work (primarily extracurricular) appears to be a very promising direction.

Mobile applications can be used quite effectively for the development of listening skills, since modern mobile devices offer extensive technical capabilities for watching videos, listening to audio fragments, recording speech segments and videos. Developers offer applications for those who wish to improve their pronunciation skills, sound recognition by ear, and the correlation of the sound and visual image of a word. Among the most successful products are Sounds Right (British Council), as well as the application Sounds: Pronunciation App (Macmillan Education). These applications include interactive phonetic charts for British and American varieties of English, exercises, games, and tests. From the perspective of developing the skills of perceiving and understanding spoken language, applications from the BBC are extremely valuable. Using them, students can access authentic audio, video, and textual materials, for example, Learning English for BBC, 6 Minute British English. These applications can be fully used for the formation and development of foreign language communicative competence, as they include specialized sections dedicated to vocabulary learning, grammar, the development of communicative skills, and speaking abilities (Kuznekoff, & Titsworth, 2013).

Virtual reality tools are also used to enhance the effectiveness of foreign language learning by creating an immersive environment that enables full engagement in foreign language communication processes. One of the promising directions for intensifying the process of forming students' foreign language competence is the use of Augmented Reality (AR) and Virtual Reality (VR) technologies. Analyzing the works of scholars such as S. Feine, H. Kauffmann, B. Peixoto, D. Pinto, A. Krassmann, M. Melo, M. Bessa, N. Guyndomush, and G. Orhan, who substantiate the prospects of their application in foreign language training, it should be noted that augmented reality is defined as a new interactive technology that makes it possible to overlay computer graphics or textual information onto real-time objects (Keegan, 2002). In the process of learning a foreign language, VR and AR technologies allow the formation of a special information space within the virtual educational environment, where students can access information, interact, and implement innovative projects and other elements of scientific and educational activity through foreign language communication.

Today, there are many technical applications with elements of augmented and virtual reality in foreign languages that, although not initially designed for learning professional foreign language vocabulary, can assist in its acquisition (Kultusministerkonferenz, 2017). In this regard, 3D visualization of professional subject content using AR and VR technologies enables instructors to engage students and attract their attention, present educational material in a visual manner, and allows students to learn foreign-language professional terms and expressions for professional communication more easily and efficiently. The multiplicity and diversity of existing applications today may facilitate the acquisition of foreign-language terminology across a wide range of subject specialties within the field of "Vocational Education." However, these applications have limited content, which is not always directly aligned with foreign language curricula, and thus can only be used as supplementary material for mastering professional vocabulary.

It should be noted that the application of augmented reality (AR) and virtual reality (VR) technologies in the educational sphere demonstrates high effectiveness when implemented in higher education institutions. This is due to the fact that these technologies are aimed at creating applied visual stimulation for the perceptual understanding of educational material, activating students' cognitive activity by expanding the potential for interactive interaction between humans and mobile devices. Accordingly, it can be concluded that these technologies have significant potential for foreign language learning through the recreation of selected situations simulated within the university environment. Such situations include not only interaction with native speakers or familiarization with the culture and history of another country, but also the study of professional foreign language terminology using 3D models. Moreover, AR and VR technologies can help bridge the gap between professional theoretical knowledge and practical skills in mastering foreign language terminology.

The use of foreign language learning tools based on artificial intelligence (AI) technologies requires a corresponding level of methodological and digital competencies on the part of the instructor, since they must ensure the formation of students' initial practical skills for the successful educational use of components of the intelligent foreign language learning environment (Ali, Asadi, Gašević, Jovanović, & Marek, 2013).

For this purpose, the instructor needs to understand the fundamental principles of the algorithms used in foreign language teaching: response classification, semantic analysis, natural language processing and generation (NLP), morphosemantic speech analysis, reinforcement learning; features of the architecture of pretrained language models (Bidirectional Encoder Representations from Transformers, or BERT), generative pretrained transformers (GPT), Text2Image models; the structure and components of intelligent learning systems (ILS); the principles of operation of dialog-based learning environments (adaptive tutors) (digital teacher twins, Mondly, AutoTutor, Watson Tutor); foundations of pedagogical course modeling using machine learning methods; how to avoid communicative breakdowns during dialogue with AI, the proficiency levels at which the use of chatbots in language learning is appropriate, and other related aspects (Malik, 2017).

Additionally, it is necessary to be able to evaluate the didactic potential of AI technologies; analyze students' digital footprints; create term taxonomies linked to learning outcomes; analyze learning analytics; design tasks for developing oral and written language skills using generative chatbots; compile hierarchical term lists to describe curricula based on taxonomy; formulate didactic prompts for AI to generate problem-oriented tasks, among other competencies.

The implementation of AI tools in the virtual educational environment addresses the typical problem of independent student learning, which is the lack of feedback. However, when a student independently masters any component of a foreign language, it is important not only to memorize rules but also to correctly apply them in practice (Murphy Odo, 2025, p. 9). To develop this skill, the student composes sentences, dialogues, and texts. During university studies, the instructor checks homework assignments. If the student studies independently, the role of the evaluator is performed by a neural network. For example, one can write a text in English and send it to Claude or DeepL asking to find deficiencies. The neural network will point out mistakes and explain how to correct them.

Moreover, AI technologies can be purposefully used by students to improve monologic and dialogic speech skills. In particular, ChatGPT can check not only grammatical and lexical correctness but also the conformity of the written text to a given genre (e.g., essay, annotation, summary, etc.), provide recommendations for improving the text, and suggest possible options for additions or reductions of the electronic text if necessary (Mouta, Sánchez, & Llorente, 2019, p. 995). Being interactive, the chatbot can assist students in practicing dialogues by asking questions on specific topics and conducting a full dialogue or responding to questions posed by the learner, offering realistic dialogue scenarios for language communication. Such tasks allow students to practice before exams, prepare for interviews, and develop compensatory skills. Through virtual simulators of foreign language communication, students have the opportunity to practice oral speech in various situations by interacting with virtual characters, which helps improve foreign language communication skills and increase self-confidence.

The approaches discussed above regarding the implementation of digital tools for the development of students' foreign language communicative competence within the virtual educational environment allow us to draw a number of conclusions.

The practice of using electronic practice-oriented foreign language courses demonstrates that the application of innovative educational technologies and digital tools for developing students' foreign language communicative competence within the virtual learning environment significantly increases student interest, promotes concentration, and facilitates more effective assimilation of the learning material. Moreover, instructors gain the opportunity to bring the learning process as close as possible to real conditions of foreign language communication, including professional communication, through the use of digital tools, resources, and virtual platforms. This enables overcoming temporal and spatial barriers, developing new methods and tools for teaching while maintaining a personalized approach.

However, the effective use of these technologies will only be possible if they are preliminarily mastered not only by instructors but also by students before they can be applied correctly and beneficially for all participants in the foreign language learning process. The increasing importance of digital communications and tools, as well as teamwork and social skills, should lead to a reconsideration of existing teaching models, integrating digital tools and collaborative learning not only as means but also as goals in the education of students within the field of "Vocational Education."

The shift in traditional roles of participants in foreign language training is a complex process because it requires a change in mindset, with students becoming aware of their responsibility for acquiring necessary knowledge, which is provided to them in a convenient and compact form within the virtual educational environment, where they must construct their own effective learning process. Instructors must also recognize their new role in transitioning from information facilitators to mentors. These changes are not always easy and require time and patience for adaptation. To these challenges should be added the fact that many students are unwilling or unprepared to work in teams. This is related to differing preferences in learning strategies, lack of interpersonal relationship competencies, as well as reluctance to share their successes with other group members or to suffer the consequences of others' failures.

The purposeful use of various resources and digital tools in the foreign language training of students in the field of "Vocational Education" provides opportunities to apply additional means for creating models of authentic communication during class or beyond the classroom. Thus, natural conditions are created for practicing and further developing different types of language activities (speaking, reading, writing, and listening), as well as for the development of communicative-cognitive skills to search for, select, classify, analyze, and summarize relevant information in a foreign language.

Practice shows that mobile learning technologies have a significant advantage over traditional foreign language teaching methods due to the intensification of independent learning activities, individualization of instruction, and the enhancement of cognitive activity and learning motivation. At the same time, the use of mobile technologies in the foreign language learning process contributes not only to enriching the learning experience but also to the acquisition of skills and abilities, the formation and development of which based on traditional teaching methods is rather labor-intensive.

The experience of applying AR and VR technologies in foreign language training at higher education institutions in various countries has shown that the introduction of augmented and virtual reality educational platforms into the language learning process represents a real advancement in the methods and tools of foreign language education. This is because AR technology is one of the most effective means of exploring the surrounding physical environment and space. A significant shift towards expanding the use of tools for implementing the visual culture of training specialists

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in the field of vocational education should lead to foreign language training incorporating more visual resources. Promising applications include the use of appropriate educational games, videoconferences, streaming video, and simulations, which could effectively recreate professional situations in the foreign language preparation of students in the "Vocational Education" field.

It should be noted that the use of AI in foreign language learning is a powerful tool that is particularly attractive to students, yet it requires a special approach from the teacher. For many students, the idea that modern chatbots can do the work for them, like writing essays and completing tasks, generating message outlines and creating presentations, is highly appealing. Therefore, the teacher must be aware not only of AI's strengths but also of its weaknesses and be able to demonstrate to students why delegating tasks entirely to chatbots is not advisable. Moreover, a key responsibility of the modern educator is to teach students how to use contemporary AI technologies in a way that accelerates their progress and leads to more meaningful achievements.

In conclusion, our experience and the results of the survey among students have allowed us to identify several promising directions for further research. The presented examples of the implementation of digital tools demonstrate how students can be engaged in independently enhancing the effectiveness of foreign language learning, and how instructors can be guided to develop relevant professional tasks by integrating them into exercises using digital tools, resources, virtual platforms, and many other modern technologies.

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1.6. Didactic conditions for the formation of students' digital competence in the process of obtaining technological education in gymnasiums and lyceums

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Digital technologies are increasingly integrated into the educational process, influencing changes in methodological approaches, content, methods and teaching aids. These changes are especially relevant for technological education, which, in accordance with its mission and objectives, involves the study of technologies, a close connection with practical activities, the use of innovative tools and technical solutions.

In gymnasiums and lyceums, where key and subject competencies of general secondary education students are formed and the foundations of professional self-determination of the individual are laid, effective formation of digital competence is a necessary component of the educational process. However, as pedagogical research shows, the introduction of digital tools into the educational process by itself does not ensure the achievement of high learning outcomes. It is no less important to create appropriate didactic conditions that will ensure targeted, systematic and motivated formation of digital competence of education students: to ensure the optimal combination of content, methods, forms and means of learning in the process of studying technologies that meet the age characteristics of education students, educational standards and modern requirements for the process and learning outcomes (State Standard ...,2020).

In order to effectively form students' digital competence in the process of obtaining technological education in gymnasiums and lyceums, it is necessary to create such didactic conditions that, in aggregate, will ensure effective learning focused on the formation of digital competence as one of the keys to a successful life and professional self-realization in a modern high-tech, information society.

Based on the conducted theoretical and applied research, we include the following conditions:

- motivational support for learning;
- targeted integration of digital technologies into the content of technological education;
- optimal selection of content, methods and forms of learning;
- individualization and differentiation of learning;
- reflection and feedback in the educational process;
- organization of a digital educational environment;
- increasing the digital competence of teachers;

Effective mastery of digital technologies in the process of technological education in gymnasiums and lyceums requires taking into account the above-mentioned didactic conditions, the implementation of systemic approaches that combine practical significance, interdisciplinary integration, and activity-based learning, ensuring the achievement of the necessary results of the educational activities of general secondary education students.

One of the most important factors of effective learning is the formation of motivation for learning in students, maintenance and development of a sustainable interest in digital technologies through demonstration of examples of their application in real life, in various spheres of economic activity. Particularly relevant in the conditions of modern Ukraine are examples from the defense, agricultural and engineering spheres, which show the applied value of digital skills and their impact on the well-being, security and innovative development of society.

Involving students in relevant socially significant projects, in particular those related to supporting the Armed Forces of Ukraine or participating in initiatives to restore damaged infrastructure, contributes to the development of personality, patriotic upbringing and the formation of a responsible attitude to learning. Participation in such projects increases the motivation of students to master digital technologies as a tool for real influence on social processes.

It is advisable to systematically include modern digital tools in the development of projects and to have students master such digital technologies as graphic editors, computer-aided design systems, visualization and modeling platforms, prototyping environments, etc. Their use ensures the development of spatial and technical thinking, skills in engineering analysis, design and solving applied problems. These digital tools should not be an addition to the lesson, but an organic part of the educational content, integrated into educational topics, projects, practical tasks and tests.

The purposeful integration of digital technologies into the content of technological education and the use of digital technologies in teaching contributes to the formation of key and subject-specific project-technological competences of secondary school students.

First of all, digital technologies affect the formation of information and digital competence. Using digital technologies, students can find the information they need and are interested in, work with data, use digital resources and online tools to search, process, comprehend and critical analyze information.

In the context of the rapid development of digital technologies and visual culture, graphic competence is becoming particularly relevant - one of the components of technological education and the basis for successful mastery of such areas as engineering, architecture, design, computer-aided design, 3D modeling, robotics and other modern industries where visualization and technical thinking are necessary (Holiiad, 2023). Knowledge of graphics allows students to read and create drawings, models, technical diagrams, navigate spatial objects and transform abstract ideas into specific visual forms. In modern technological education, graphic skills become a tool for visual thinking, which helps to analyze, plan, design, optimize technological processes.

The use of digital graphics platforms – such as graphic editors, computer-aided design (CAD) systems, 3D modeling programs – requires software proficiency, understanding of composition principles, scale, proportion, symbols, technical standards

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(ISO standards). This allows students to create real professional projects that can be integrated into production or educational and research processes.

The formation of graphic skills within the framework of the educational subject «Technology» requires targeted pedagogical support: from elementary acquaintance with visual forms to the creation of complex digital models and drawings. This approach ensures the development of spatial and logical thinking in students, forms creativity, accuracy, attentiveness - qualities important for future professional growth in the digital economy. Graphic training is a necessary component of technological education of the new generation. It forms fundamental skills that combine traditional knowledge with modern digital capabilities, ensuring the readiness of students for further education, professional activity and active participation in the innovative development of society.

The processing of information from different sources by students creates ample opportunities for its comparison, comprehension and influences the development of critical thinking and creative abilities of students.

During the learning process, students can create their own digital projects, use online resources to search for information, use design software and digital modeling tools. For example, when studying methods of modeling products, you can use 3D design programs (Fusion 360, SolidWorks), which provides the opportunity to develop digital models before their physical implementation.

The use of mobile applications, such as Khan Academy, Coursera, helps to obtain the necessary additional information, increases the level of student independence, develops communication skills, creativity and entrepreneurial abilities.

However, it is necessary to study in more detail how effectively students of secondary education institutions use these opportunities in technology classes.

For digital design and planning, programs such as AutoCAD, TinkerCAD, Canva, Adobe Spark can be used.

In order to automate the design process, the result of which is a set of design documentation, it is advisable to teach students to use an automated design system (CAD). It is used on the basis of special software, automated data banks, a wide range of peripheral devices. With the help of CAD, you can develop a full set of design documentation, calculate and design technological schemes, technological equipment, prepare specifications, estimates, etc.

- CAD includes the following digital technologies:
- CAD (Computer-aided design)

- CAM (Computer-aided manufacturing)
- CAE (Computer-aided engineering)
- CALS (Computer-Acguisition and Life cycle Support).

AutoCAD has versions designed for educational purposes, which are available for free download from the Autodesk educational community website. The educational version of AutoCAD is functionally no different from the full version.

To build clothing patterns, you will need the skills to use the PatternsCAD program. This program provides the ability to build clothing patterns in their natural size or on a different scale, or according to individual measurements.

The content of technology training may also include the use of other digital technologies that are constantly developing.

Experimental studies conducted in Ukrainian lyceums prove that the purposeful use of digital technologies in the educational process stimulates the creative thinking of students, develops creativity and forms the qualities of a person with an innovative type of thinking. In particular, the use of 3D modeling, animation software (Blender, SketchUp), artificial intelligence generators contributes to the search for new ideas and their implementation in the process of project activities on technologies (Holiiad, 2023).

The study of 3D printing technology is being introduced more and more widely, not only in experimental gymnasiums and lyceums of Ukraine. For this purpose, new special courses and other forms of classes are being developed. The relevance of studying 3D printing by secondary school students lies in its ability to interest and make learning more active. As our research and study of teachers' work experience show, the advantages of implementing 3D technology in secondary school institutions are:

- formation of STEM skills of students;
- development of imagination, fantasy, spatial and technical thinking of students;
- improvement of digital interaction of students;
- increase of motivation of students for scientific and research activities;
- growth of interest in studying fundamental and applied disciplines;
- visual acquaintance with three-dimensional visualization and modeling;
- strong interdisciplinary connections in practical application;
- compatibility with other educational programs (Lego, Tetrix and others);
- the possibility of using 3D technologies at different levels of education;

- promoting professional self-determination of high school students and their conscious choice of engineering professions.

The above arguments are weighty factors for the wider introduction of a course on 3D printing into the educational process of secondary education institutions. It should be noted that the modern educational process is characterized by a certain inconsistency between the dynamics of innovation development and the inconsistency of the content of curricula in subjects and courses related to additive technologies.

Analysis of the content of the curricula approved by the Ministry of Education and Science of Ukraine shows that the topic «Modeling and 3D printing» is studied in the interdisciplinary integrated course «STEM» for grades 7-9» (Model Curriculum ..., 2024) on the examples of 3-D modeling of the human circulatory system, development of 3D architectural design of a building. The educational module «3D modeling and printing» is proposed for study in the curriculum for grades 7-9 «Technologies. STEM projects». The main tasks of the program are related to the formation of design and technological competence in students using 3D modeling. Their solution is subject to the structure and content of the modules, which correspond to the age of children in grades 7-9.

The content of the new elective course "3D Printing and Modeling" for students in grades 9, 10, and 11 of secondary education institutions logically ensures the continuation of the formation of digital competencies in senior classes. The peculiarity of the course is its focus on acquiring practical skills in using 3D printers and making 3D models, primarily in the environment of the technological educational industry.

The introduction of the elective course "3D Printing and Modeling" in secondary education institutions can contribute to the creation of an educational environment for the implementation of such general educational tasks as:

- the ability to work with a variety of information;
- the development of a tendency to scientific and research activities;
- the ability to independently design educational activities;
- the ability to carry out self-assessment and self-control;
- the desire and ability to demonstrate purposefulness,
- initiative and independence;
- the tendency to new ideas, the search for new non-standard solutions;
- the ability to respond adequately to various, often non-standard situations, etc.

Significant in the formation of digital competence of education seekers is the role of the special course «Technologies of Modern Production», which has been experimentally tested and is already studied in academic and professional lyceums of Ukraine. The content of this special course involves the use of digital technologies and modern teaching aids in project and technological activities and mastering Industry 4.0 technologies.

It is Industry 4.0 technologies that are already contributing to the creation of effective production, influencing the increase in competitiveness and defense capability. A new generation of industrial systems using augmented reality and multimodal interaction helps to operate effectively in difficult conditions, to develop modern production, in which digital technologies are widely used.

The development of digital technologies has led to the development of cyber-physical systems (CPS), which have united the digital virtual world and the real one. CPS production systems, consisting of smart machines and logistics systems, allow for ICT-based integration for vertically integrated systems and production networks. Cyber-physical systems increase resource productivity and production efficiency.

Technological leadership and focus on modern production industries, automation and software based on embedded systems, as well as strong industrial networks lay the cornerstone for the success of Industry 4.0, which is actively developing in the world.

Industry 4.0 technologies ensure the development of smart industry and are associated with the technological evolution from embedded to cyber-physical systems (Holiiad, 2023).

Artificial intelligence is increasingly influencing the development of modern industry. Decentralized artificial intelligence will help create smart industrial networks and set up an independent control process with the interaction of the real and virtual worlds, which represent the most important new aspect of the production process. Industry 4.0 ensures the transition from centralized production to decentralized. There is interaction between the product of production and the machine. Industry 4.0 connects system industrial technologies and smart production processes to open the door to a new technological era.

Digital technologies are the foundation on which innovative solutions of the future are built.

Cyber-physical systems are high-performance technologies that combine the virtual and real worlds to create a truly networked space in which smart objects can communicate and interact with each other. Cyber-physical systems can be combined with the Internet of Things, data and services to form fully-fledged cyber-physical systems. At the same time, CPS provides the foundation for the creation of the Internet of Things, data and services, thereby making the implementation of "Industry 4.0" possible. These are high-performance technologies that, through innovative applications and processes, are able to blur the line between the real and virtual worlds. As such, they promise to revolutionize our interaction with the physical world in the same way that the Internet has changed personal communication. The interaction of high-performance embedded systems and specialized user interfaces integrated into digital networks opens up a whole new world of system functionality.

Among such new opportunities is the Internet of Things, which provides the ability to carry out many processes without direct human participation and is capable of radically interfering in the development of society and the global economy (Tutashynskyi, 2021a; p.101).

The Internet of Things has become popular for describing scenarios in which Internet connectivity and computing power extend to a large number of objects, devices, sensors, and everyday objects. The main concept of the Internet is the ability to connect things that a person can use in everyday life, for example, a refrigerator, air conditioner, car, bicycle. All these things must be equipped with built-in sensors that have the ability to process information coming from the environment, exchange it, and perform various actions depending on the information received. An example of the implementation of such a concept is the "smart home" or "smart farm" system, which can be designed by students in technology classes. This system analyzes environmental data and, depending on the indicators, regulates the temperature in the room. In winter, the heating intensity is regulated, and in case of hot weather, the house has mechanisms for opening and closing windows, thanks to which the house is ventilated, and all this happens without human intervention.

Several technologies are required to connect everyday objects into a network. To identify each object, a simple, compact technology is required. Only with a unique identification system can information about a specific object be collected and stored. Such functionality can be provided using RFID (Radio-Frequency IDentification) chips. They are capable of transmitting information to reading devices without their own power source. Each chip has an individual number. As an alternative to this technology, QR codes can be used to identify objects. To determine the exact location of an object, GPS technology, which is effectively used in smartphones and navigators, is suitable. To track changes in the state of an element or the environment, objects must be equipped with sensors. An embedded computer must be used to process and store data from sensors. Wireless network technologies (Wi-Fi, Blutooth, ZigBee, 6 LoWPAN) can be used to exchange information between devices. Integration with the Internet should provide that devices will use the IP address as a unique identifier. Objects in the Internet of Things will not only be devices with sensor capabilities, but also devices that can perform certain actions. To a large extent, the future of the Internet of Things will not be possible without support for IP v6, therefore, the global implementation of IP v6 in the coming years will be crucial for the successful development of the Internet of Things in the future. For wireless data transmission, characteristics such as efficiency, adaptability, and the ability to self-organize play a particularly important role in building the Internet of Things.

Among the leading technologies, PLC solutions play an important role in the spread of the Internet of Things - technologies for building data transmission networks over electrical transmission lines, since many applications have access to electrical networks (for example, vending machines, ATMs, smart meters, lighting controllers are initially connected to the power supply network). 6LoWPAN, which implements the IPv6 layer over both IEEE 802.15.4 and PLC, being an open protocol standardized by the IETF, is noted as being particularly important for the development of the Internet of Things. According to analysts' forecasts, a real boom in the Internet of Things is expected in the coming years. Now IoT is no longer just a network of «smart» devices connected by wired or mobile communication channels, but also a person who communicates with them. Using the opportunities provided by the Internet of Things is transforming not only personal or social aspects of life, but has also affected most areas of business and the economy. In the world, most companies are implementing technological solutions using IoT, with electronics, transport, control systems, logistics, finance and the military sphere as a priority. Today, few people are surprised by a "smart home", in which you can control household appliances and heat, water and electricity supply using a regular smartphone. Remote car start, GPS navigators, Smart TV, smart glasses have become familiar to many. There are enough examples around us to understand how much the Internet of Things has entered everyday life and various sectors of the economy. Among the capabilities of "smart" devices are monitoring meteorological conditions, seismic hazard, the state of the atmosphere and water. It should be noted that the transition to the 5G mobile communication standard will contribute to the implementation of even greater IoT capabilities. This will reduce connection delays between devices and simultaneously support a huge number of connections, extend the service of "smart" devices, as

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well as achieve incredible mobile data transfer speeds by today's standards. The military industry has also not remained aloof from global processes associated with mass «digitalization» and the transformation of the relationship between humans and devices. Technological innovations are first used to strengthen the country's defense capabilities. The technological trend of the last decade in the armies of many countries, a kind of indicator of the modernity of the armed forces, has been the use of the IoT concept. At the same time, it is difficult to surprise with aerial or ground-based unmanned aerial vehicles and robotic combat vehicles today. As new technologies emerge, the range of tasks and capabilities of military «smart devices» is expanding rapidly, starting from solving complex tasks of enemy detection and ending with monitoring the physical condition of each serviceman. Today's technical capabilities for enemy detection and the availability of high-precision weapons force high mobility and quick decision-making. This is possible only if all units involved in the operation promptly receive information from various sources in real time. One way to solve this problem is to use solutions based on the IoT concept, which are called the Internet of Battle Things (IoBT). Currently, IoT technologies are already used to monitor the current situation on the battlefield, in logistical support, and medical support for troops. IoT devices have also found wide use in various educational and training programs in virtual combat mode. For Ukraine, which is forced to counter the aggressor, the implementation of the Internet of Battle Things in practice is very relevant. In conditions of high-tech confrontation, the one who is better equipped and uses advanced high-tech things in everyday practice has the advantage. The Ukrainian army already uses individual elements from the Internet of Battle Things sphere; "Military tablets", GPS navigation devices, wireless communication devices, unmanned aerial vehicles, etc.

Providing opportunities for students to choose elective courses to study should contribute to the individualization and differentiation of learning, taking into account the interests and abilities of students, the formation of their digital competence, and the ability to interact in a digital environment.

The use of online platforms has been increasingly used in the educational process in recent years. Google Classroom, Microsoft Teams, Padlet, and other online platforms allow students to discuss projects, develop teamwork skills, and, as a result, contribute to the development of communication competence.

An important component of the educational process is the interdisciplinary integration of the subjects «Technology», «Informatics», «Physics», «Mathematics», «Art», which provides an opportunity to form comprehensively digital competencies and ensure the transfer of knowledge and skills to other educational and life situations. Such a combination of educational subjects contributes to a deeper understanding of the principles of digital systems, the formation of algorithmic thinking and the ability to model in the process of implementing various projects.

In conditions of martial law, an unstable educational environment and unequal access to resources, the implementation of blended and distance learning, digital laboratories and virtual modeling platforms becomes particularly relevant. They ensure flexibility and continuity of the educational process, adaptability to different educational conditions, as well as the preservation of educational interaction even in the physical absence of students in an educational institution (Bieliaieva, 2023).

For the effective formation of digital competence of education seekers, it is important to use an activity approach, which involves solving real practical problems by students, carrying out creative projects, participating in collective or individual work focused on creating their own digital or technological product. In this way, the assimilation of new knowledge, the development of initiative, creativity, responsibility, the ability to cooperate and self-education are ensured - as the main components of digital literacy and technological culture of the individual.

In the digital educational environment, technology teachers are intermediaries between the digital environment and students, actively promoting comprehension, critical perception and responsible use of digital tools. The professional and communicative role of teachers becomes key in the context of the transformation of the educational process: they must have a high level of communicative culture, be able to create a positive atmosphere of cooperation and trust, and maintain dialogue and mutual understanding with each student. It is through personal example that teachers form in students the ethics of using technology, responsibility, and digital culture, which are the basis for safe and productive interaction in the information space.

An equally important factor in effective digital transformation is the ability of teachers to use model programs creatively and create their own original methodology. The digitalization of the educational process is not reduced to the mechanical use of ready-made solutions - it requires creative rethinking, pedagogical vision and the ability to adapt approaches to a specific context. Creative technology teachers develop microcourses independently, create digital tasks, projects, combine face-to-face and distance learning formats. This approach provides flexible adjustment of the educational process in accordance with the level of training of students, the material and technical capabilities of the educational institution, the specifics of wartime or distance learning format. The author's methodology forms a unique teaching style that activates the cognitive activity of students, forms a stable motivation for learning and ensures the achievement of expected learning outcomes.

An important condition for high-quality digital education is the teachers' comprehensive knowledge of the subject. Teachers who have deep and systematic knowledge in the field of technology, understand the principles of functioning of modern equipment, software and technological processes, are able to explain to students how a particular digital tool works, show its connection with real production, engineering, economics. Pedagogical skills of teachers are also manifested in their ability to select digital tools reasonably in accordance with the topic, type of task, age and cognitive characteristics of students. It is digital technology that should enhance visibility, accessibility, individualization, control and self-control in learning. Professional intuition and digital flexibility make it possible to turn the use of technology into a powerful tool for pedagogical influence and student development.

Increasing the digital competence of teachers is a condition that allows ensuring the quality of education, its resilience to the challenges of wartime, its openness to innovation, partnership and development. This is primarily an awareness that modern teachers act as mediators, facilitators, organizers of the educational environment in which students acquire knowledge in conditions of an excess of information and are not always ready to interpret it critically and select it for learning purposes. Modern teachers must deeply understand why and in what way it is advisable to use digital technologies in order to enhance the cognitive activity of students, to form in them critical thinking, creativity, the ability to work in a team and solve problems independently.

Mastering digital tools should be accompanied by a change in the pedagogical worldview: from the traditional transmission of information to creating conditions for independent knowledge, research, design, and application in practical activities. Teachers become participants in an open digital space, where it is important to own the means of communication, be able to demonstrate and maintain professionalism, ethics, and pedagogical tact.

A deep rethinking of the role of teachers is also associated with responsibility for the digital security of education seekers, the ecology of the digital environment, the culture of using information resources, compliance with copyright, and the formation of digital ethics in students. In the new role, teachers creatively adapt technologies to the educational process, develop original digital products, and construct educational situations where students demonstrate and develop their abilities. Such teachers are constantly learning, are in professional interaction with colleagues, and are looking for effective pedagogical solutions that meet the challenges of the time - in particular, the threats of war, the conditions of hybrid or distance learning, and the lack of resources (Tutashynskyi, 2021b; p.137). Improving digital competence is a path to the personal and professional transformation of teachers, to rethinking their educational mission in the age of digital technologies, instability, and rapid change. This is the ability to be modern, ready for change, responsible and value-oriented leaders of education seekers in the world of modern technologies. At the same time, professional support for teachers within the framework of cluster partnership, through internships, webinars, mentoring from IT specialists and industrial practitioners is important (Multilevel system ..., 2025).

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1.7. TEACHER PREPARATION FOR A MODERN LESSON IN THE CONTEXT OF A DIGITAL EDUCATIONAL ENVIRONMENT

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It is essential to recognize that the process of societal informatization, which has led to the emergence and development of the modern digital educational environment, creates a set of conditions that, to varying degrees, influence all components of the educational process. The Ukrainian researcher of educational informatization, O. Spirin, emphasizes that the "objective conditions and current trends in the development of the information society <…> include artificial intelligence, machine learning, neural networks; blockchain and cryptocurrencies; big data; telemedicine; augmented and virtual reality; chatbots and virtual assistants; mobility and cybersecurity; the Internet of Things; robotics and robotic systems; computer vision; cloud and fog computing" (Kremen, Ed., 2021, p. 1099).

Based on the above, it is possible to identify the key conditions of the information society that have the greatest impact on the educational process within Ukraine's general secondary education system, as well as on the formation and development of its digital educational environment. These include:

- an increasing level of digital literacy among the population in general and educational stakeholders in particular;
- a growing share of employment in the IT sector, including individuals involved in software development (programming), information process management, and maintenance of information technologies across various economic sectors;

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- a positive societal attitude toward IT professions and their growing attractiveness to students pursuing general secondary and higher education;
- the digitalization of interactions within the contemporary social environment, including economic, political, social, and cultural-educational relations, and, above all, interpersonal communication;
- the accessibility of modern information and communication technologies (ICTs), including search engines and various Google web services (which serve as free online alternatives to Microsoft Office products), messaging applications such as Viber and WhatsApp, and social media platforms like X, Facebook, Instagram, and LinkedIn, both for the general public and for participants in the educational process at general secondary education institutions in particular;
- widespread access to broadband and mobile internet;
- the saturation of Ukrainian society in general, and domestic educational institutions in particular, with software and hardware tools, especially multimedia devices (reflected in the increasing number of users, devices, and applications);
- the proliferation of smartphones, enabling the use of mobile phones as pocket-sized computers with access to mobile internet;
- the growing importance of school-based informatics education (as a component of general secondary education) for future professional training, employment, and labor market engagement of graduates;
- the expansion of online educational websites, services, and platforms providing participants in the general secondary education system with access to digital educational resources;
- the emergence of an urgent societal demand for distance learning in Ukrainian general secondary education institutions, intensified by the COVID-19 pandemic and the full-scale russian aggression against Ukraine (the russo-Ukrainian war), which is now being implemented through modern ICT tools.

Since the aforementioned conditions affect the educational process in general secondary education institutions as a whole, it is reasonable to examine in greater detail how they influence its individual components. According to academician O. Topuzov, these components include the “target, content-related, activity-based (procedural and methodological), resource-environmental, and outcome-related” aspects (Topuzov, 2021, p. 47).

The acquisition of computer science knowledge, skills, and competencies by students of general secondary education, as well as their experience in using modern information and communication technologies (ICT), has become a key aim of the educational process in institutions of general secondary education, as stated in the Law of Ukraine "On Education". This aim is closely linked to other educational goals and objectives. Moreover, certain goals and objectives of general secondary education that are not directly related to the field of computer science can be identified and implemented in the educational process, specifically due to students' informatics training and the integration of modern ICT tools in the classroom. The content of modern general secondary education, particularly when understood in a broad sense, that is, in conjunction with various modes of learning (reproductive, problem-based, research-based, etc.) that determine the nature of students' learning activities, as well as the methods, tools, and forms of organizing the educational process, is also heavily influenced by the phenomenon of digitalization.

Even without focusing specifically on the increasing role of the informatics education domain, it can be argued that the path of educational content, from a sentence or phrase in the state standard to the content of an individual lesson, necessarily involves a teacher's engagement in searching for, selecting, organizing, or creating appropriate digital content, as well as in choosing and utilizing modern digital tools (both software and hardware) required for its delivery and acquisition by students. It is also important to recall the extended periods of distance learning in Ukrainian schools caused by the COVID-19 pandemic and the onset of the full-scale armed aggression of the russia against Ukraine, during which the educational process (i.e., the transmission and assimilation of educational content through teacher-student interaction) was mediated and enabled by information and communication technologies (ICTs). In light of the above, it hardly requires justification to claim that digitalization has a significant influence on the development of the organizational and methodological support of the educational process and the internal structure of its activity-based (procedural and methodological) component at the current stage of educational science and practice. Equally significant is the impact of digitalization on the resource-environmental component of the educational process. It is no coincidence that in contemporary Ukrainian scholarly and pedagogical literature, the concept of the "educational environment" is gradually being transformed into that of an "information and educational environment". In addition to the fact that the information and ICT resources of general secondary education institutions have long been viewed as a substantial and independent element of a school's resource provision, digitalization-related requirements are increasingly being applied to other components as well. These include, but are not limited to: the level of digital literacy among teaching staff; the informatization of institutional management processes; the visibility of educational activities in the information space (particularly on the school's website and in the media); and expenditures related to school informatization.

In studying the impact of digitalization on the educational process in schools, it is essential to address the issue of teacher preparation for lessons within the context of the modern digital learning environment. This serves as a critical juncture where the influence of digitalization extends beyond the educational process itself to encompass the domain of methodological (scientific-methodological) work in schools, as well as postgraduate non-formal (in-service training) and informal (self-directed) education of teaching staff.

To address this issue, it is necessary to examine the theoretical foundations (principles) and specific features of the process of preparing educators for teaching in the context of a contemporary digital educational environment.

The results of an analysis of scientific and methodological literature allow for the identification and substantiation of core principles that underpin the preparation of teachers for conducting lessons in a digital learning environment. These include: child-centered digitalization; the legality of digitalization; digitalization aligned with natural developmental principles; conscious and goal-oriented digital educational interaction; anticipatory alignment with the life tasks of learners (a prognostic orientation toward the learner's future); accessibility of digitalization; variability in digital approaches; and the effectiveness of digitalization.

Let us examine these principles in more detail.

The principle of child-centered digitalization implies that the use of diverse digital educational content, relevant software (applications), and hardware (information technologies) is a necessary condition and a powerful means of optimizing the educational process, ensuring its alignment with the demands of the information society. However, these tools should not be regarded as ends in themselves or become the ultimate goal of education. The overarching aim of acquiring complete general secondary education is "the comprehensive development, learning, value-oriented education, identification of giftedness, and socialization of the individual, who is capable of living in society and interacting civilly with nature; possesses a desire for self-improvement and lifelong learning; is prepared for conscious life choices and self-realization, responsibility, professional activity, and civic engagement; and shows care for family, the nation, the environment, and dedicates their actions to the benefit of others and society" (Law of Ukraine "On Complete General Secondary Education", 2020). The digitalization of the educational process and the learning environment within general secondary schools must not contradict this aim. On the contrary, it should serve to support and maximize its effective realization. In other words, digitalization in education must serve for the benefit of the learner, helping all stakeholders of the educational process to implement it optimally, productively, and efficiently, not for the sake of digitalization itself.

Adhering to this principle during lesson preparation in a digital educational environment requires teachers to carefully select digital (digitized) instructional content and informational tools (both software and hardware) that will ensure the most effective achievement of the lesson's goals and objectives, and facilitate the implementation of its stages. The teacher must also identify and anticipate lesson objectives and materials directly related to the phenomenon of digitalization, specifically, the development of students' information and communication competence. However, the aforementioned objectives, materials, and instructional tools must align with the goals of the lesson, correlate with other learning goals, and contribute to the achievement of expected educational outcomes in terms of student learning, value-oriented education, and personal development during this segment of the educational process.

Moreover, this principle emphasizes the need to ensure conditions that support the student's normal physical, psychological, and social development within the school's digital learning environment. The digitalization of the educational process must under no circumstances restrict meaningful pedagogical communication among participants, especially between the child and teachers, among classmates and peers within the school, or between the child and nature.

In the context of the digitalization of the educational process, it becomes critically important for students to engage in appropriate physical and motor activity. It can be anticipated that, in the near future, digitalization will lead to more ergonomic student workstations in schools, equipped with computer-based systems and sensors for automatically measuring key indicators of the child's physical condition (such as heart rate, blood pressure, and possibly blood oxygen levels). The teacher conducting the lesson would receive real-time data on students' fatigue levels (potentially including objective indicators of elevated stress levels in individual learners), enabling timely and informed responses.

Additionally, a student's workstation may be equipped with integrated elements of fitness equipment, allowing for the safe performance of short physical activity sessions within the classroom that would, among other benefits, help alleviate fatigue.

The principle of legal compliance in digitalization requires educators to strictly adhere to the legal norms governing the use of software and hardware tools in institutions of general secondary education. Among these requirements, several key aspects should be highlighted: compliance by all participants in the educational process with safety protocols and sanitary standards when using information and communication technologies and working with digital equipment; the use of safe, verified information materials that conform to legal and ethical standards, match developmental characteristics appropriate to students' age, and align with modern anti-discrimination practices; respect for copyright (i.e., proper use of copyrighted materials within the educational process); and the use of licensed software. It is essential to emphasize that the thorough verification of the safety and legal compliance of digital lesson materials is a necessary component of a teacher's preparation for instruction.

The principle of natural conformity in digitalization refers to the alignment of software, hardware, and digital learning materials used by teachers during lessons with the age-related characteristics of students' physical, psychological, and social development, as well as their educational needs, interests, aptitudes, and abilities.

The principle of awareness and goal-orientation in digital educational interaction implies that every software and/or hardware tool or element of digital learning content used by a teacher during a lesson should be employed consciously and purposefully. Its use must contribute to achieving specific lesson goals (whether educational, developmental, and value-oriented), and to helping learners obtain meaningful academic and life-related outcomes. Where necessary, the teacher should be able to explain to students the rationale behind using a particular digital tool or content, indicate the educational benefits, and motivate them toward achieving the intended learning goals.

The principle of anticipatory alignment with students' life tasks (a prognostic approach to learners' future lives) emphasizes the need to connect the educational outcomes of using digital tools and/or content with real-life contexts, specifically, with students' ability to solve everyday problems, particularly those involving information and communication technologies and digital equipment. However, a challenge arises: in today's world, digital technologies and ICT (especially AI-driven tools) are evolving rapidly, and this pace continues to accelerate. As a result, teachers face the risk of preparing students for the demands of the past rather than the future. A viable solution to this challenge is to design learning processes with a problem-based or research-based approach, encouraging students to think about how technological situations may evolve in the future, what challenges and tasks this might create, and what solutions could emerge. Additionally, the focus should be placed on cultivating students' values, transversal skills, and abilities such as independent information-seeking and developing information-based solutions.

The principle of accessibility in digitalization requires the teacher to ensure that students possess the necessary informatics background and that the general secondary school (and its students) are equipped with the software and hardware tools needed to achieve the lesson's objectives and implement its content.

The principle of variability in digitalization presumes that, during lesson planning, the teacher should consider (and create conditions for) various methods of delivering instructional content to students (e.g. with the help of multimedia (digital or digitized information), printed materials (textbooks, structured lesson plans, workbooks, stimulus materials), and verbal delivery (teacher's oral explanations). Furthermore, digital tools and digital content used in a lesson should also be differentiated based on the lesson's objectives, student activities, content complexity, and students' interests. Teachers are advised to avoid the constant use of the same digital tools, technologies, and educational platforms for introducing new content, developing and applying skills, or assessing and adjusting students' learning outcomes. Such digital uniformity may hinder student interest in the subject or course, reduce motivation, and limit the development of students' information and communication competence within the framework of complete general secondary education. Therefore, when preparing for a lesson, teachers should take this into account and reasonably vary the digital tools they employ.

The principle of effectiveness in digitalization encourages teachers to meaningfully combine digital tools with active and interactive teaching methods, and to incorporate into the lesson content tasks that foster students' experience in creative activity and the production of educational artifacts.

It should be noted that the above set of principles is subject to further refinement and expansion in the course of ongoing research on this issue.

The digitalization of the educational process and the learning environment in general secondary education institutions necessitates the purposeful integration of digital technologies into the lesson – a segment of this process that synthesizes and utilizes a combination of elements from the modern information environment. It can be argued that the lesson becomes the most significant setting and the most responsible moment, as well as the primary form and measure through which the conditions of a digitalized society are reflected and implemented in the school educational process. The appropriateness and effectiveness of digitalizing a particular lesson primarily depend on the teacher's overall preparedness, as well as their readiness to address lesson objectives, deliver content, apply relevant tools, and achieve the intended digital learning outcomes.

The algorithm (or sequence of actions) (Savchenko, 2013, p. 344) for preparing a teacher to conduct a lesson has been thoroughly examined and described in academic and methodological literature. Prominent Ukrainian didactic scholar O. Savchenko identifies several consecutive steps in lesson preparation, namely: (1) "defining the lesson's objectives within their broader system"; (2) "determining the content of the lesson and analyzing the potential of the textbook (and other sources) to fulfill the objectives in accordance with students' readiness to absorb the material"; (3) "selecting and combining instructional methods and techniques"; (4) "choosing forms of organizing students' learning activities"; (5) "establishing the relationship between structural components of the lesson and ensuring its internal coherence"; (6) "planning means of feedback, assessment, and evaluation of student achievement"; and (7) "preparing a detailed lesson plan" (Savchenko, 2013, pp. 344-355). Another Ukrainian didactic scholar, M. Fitsula, likewise outlines several sequential structural elements in lesson planning, including: formulation of lesson goals and objectives; determining the scope and content of instructional material; selection of instructional organization forms; selection of teaching methods and techniques; audiovisual and technical support for the lesson; determining the content and method of completing homework; and drafting the lesson plan-summary (Fitsula, 2000, pp. 173-174).

The results of analyzing and synthesizing the structural components of the lesson preparation process described above (Savchenko, 2013; Fitsula, 2000) allow us to propose a sequence of stages for preparing a teacher to conduct a contemporary lesson within a digital educational environment. These stages include: goal-setting stage (establishing the goals and objectives of a specific lesson in accordance with directive documents, such as the model curriculum/ curriculum for a course or integrated course, the educational program of the institution, and the State Standard for the appropriate stage of general secondary education, while also taking into account the teacher's individual instructional concept, which may be proposed within the legal boundaries of their academic freedom); content-construction stage (selecting/designing and organizing the lesson content based on its goals and objectives, while considering the age-specific and academic capabilities of the student group); organizational-methodological stage (determining the form of organizing the lesson and the forms of organizing students' learning activities during its delivery, selecting appropriate teaching methods and techniques that will support the implementation of these forms and ensure the achievement of the stated goals and objectives through the delivery of the selected content); resource-instrumental stage (identifying the learning tools required to apply the chosen instructional methods and techniques, facilitate student acquisition of lesson material, the material and technical resources (including consumable materials) needed for conducting the lesson); design-planning stage (systematizing the future lesson, integrating and coordinating its structural (static component) and procedural (dynamic component) elements, determining the scope and content of students' independent work (including homework), and preparing a lesson plan); self-evaluation stage (conducting an analysis and evaluation of the course and outcomes of the delivered lesson by the teacher, using either existing evaluation methodologies or teacher-designed tools (e.g., a self-reflection form); this may also involve collecting student feedback on their impressions of the lesson (for example, through a survey conducted via the class messenger group); adjustment stage (making necessary revisions to the lesson plan, which may include changes to the content, organizational forms, methods and techniques, or learning tools, etc.).

It is worth noting that the completion of the final two stages is essential for the teacher's professional growth and the development of pedagogical mastery; it becomes particularly relevant and beneficial when the teacher is expected to deliver a lesson on the same topic or content area in the following academic year. It is advisable for teachers to create a dedicated folder (or maintain a comprehensive notebook) for recording the results of self-analysis and self-evaluation of their lessons, as well as adjustments to their lesson plans. An even more optimal approach would involve the use of electronic documents (a dedicated digital folder containing files with the results of lesson self-analysis and revised lesson plans) or the implementation of specialized software designed for educational planning and teacher workflow management.

Let us now examine the specific features of teacher preparation for a lesson in the context of the modern digital educational environment, regarding each of the previously defined stages of this process.

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At the goal-setting stage of lesson preparation under the conditions of digitalization of the educational process, the teacher should identify the learning goals that relate to the development of students' information and communication competence, including its specific structural components ("knowledge, skills, abilities, modes of thinking, views, values, and other personal qualities" (Law of Ukraine "On Education", 2017). It is also advisable for teachers to differentiate these goals according to the essential components of the contemporary educational process (namely, educational, developmental, and value-oriented). It should be clarified that the reference is to a lesson within a course or integrated course outside the domain of the informatics (computer science) education area, as lessons within this domain inherently include such goals.

During the content-construction stage of lesson preparation, the teacher identifies, selects, and often creates multimedia materials that represent the lesson content and align with its objectives. This process involves not only the digitalization (typically in the form of a presentation created using Microsoft PowerPoint or Google Slides) of the lesson's textual material and printed photographs, illustrations, diagrams, charts, and tables used to visualize this content (i.e., static projection). For the vast majority of Ukrainian educators, the presence of a presentation that contains the core instructional material and reflects the structure and dynamics of the lesson has become a component of lesson planning as standard as the written lesson plan itself. Substantive digitalization of lesson content entails the pedagogically appropriate use of educational audio and video materials, "complex video effects, animations (including animated simulations), and simulations" (Zakharevych, 2012, p. 44). Increasingly, teachers themselves are the creators of these multimedia materials (recording audio, filming or editing video, and using specialized applications (including those powered by AI) to generate complex visual effects and animated content). These multimedia materials are typically integrated into a presentation for the lesson.

The organizational-methodological stage of lesson preparation involves the teacher's identification of information and communication technologies and specific software tools (applications) that best align with the objectives and content of the lesson. These tools should, among other things, support the development of students' information and communication competence, correspond to the selected form of lesson organization, suit the modes of organizing students' learning activities, and be consistent with the other teaching methods and techniques employed during the lesson.

It is important for teachers to consider several key points regarding the use of software applications in the classroom. First, the use of modern applications during a lesson is not an end in itself but rather a means of fulfilling educational objectives (including those related to digital literacy) and achieving learning outcomes. Second, for the successful use of any application in a lesson, the teacher must ensure that both they and their students possess (1) adequate digital literacy, (2) the necessary hardware, and (3) access to the required resources (such as mobile internet). Third, before using a new application in a full-class setting, it is advisable to pilot it with a smaller group of students. Fourth, even highly effective applications should not be used in every single lesson.

The resource-instrumental stage of lesson preparation involves identification by the teacher of the necessary software (digital tools) and relevant consumable materials (such as paper, cartridges, ink, etc.). The absence of certain resources should not be viewed as an obstacle but rather as an incentive for the teacher to engage in fundraising activities and to foster the development of the school's educational partnership system (Topuzov, 2021).

The design-planning stage entails the teacher's development of a detailed lesson plan, including the use of specialized planning software designed for teachers. In agreement with L. Riabovol's view that a lesson plan represents a "model of the lesson" (Riabovol, 2014, p. 58), we argue that within the context of the school's modern information-educational environment, where the educational process is being digitalized, the textbook's role as the primary source of instructional content is diminishing, and teachers have gained greater academic autonomy, the lesson plan is transformed into an informational model of the lesson delivered by a particular teacher to a specific class or classes.

During the self-evaluation stage, the teacher analyzes and evaluates the outcomes of the lesson (including its objectives and content related to the digitalization of society and education, as well as the use of information-related hardware and software). L. Riabovol outlines a set of questions to guide teachers' self-analysis of the lesson delivered: "What is the place of the lesson within the topic, section, or course? What is its specificity? Were the educational, value-oriented, and developmental goals formulated correctly? Were they achieved during the lesson? What objectives were addressed: educational, developmental, or value-oriented? Which of them were the main ones? Were they achieved during the lesson? To what extent did the selected educational content contribute to uncovering the topic? How thoroughly were the characteristics of the class, specific student groups, and individual students taken into account? How justified was the choice of lesson type and its structure? What guided the teacher in preparing for the lesson? How appropriate were the selected forms and methods of instruction? What were the learning outcomes?" (Riabovol, 2014, pp. 58–59).

Based on the works of the aforementioned scholar, a set of reflective questions can be formulated for analyzing the technological dimension of a lesson and its outcomes within the context of societal and educational digitalization, specifically: 1. What goals related to developing students' information-communication competence were set? Were they achieved during the lesson? To what extent? If not fully achieved, what obstacles prevented their realization? 2. Which multimedia instructional materials were used during the lesson? How effective was their use? What factors explain their efficacy or lack thereof? If they were ineffective, what alternative materials would be more suitable? 3. What information and communication technologies (software and hardware tools) were employed in the lesson? Did they correspond appropriately to the lesson's type and structure? Were they effective? Should they be replaced? If so, by what alternatives? 4. Did the school's provided material and technical resources sufficiently support the information and communication technologies necessary for the lesson? How could any shortcomings be addressed? 5. What adjustments are necessary in the lesson plan?

The adjustment stage involves preparing for forthcoming lessons on the same topic in the next academic year. The primary aim of this stage is to define and document revisions to the lesson plan, particularly concerning its technological components.

Future research directions in teacher preparation for lessons in a digital educational environment (i.e., considering the appropriate integration of digital content and modern technological tools during instruction) involve exploring and justifying the specific features of lesson digitalization across different levels of general secondary education (primary, basic, and upper-secondary), as well as across various lesson types (e.g., combined lessons).

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Chapter 2.
DIGITAL AND COMPUTER SCIENCE EDUCATION: EXPERIENCE AND PROSPECTS FOR IMPLEMENTATION

2.1. METHODOLOGICAL ASPECTS OF INTRODUCING THE SUBJECT “COMPUTER SCIENCE” INTO SPECIALIZED SECONDARY EDUCATION IN UKRAINE AMID DIGITAL TRANSFORMATION

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Education plays a key role in today's information society. It is the foundation for personal and professional development, a force for information and technological progress, and one of the main means of ensuring success in a globalized world. Transformational processes in the educational systems of countries around the world are determined by the constant active development of information technologies, technological progress, globalization, and other political or economic factors. On the one hand, "...education is changing toward actively using information technology in the educational process, and on the other side, it's the main driver of the development of information technology and information society in general" (Leshchuk S., 2025).

Svitlana Trubacheva, together with her colleagues (Trubacheva S., 2024), are analyzing the directions of development of digital technologies and trends in the organization of the educational process in general secondary education institutions during martial law, and are identifying priority areas of transformation in education that will influence the development of the education system in Ukraine in the near future. These include: distance and blended learning; informal education; cloud technologies; gamification; virtual and augmented reality; mobile technologies in education; STEM education; educational robotics; 3D technologies; programming or coding.

Artificial intelligence systems are considered one of the engines of digital transformation in education and global change in general. The use of AI is transforming all areas of human activity (industry, technology, engineering, education, media, marketing, advertising, trade, financial sector, gaming industry) and causing changes in the labor market. Given that AI will be a big deal for economic, industrial, and technological development in the near future, we need to rethink how countries around the world set up their education systems.

The key tasks of the digital transformation of education and science in Ukraine include: developing an accessible and modern digital educational environment, forming digital competencies among education and science professionals, regularly updating the content of ICT education in step with the development of information technologies (Concept, 2021).

Thus, the success of the digital transformation of education and science is directly proportional to the level of information culture, digital competencies of graduates of general secondary education institutions, and the provision of educational and scientific institutions with appropriate hardware and software.

The definition of the purpose of specialized secondary education indicates the need to develop pupils' personalities by establishing their Ukrainian national and civic identity and forming the competencies necessary for their resilience, independence, responsibility, communication, and interpersonal interaction, teaching pupils to use information technology in everyday life and learning, developing a responsible attitude toward the environment based on a scientific worldview and the principles of sustainable development.

The main task of developing pupils' information and communication competence lies with the field of computer science education. In grades 5–9, the study of computer science involved teaching pupils the basics of information culture and key competences (State Standard, 2020). Studying computer science in a specialized school involves summarizing and deepening the key competencies and skills that pupils have developed in using digital tools and resources in their chosen subject area, educational activities, everyday life and digital communication. At the same time, it is important to develop students' information and communication competence, which involves the confident, critical, and responsible use of digital technologies for their own development and communication; the ability to safely apply information and communication tools in learning, personal, and social life, adhering to the principles of academic integrity.

The State Standard for Specialized Secondary Education (State Standard, 2024) provides for the study of the subject «Computer Science» at the basic level only in the 10th grade. According to the Typical Educational Program (Typical Program, 2025), the 10th grade is a specialized adaptation cycle of specialized secondary education. In this cycle, the subject "Computer Science" is studied equally for all educational profiles. The content of computer science education during this period should include practice-oriented tasks from other disciplines. This will increase the applied focus of computer science education and familiarize pupils more deeply with various fields of human activity, creating better conditions for their future choice of profile.

The number of hours for compulsory educational components in the first semester of grade 10 is the same for all clusters. This creates conditions for compensating possible educational losses and also gives pupils the opportunity to familiarise themselves with the specifics of their chosen field of study and make an informed decision about their future educational path in the profiled adaptation cycle (Typical

Programme, 2025, p. 4). Directly specialized education is planned for grades 11-12 (cycle of specialized education in specialized secondary education).

Thus, the subject “Computer Science” in a specialized school can be studied at the basic level as a compulsory educational component for most study profiles for 1 hour per week only in the 10th grade. Advanced study of computer science is provided only as part of a profile with advanced study of mathematics, computer science, and technology. Figure 1 shows possible options for implementing the computer science educational component in the content of specialized secondary education.

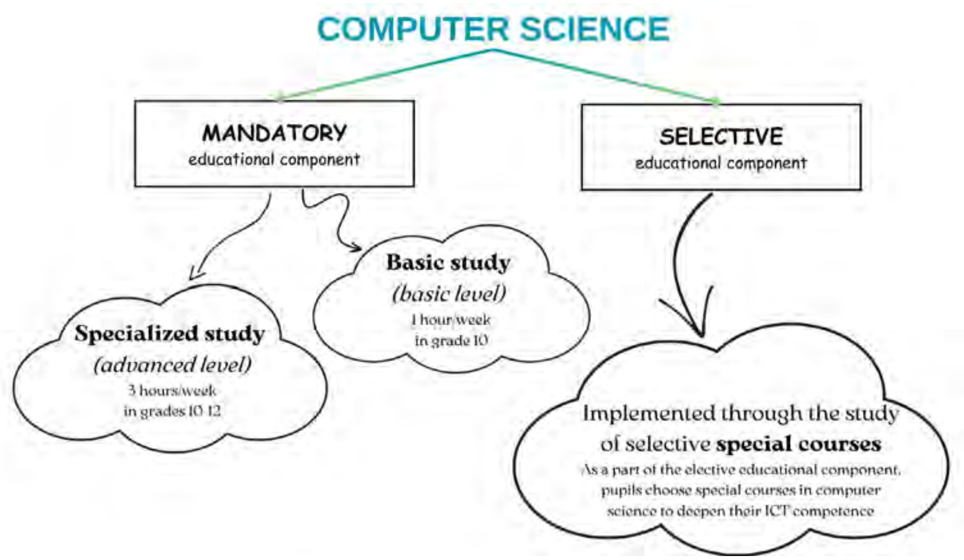

Рис. 1. Options for implementing the computer science educational component in the content of specialized secondary education

In our opinion, it is necessary to intensify teaching of computer science in all study profiles, since the subjects of the computer science educational field (directly the subject “Computer Science” or elective subjects of a computer science orientation) play a decisive role in the formation of the information and communication competence of graduates.

Basic level of computer science education

The purpose of studying the subject “Computer Science” in a specialized school at the basic level is to develop the personality of the pupil, enabling them to effectively use digital tools and technologies to solve problems, personal and professional development, creative self-expression, ensuring their own and social well-being, thinking critically and creatively, and acting safely and responsibly in the information society.

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The goal of studying the subject is achieved by solving tasks aimed at implementing the mandatory learning outcomes of the computer science educational field (State Standard, 2024), which provide that the pupil:

- finds, analyzes, transforms, generalizes, systematizes, and presents data; critically evaluates information to solve real-life problems;
- creates information products and programs for effective problem solving and creative self-expression, individually and in collaboration with others, with or without digital devices;
- organizes and consciously uses digital environments to access information, communicate, and collaborate as a creator and/or consumer;
- is aware of the results of using information technologies for themselves, society, the environment, and sustainable development of society, adheres to ethical and legal norms of information interaction.

During the research, we highlighted particular tasks for studying the subject:

- forming a modern informational worldview in pupils and understanding the paths of its further development;
- forming digital competence and skills for the safe use of information technologies in pupils;
- developing pupils' readiness to apply information and communication technologies in their chosen field in the information society;
- developing thinking, learning and lifelong development skills.

The priority goals of computer science education at the basic level were defined as follows:

- stimulate children's interest in learning;
- create opportunities for the creative development and self-realization of pupils, in particular through the use of digital tools;
- teach pupils to critically evaluate information disseminated by media resources and on the Internet;
- develop the ability to configure a personal information environment and organize its information protection;
- teach how to set learning goals and select digital tools to achieve them;
- use technologies for creating information products in educational and daily activities;
- develop the ability to use information modeling capabilities to solve applied problems;

- develop an understanding of the world of professions in the chosen field and the IT industry;
- develop logical, systematic, structural, and algorithmic thinking in pupils;
- ensure the comprehensive development of the child.

According to the distribution of the general workload of specialized secondary education pupils by class and educational field, computer science is taught at the basic level in the 10th grade for all educational profiles. At the same time, the subject "Computer Science" should be taught according to the model curriculum "Computer Science. 10th grade. Basic level."

The list of topics covered in the basic knowledge section of the State Standard for Specialized Secondary Education defines the content of computer science education at the basic, sufficient, and advanced levels. Based on the list of basic knowledge and corresponding groups of learning outcomes provided in the standard, we have identified four main topics that fully cover the list of issues in the field of computer science education and roughly correspond to the four groups of learning outcomes listed in the State Standard for Specialized Secondary Education.

Table 1.

Proposed distribution of topics for the subject "Computer Science" in 10th grade (basic level)

Semester	Topic
1	**Modern information systems. Personal information environment** The information picture of the world. The place of humans in today's information society. Information technologies in the digital society and promising areas for their development. Field-specific information systems. Their structure and functional features. Information processes in field-specific information systems. Use of information systems based on artificial intelligence. Internet of Things. Smart technologies. Personal information environment and its technical support. Hardware and software for digital communication. Their main characteristics. Selection criteria. Configuration of hardware and software for digital communication. Software and/or hardware failures, their possible causes and ways to eliminate them.
1	**Digital communication. Information security** The global information space as an environment for communication and cooperation. Digital communication and its characteristics in the chosen field. Social networks and professional digital communities. Messengers and chatbots. The digital divide and ways to overcome it.

1	Cybersecurity in the information environment. Types of cyber threats. Ways to avoid them. International standards of information security. Critical thinking methods for verifying the accuracy of information and the reliability of information sources, counteracting/protecting against manipulation. Information wars. Health-saving approaches in organizing a personal information environment. Digital hygiene, digital addiction. Legal relations and ethical norms in the field of intellectual property and the use of information technologies. Subjects of information relations, their interests and security, prevention of harm to them. The definition of plagiarism. Licensing of intellectual property. Rules for citing and referencing such objects. Digital citizenship. E-government systems. Digital reputation, digital footprint, digital competence of a specialist in a chosen field.
2	**Information product development technologies** Software and digital devices used to solve problems in the selected field. Analysis of requirements for information systems in the subject area and their configuration. Technologies for creating information products. The concept of the life cycle of an information product. Stages of creating an information product. Criteria for evaluating the quality of information products in a selected field. The concept of testing information products. Design of information products, its principles and development tools. Organization of teamwork for the creation of information products. Principles of team interaction. Rules of teamwork Effective interaction and communication, technologies and tools for their implementation during project development. The concept of project management.
	Information modeling as a means of solving applied problems Modeling in the selected subject area. Stages of building an information model. Types of computer modeling. Data, its types, features of processing and presentation in the selected field. Coding and visualization of digital data in the selected field and features of its use. Infographics. Principles of synthesis and decomposition in solving problems in a selected field. Algorithms for solving problems in a selected field: selection, development, evaluation of effectiveness. Structured data and algorithms for processing it. Software tools for performing calculations and data analysis. Processing sets of similar data.

In the first semester of 10th grade, we propose studying the topics "Modern Information Systems. Personal Information Environment" and "Digital Communication. Information Security" (Table 1). The aim of studying these topics is to review the computer science material covered in gymnasium and to develop pupils' ability to consciously and effectively use information technologies to organize their own digital educational environment, as well as to deepen their digital communication and information security skills in the information society. One of the main tasks of studying the first topic is to complete the formation of pupils' information worldview. This involves familiarizing pupils with promising areas of digital technology development (such as artificial intelligence, smart systems, Internet of Things) and an overview of industry-specific information technologies. Based on this picture, a pupil can build a personal information environment for solving professional and life tasks using information technologies. The second topic is devoted to the study of information and cybersecurity issues in the information environment, teaching critical thinking methods and their application, particularly in the field of digital communication.

Since the study time for the compulsory educational component common to all profiles is allocated for the entire year of study, we propose to continue the study of computer science in the 2nd semester of grade 10 with the topics " Information Product Development Technologies" and "Information Modeling as a Means of Solving Applied Problems". In the topic " Information Product Development Technologies", students learn more about specialized information technologies. In the course of studying the topic "Information Modeling as a Means of Solving Applied Problems", pupils consider ways to use them to solve applied problems in the chosen subject area.

Compliance with the State Standard and assessment methodology

The structure of the subject " Computer Science" in grade 10 (basic level) is developed in accordance with the structure of the description of the computer science educational field in the State Standard. The four topics proposed by the authors for the 10th grade computer science course at an academic lyceum roughly correspond to the four groups of learning outcomes in the State Standard of specialized secondary education. These groups of outcomes correspond to such key aspects as theoretical knowledge, practical skills, technical skills, and ethical attitudes. The assessment of pupils' learning achievements in a specialized school will be carried out according to the groups of results, that is, each current and semester assessment will correspond to one of the four groups. Both grades by outcome groups and a generalized grade will be given for the year.

- Search, presentation, transformation, analysis, generalization and systematization of data, critical evaluation of information to solve life problems (theoretical knowledge). Assessment of the first group of learning outcomes is aimed at checking pupils' understanding of the impact of information technology on their own lives, society and the world around them; the ability to work effectively with information; assess the reliability of information from various sources; build information models of real objects, events and processes for better understanding. Tests, surveys, discussions, and informational mini-compositions on the use of digital technologies to solve life situations can be used to test understanding and evaluation of information.

- Creating information products and programs for effective problem solving and creative expression, individually and in collaboration with others, with or without digital devices (practical skills). When assessing the second group of learning outcomes, the teacher checks pupils' ability to develop and implement algorithms, create and debug software projects; develop modular projects; create and process information products using different types of data, as well as skills in teamwork to create an information product. To do this, the pupil can use a variety of exercises, tests, practical work, group and individual projects, and competency tasks. To evaluate various aspects of pupils' group and individual activities in creating information products, it is advisable to use mutual and self-assessment. This promotes reflection, critical thinking, and the ability to self-analyze.
- Organization and conscious use of digital environments to access information, communicate and collaborate as a creator and/or consumer (technical skills). The third group of learning outcomes assesses the teacher's conscious use of information and communication technologies and digital devices to access information, communicate and collaborate as a creator and/or consumer. It assesses how pupils use a wide range of digital devices, organize their own information environment, use communication technologies and networks for their own development, communication and collaboration. That is, when assessing pupils' performance, not only the content of the tasks performed, but also the process of performing them should be taken into account. To assess these skills, the teacher can use rubric-based assessments with appropriate criteria, analyze pupils' actions in the digital environment (whether they choose appropriate tools, how they work in a team online), questionnaires and reflective questionnaires, projects and competency tasks that involve online collaboration, online discussions, debates, etc.
- Understanding the results of using information technologies for oneself, society, the environment and sustainable development of society, compliance with ethical and legal norms of information interaction (ethical attitude). Assessment of

the fourth group of learning outcomes is aimed at checking the formed attitudes of pupils towards ethical and safe interaction in the digital space, compliance with the rules of digital ethics and legal norms when using digital technologies and resources, understanding the positive and negative consequences of the spread of digital technologies and their impact on the environment, society and the individual. To check the formation of relevant attitudes, the teacher can use surveys, discussions, mini-studies, creative essays, reflections, individual and group projects on relevant topics, reflective questionnaires and case studies, etc.

Table 2 shows how many outcomes from each group are achieved in each topic. This information can be used for thematic and semester assessments by learning outcome groups.

Table 2.

Formation of learning outcome groups by topics of the 10th grade computer science course

	I group	II group	III group	IV group
Modern information systems. Personal information environment	✶✶✶ ✶✶		✶✶✶	
Digital communication. Information security	✶✶		✶	✶✶✶ ✶✶
Information product development technologies		✶✶✶ ✶✶✶ ✶✶✶		✶
Information modeling as a means of solving applied problems	✶✶✶ ✶✶	✶✶✶	✶	

Advanced level of study of computer science

The goal of studying computer science at the advanced level of education is to provide pupils with fundamental knowledge in this field, to develop and deepen practical skills in using information technology tools in everyday life and educational activities, to prepare pupils for participation in competitions, research, and to form a strong interest in computer science and related future professional activities or for successful study in higher education.

Pupils who have chosen advanced study of computer science within the profiles with in-depth study of mathematics, computer science and technology of the STEM cluster will study computer science at an advanced level starting from the 2nd se-

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mester of the 10th grade. This will be ensured by expanding the content of the basic course, strengthening its applied focus, solving problems of increased complexity and performing creative tasks, educational projects, writing research works, and actively creating new information products in computer science classes.

Thus, the study of computer science at the advanced level is ensured by deepening and expanding the content of computer science education at the basic level in accordance with the State Standard of specialized secondary education and should be carried out according to the model curriculum “Computer Science. Grades 10 - 12. Advanced level”. The weekly load is increased to 3 hours per week and can be supplemented by compulsory educational components in the chosen profile of study and elective educational components.

Table 3 shows the special courses for the computer science education field, which will help to expand pupils’ knowledge and deepen their skills in modern areas of information technology.

Table 3.

List of special courses for advanced study of computer science

Title of the special course	**Purpose of study**	**Methodological support**
Theoretical foundations of computer science	forming pupils’ knowledge of the mathematical foundations of the functioning of digital devices and information technologies, which is the basis for further mastering knowledge in this area	Curriculum, study book, digital application
Databases	developing pupils’ knowledge of the theoretical foundations of database design and functioning, skills in creating and managing databases, and the ability to organize data integrity and protection.	Curriculum, study book, digital application
Web Technologies	formation pupils’ skills in creating and developing websites, knowledge of basic web development technologies (HTML, CSS, JavaScript), development of the ability to work with tools for creating interactive and functional web resources, development of critical thinking and creative abilities through the creation of their own web projects	Curriculum, study book, digital application
3D modeling / 3D graphics and animation	learning by pupils the basics of creating three-dimensional models with the help of specialized programs, development of spatial thinking, creativity and visualization skills	Curriculum, study book, digital application

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Cybersecurity and information protection	pupils learn the basics of protecting data and information systems from threats in cyberspace	Curriculum, study book, digital application
Robotics	learning by pupils the basics of designing, assembling and programming robots	Curriculum, study book, digital application
Basics of drones control	learning by pupils the basics of control and programming of drones, training flights on drones in a computer simulator	Curriculum, study book, digital application
Artificial intelligence technologies	familiarizing pupils with the basics of artificial intelligence, its application in various spheres of life and the principles of operation of major technologies such as machine learning, neural networks, natural language processing and computer vision	Curriculum, study book, digital application

The special courses proposed in Table 3 would also be appropriate to study as interdisciplinary integrated courses in the structure of other STEM cluster profiles and profiles of other clusters. Their study will help pupils develop skills in using modern information technologies in educational activities and everyday life.

Advanced study of computer science is closely related to mathematics, as it provides the necessary tools for solving problems, understanding complex theoretical concepts, and building effective solutions in various fields of computer science. In this context, learning mathematics not only complements but also actively contributes to a deeper understanding of key concepts and technologies in computer science. On the other hand, the use of information technologies to master mathematical concepts allows us to visualize them and realize their practical value. Thus, combining the study of these two subjects at a deeper level makes both computer science and mathematics education thorough and comprehensive.

According to the typical educational program the profiles with in-depth study of mathematics, computer science and technology of the STEM cluster should also study mathematics and technology at a deeper level. This implies an increase in the number of hours of mathematics study at the expense of hours of choosing a profile of the compulsory educational component. The content of mathematics education within this profile should be expanded and deepened.

For profiles with in-depth study of mathematics, computer science and technology of the STEM cluster, we recommend studying Algebra and Beginning Analysis

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and Geometry separately in grades 10-12. To deepen the mathematical training of pupils studying in profiles with in-depth study of mathematics, computer science and technology of the STEM cluster, depending on educational needs, you can study the following special courses:

- Mathematical logic
- Discrete mathematics
- Theory of probability
- Mathematical modeling
- Data analysis
- Cryptography
- Theory of games
- Mathematics in programming

In-depth study of computer science at school involves its integration with other disciplines, among which a foreign language plays an important role. Knowledge of a foreign language (primarily English) provides access to the best international learning resources, allows you to actively participate in the global exchange of knowledge and experience, and is essential for professional development in the modern technological environment. There are numerous examples of areas where foreign language skills are required: working with English-language software interfaces, working with online resources, programming, reading programming documentation, communicating during team projects, participating in international research and publications, etc.

Pupils' English language skills (speaking, reading reference books, and writing code) are essential for in-depth study of computer science. Therefore, we propose to strengthen this direction by studying separate special courses in English focused on working with information technology. We offer such special courses that can be implemented in specialized secondary education through an elective educational component:

- English in IT
- English for STEM
- English Conversation Club

Besides, pupils have the opportunity to take other courses that are not related to the profile, but are quite important in terms of future professional activity (subjects and special courses of the language and literature cluster and the social and humanitarian cluster). These courses are selected from the list of special courses (modules) that are mandatory for the formation of certain profiles or elective for other profiles (listed in the typical educational program). Pupils can attend project classes, circles, and clubs that meet the educational needs of learners.

Studying computer science as a part of the elective educational component

A modern person is a member of the information society who probably spends most of his or her life actively using information technology. Therefore, a modern graduate of both a school and a higher education institution should have information and communication competence at the same level as professional (subject) competence.

Studying computer science at the basic level only in the 10th grade of an academic lyceum, on the one hand, and the increased requirements for graduates of general secondary education in terms of their digital competence, on the other hand, necessitate strengthening the study of computer science in all study profiles. This is possible through the study of individual course topics as elective educational components.

The set of elective educational components depends on the study profile chosen by the pupil. For example, in profiles with in-depth study of mathematics, computer science and technology of the STEM cluster, elective educational components are formed to strengthen pupils' mathematical, computer science and technological training by deepening and expanding the content of study. These profiles are focused, in particular, on the pre-professional preparation of pupils for studying in higher education institutions in the specialties of the field of knowledge "Information Technology". In the modern information society, specialists of such profiles are in great demand, especially in the era of digital transformation and the development of artificial intelligence technologies. Computer science and mathematics are a basic component of education for all professions that require an understanding of algorithms, data structures, process modeling, and data analytics. Examples of such professionals include specialists in software development, artificial intelligence and machine learning, cybersecurity, data analysis, financial technologies, robotics, computer graphics, computer systems engineering, control systems, business process optimization, game development, algorithm development for autonomous systems, and optimization of data flows between devices.

The proposed number of hours for basic learning of computer science in the State Standard of specialized secondary education is not enough, even though pupils have been studying this subject since elementary school. Therefore, we propose to integrate into the educational process of any profile of study subjects whose content covers promising modern areas of information technology development. Studying them will allow pupils to become more familiar with the possibilities of

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using IT in the subject area corresponding to the chosen study profile. Such subjects (special courses) include:

- Information Security and Media Literacy
- Fundamentals of Media Literacy
- Fundamentals of Artificial Intelligence
- Information Technology in a selected field
- Computer Modeling in a selected field
- Web Technologies and Web Design

The study of these subjects will allow pupils to become more familiar with the possibilities of using information technology in the subject area that will correspond to their chosen study profile.

Another methodological approach to realizing the unique integration potential of the subject “Computer Science”, which overcomes the contradiction between the universal nature of information technology and the predominantly isolated teaching of computer science in general secondary education, is the introduction of interdisciplinary integrated courses.

Teaching at a specialized school should be based on problem-based, project-based learning, research methods for applying theoretical knowledge in real-life situations, and be close to real professional activities in accordance with the profile (Conceptual Framework, 2024). The introduction of interdisciplinary integrated courses with a practical focus can provide a synergistic effect of combining computer science and other subjects, and help pupils form a holistic picture of the world. Such courses can complement and expand the content of subjects at the basic level, and be part of a variable educational component both within and outside the profile. Interdisciplinary integrated courses for non-informatics profiles of the STEM cluster can be:

- Digital Technologies in Natural Sciences
- Modeling of Natural Processes with IT
- Digital Cartography
- Geographic Information Systems and Environmental Monitoring
- Fundamentals of Bioinformatics: Genome and Protein Analysis
- Programming for Ecologists and Natural Scientists

General secondary education institutions already have experience in introducing interdisciplinary integrated courses in basic education, including STEM (integration of natural, mathematical, technological, informatics, social and health education) and Robotics (integration of natural, mathematical, technological and informatics education).

The above topics of the subject “ Computer Science” in grade 10 (basic level): “Information product development technologies” and “Information modeling as a means of solving applied problems” become an integrative basis for selecting content and building course programs.

The implementation of this methodological approach consists of three consecutive stages:

- Conceptualization and goal setting. At this stage, the curricula of selected basic-level subjects are analyzed to identify “intersection points” - topics where subjects complement each other to solve real professional problems, and knowledge and skills can be combined. The integrative goal of the course is defined not as the sum of two subject goals, but as a new, synergistic goal aimed at forming specific competencies and creating an educational product.
- Choosing a didactic model and integrating content. Interdisciplinary integrated courses should be focused on solving real-world problems, and pupils’ learning activities should be built around the implementation of complex projects. Teaching of courses can be implemented as joint teaching by several subject teachers (co-teaching or team teaching) or by one teacher with the relevant competencies.
- Development of educational and methodological support and assessment tools in the course. This stage involves creating a course curriculum, guidelines for project implementation, practical work, etc., selecting digital tools, and developing assessment criteria. The evaluation system should be comprehensive, taking into account both the quality of the final product and the process of working on it, the level of subject knowledge and digital skills.

Examples of such courses include:

- Digital Philology (Ukrainian Language and Literature and Computer Science);
- Digital Design (Arts, Technology and Computer Science);
- Analysis of Historical and Sociological Data (History, Civic Education and Computer Science)

In such courses, computer science turns into a universal tool for cognition, creativity, and problem solving, and integration through project activities ensures the comprehensive achievement of all groups of results in the computer science education field, increases pupils’ motivation, and forms holistic, interdisciplinary thinking, which is critical for successful self-realization in the modern world. This makes it possible to effectively implement the requirements of the new State Standard of Specialized Education.

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Continuous informatization and digitalization of educational, scientific and other spheres of human life form a number of requirements for the training of graduates of higher and general secondary education. In particular, the requirements for the formation of digital (information and communication) competence of a school graduate are growing. To achieve these requirements, it is necessary to rationally approach the formation of an educational program of a certain profile of study at an academic lyceum, while enhancing the training of pupils in computer science. The study of computer science should not be limited to the 10th grade at the basic level. It is necessary to expand the study of information technology tools for pupils in certain fields (in accordance with the chosen profile of study) through elective educational components, in particular, interdisciplinary integrated courses.

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2.2. AUGMENTED AND VIRTUAL REALITY IN THE TRAINING OF FUTURE TEACHERS: METHODOLOGICAL ASPECTS

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Technological development has a direct impact on education, which in turn requires the teacher training system to implement innovative approaches. The introduction of such approaches will ensure that future teachers acquire not only in-depth subject knowledge, but also a set of professional competencies necessary for effective work in a dynamic educational environment. Traditional training methods, in particular teaching practice, do not always fully enable the necessary skills to be developed in a safe environment and prepare teachers for the various challenges of modern reality. In this context, immersive technologies – virtual reality (VR) and augmented reality (AR) – have significant potential. AR integrates digital elements into the real environment, enriching it with interactive information, while VR creates fully immersive, artificially created worlds that allow users to immerse themselves in simulated situations and interact with them (Maro & Prosper, 2024).

Training future teachers in the context of rapid digitalisation of society requires not only the acquisition of fundamental theoretical knowledge and classical methodologies, but also the development of readiness to effectively use modern technological tools, in particular AR and VR, in their future professional activities. These technologies open new horizons for practical training, enabling the simulation of complex pedagogical situations, the development of specific skills and the formation of key professional competencies in a safe and controlled environment (Pellas et al., 2024).

The relevance of researching the use of VR and AR technologies in the training of future teachers is determined by several factors. These technologies provide unique opportunities for modelling realistic educational situations, creating a sense of presence and active interaction, which contributes to better acquisition of practical skills by higher education students (Lorenzo et al., 2023). The integration of VR/AR is a sign of global trends in the digitalisation of education and justifies the need to develop digital competence among teachers (Johnston et al., 2018). Identifying effective models and practices for applying these technologies, as well as potential risks, is an important process in adapting and implementing these technologies in the Ukrainian teacher education system. The need to train teachers to use these tools and develop appropriate methodological materials is also an important task (Yang et al., 2025).

The use of VR/AR technologies in teacher training is still in its formation stage. There is a need to systematise and analyse the accumulated experience of using immersive technologies, in particular, specific forms, methods, advantages and challenges in teacher education. The issue of pedagogical expediency, integration of VR/AR into curricula and their impact on the formation of specific professional competencies of future teachers has not been sufficiently researched.

The aim of the study is to analyse and summarise the pedagogical possibilities of virtual and augmented reality technologies in the system of professional training of future teachers, and to identify methodological directions for their use in the educational process.

In the context of constructivism, AR and VR provide the opportunity to create active learning environments in which future educators can actively perceive information, independently construct knowledge through action, experiment, and interact with immersive content. AR provides the opportunity to enrich real-life experiences with digital information, while VR allows users to immerse themselves in contextualised scenarios, promoting deeper understanding and application of knowledge (Maro & Prosper, 2024).

The use of immersive technologies in education is based on several pedagogical theories. The theory of experiential learning, according to which D. Kolb emphasises the importance of active experience and reflection for the acquisition of knowledge and skills (Kolb, 1984). This experience becomes the basis for further reflection, conceptualisation and planning of new actions, which completes the learning cycle. The ability to practise repeatedly and make mistakes in a safe environment is a key advantage of VR for developing pedagogical skills. VR and AR make it possible to create a variety of experiences that are difficult or impossible to obtain in real life. According to the theory of situated learning, J. Lave and E. Wenger emphasise that learning is effective when it takes place in an authentic context (Lave & Wenger, 1991). VR/AR can simulate such contexts, for example, a real classroom learning environment. Constructivist approaches emphasise the active role of the student in constructing knowledge, which is well implemented through the interactive capabilities of VR/AR.

Pedagogical possibilities of AR/VR for teacher training:

- Visualisation and concretisation of complex abstract concepts, processes, and objects using AR/VR technologies (e.g., 3D models in AR, virtual laboratories in VR) facilitates their understanding by future teachers of various specialities (Maro & Prosper, 2024).
- VR provides a unique opportunity for practical training in teaching methods (how to teach?) and management skills in conditions close to real life, bridging the gap between theory and practice (Yang et al., 2025).
- The ability to practise actions in complex or atypical pedagogical situations (e.g., conflict management, teaching children with special educational needs) without risk to real students and without fear of making mistakes (Pellas et al., 2024).
- VR simulations allow future teachers to put themselves in the position of a student with certain difficulties or to look at a situation from different perspectives, which promotes the development of empathy and inclusive competence (Pellas et al., 2024).
- AR/VR can be customized to consider the individual needs and learning pace of students, with the ability to differentiate levels of difficulty and support (Maro & Prosper, 2024).
- The novelty, interactivity, and playful nature of AR/VR significantly increase future teachers' interest in the learning material and the educational process (Maro & Prosper, 2024).

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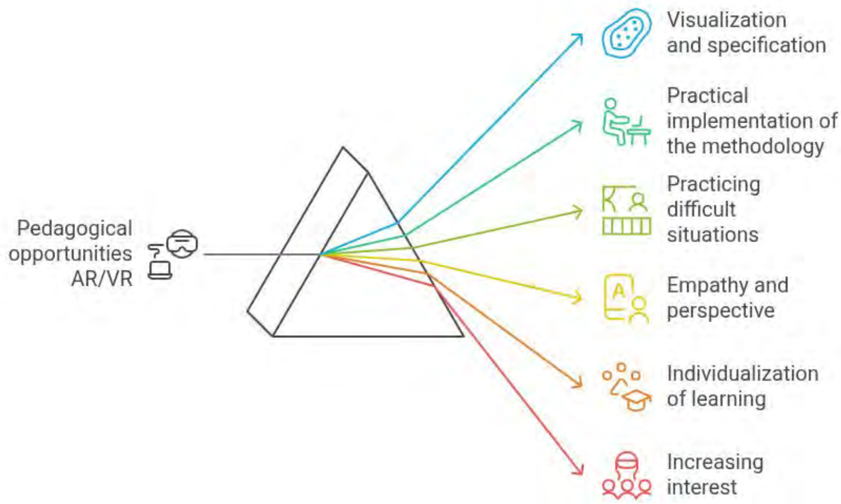

Fig. 1. AR/VR capabilities in the context of teacher training

Let us consider the types of immersive technologies. Virtual reality (VR) is a technology that creates a completely artificial, digital environment in which the user can immerse themselves using special devices (helmets, gloves, controllers). The key characteristics of VR are immersion – the feeling of being completely immersed in the virtual world, disconnected from the real environment; interaction – the ability to interact with objects and characters in the virtual environment; and presence – the subjective feeling of being 'right there' in virtual space (Dieker et al., 2008, pp. 3-7); (Hamilton et al., 2021, pp. 22-29).

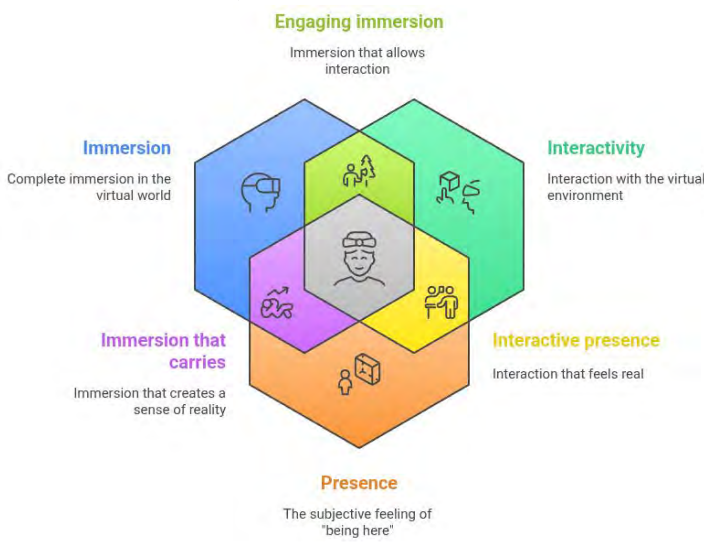

Fig. 2. Virtual reality characteristics

In education, both fully immersive VR systems (with headsets such as Meta Quest, HTC Vive, Pico) and less immersive ones (e.g., 360-degree videos on a computer or smartphone screen) are used.

Augmented reality (AR) is a component of mixed reality, which also includes 'augmented virtuality' (when real objects are integrated into a virtual environment), a technology that superimposes digital information (text, images, 3D models, videos) onto the real world that the user sees through the camera of a device (smartphone, tablet, AR glasses, etc.) (Wikipedia – free encyclopedia). AR does not replace reality but complements it. The key characteristics of AR are the combination of the real and the virtual, real-time interaction, and the registration (linking) of virtual objects to the real environment. AR technologies are more accessible, as all you need to use them is a smartphone or a tablet.

Although VR and AR are different technologies, they can be used complementarily. For example, VR is ideal for creating controlled simulations and immersion in abstract or inaccessible environments. AR is effective for enriching the real learning space, visualising complex objects and processes directly in the classroom or during excursions (Freina & Ott, 2015). Both technologies have significant potential to transform traditional teacher training methods.

We propose areas of application for VR and AR in the training of future teachers. Simulating classroom management and recreating pedagogical situations (VR) is one of the most common areas of application. VR simulators enable future teachers to practise classroom management skills and interact with students (including those with special educational needs or challenging behaviour) in a realistic but safe environment (Akçayır M. & Akçayır G., 2017); (Chernikova et al., 2020). An example of such use is the TeachLivE project (University of Central Florida, USA). It involves the use of mixed reality (human-avatar) to simulate a classroom in which future teachers can apply teaching techniques and receive instant feedback (Billingsley et al., 2019). Mursion is another platform with similar functionality. Such simulations help reduce the anxiety of future teachers before real practice, increase their confidence in their own abilities, and effectively learn specific classroom management strategies (Akçayır M. & Akçayır G., 2017); (Pellas et al., 2024). The ability to record pedagogical mistakes made by future teachers without real consequences for students is a valuable result of such use of these technologies.

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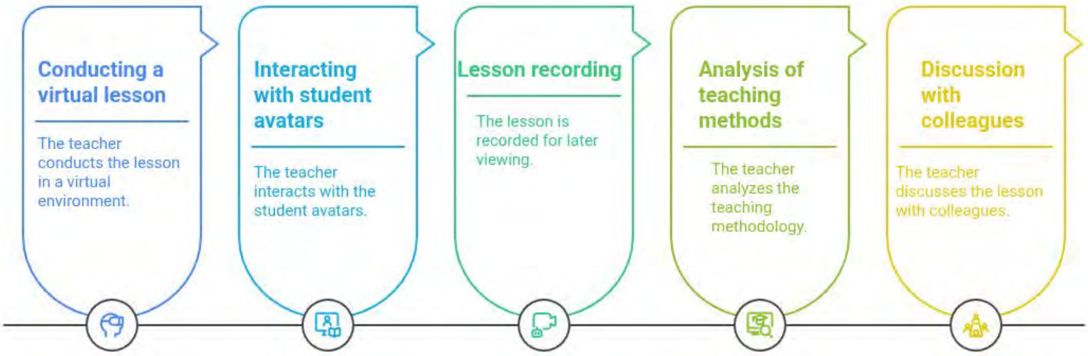

Fig. 3. Virtual classroom model

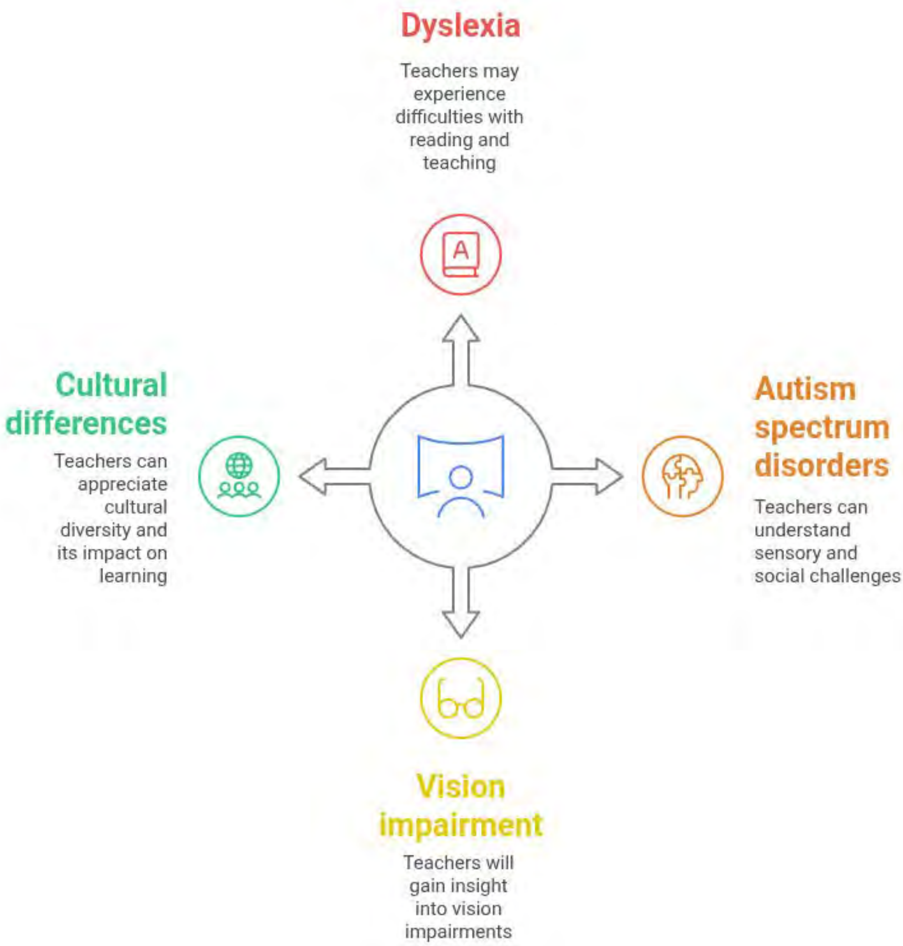

Fig. 4. The potential of virtual technologies for effective learning for students with special educational needs

VR technology allows you to conduct virtual lessons in front of student avatars, record them, and then analyse the teaching methods and micro-learning together with the teacher or colleagues. AR technology is convenient for overlaying hints, diagrams, or visualisations directly during a real (or simulated) lesson (Garzón & Acevedo, 2019). VR is used to simulate physics and chemistry lab work, where future teachers explain the steps of the experiment and safety techniques (Jensen & Konradsen, 2018). AR applications are used to visualise three-dimensional models in geometry and biology lessons during trial lessons. After such lessons, there is an increase in the level of methodological training, the ability to explain complex material, use visual aids, and the opportunity for repetition and analysis, which contributes to reflection and improvement of the pedagogical skills of future teachers.

VR technology allows future teachers to experience what it is like to be a student with special educational needs (e.g., dyslexia, autism spectrum disorders, visual impairments) or a student from a different cultural background (Lave & Wenger, 1991). For example, there are simulations that reproduce the sensory overload experienced by children with autism in the classroom or the reading difficulties of a child with dyslexia. Such experiences promote a deeper understanding of the challenges faced by students, the development of empathy, and the formation of readiness to work in an inclusive environment (Maro & Prosper, 2024).

Virtual tours and observations (VR), such as 360-degree videos and VR tours, allow future teachers to visit various educational institutions, observe lessons taught by experienced teachers, and explore innovative educational spaces without physically moving (Mursion, 2025). For example, higher education students made a virtual visit to a Finnish school, observed a lesson based on the Montessori method, which broadened their professional horizons, provided an opportunity to familiarise themselves with advanced pedagogical experience, and allowed them to analyse different pedagogical approaches and styles.

In addition to using ready-made applications, future teachers also learn to create AR content for their future lessons, for example, to make textbook pages 'come alive,' create interactive posters, etc. (Wikipedia – free encyclopedia); (Freina & Ott, 2015). For example, creating AR markers on a map of the solar system is useful when studying astronomy. When the cursor is hovered over objects on such a map, 3D models of planets and information about them appear. This contributes to the formation of digital competence, media design skills, and the implementation of innovative teaching methods.

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We see the implementation of VR/AR technologies in teacher training in Ukraine in the creation of pilot projects and VR/AR laboratories at higher education institutions, the development and adaptation of VR simulators for practising classroom management skills in line with the concept of the new Ukrainian school, using available AR technologies to visualise teaching materials and develop digital content creation skills in future teachers, adding modules on the use of immersive technologies to teacher training programmes, promoting research into the effectiveness of VR/AR as a means of developing teachers' professional competencies in the Ukrainian context, seeking ways to collaborate with international projects and IT companies to gain access to technologies and content.

The examples of the use of AR technology are highlighted below (Fig. 5).

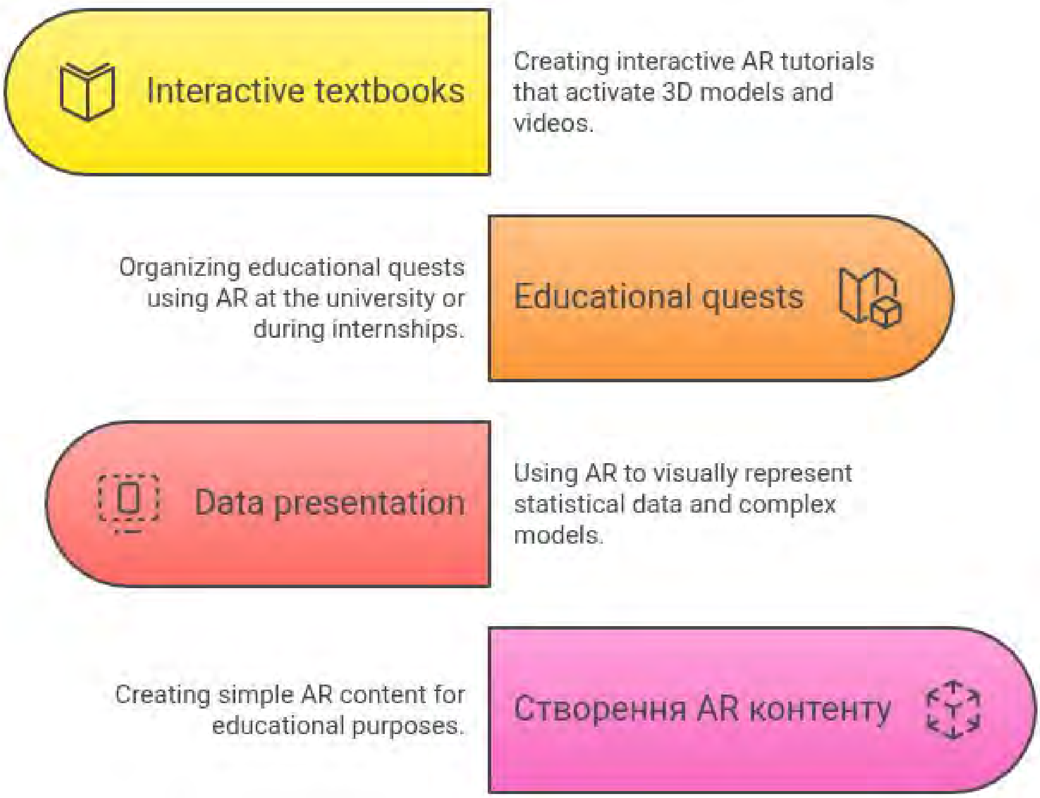

Fig. 5. Ways to use AR tech in education

The first of these is the creation of interactive 'live' textbooks and teaching aids in which AR tags are used to activate 3D models, video explanations of teaching techniques, animations, and links to additional resources. These advantages contribute to better visualisation and a deeper understanding of new material.

Organising educational quests on university premises or during teaching practice using AR to search for information, solve situational tasks, and familiarise oneself with the educational environment.

Using AR to visually present statistical data from educational research, complex pedagogical models, and lesson stages.

Teaching students not only to use ready-made AR applications (such as Google Lens or Artivive), but also to create their own simple AR content, for example, using platforms such as Zappar, Assemblr EDU, etc., which students will be able to apply in their future work with pupils.

When using these technologies, certain methodological rules must be followed.

In particular, the use of AR should be subordinated to a specific educational goal, rather than being merely a technological entertainment.

AR tasks should logically fit into the content of a lecture, seminar or practical class, complementing rather than replacing other teaching methods.

Overloading classes with AR elements should be avoided in order not to create excessive cognitive load and distract students from their main learning tasks.

The auditorium/classroom must be equipped with all necessary devices (smartphones, tablets) and a stable Internet connection. Students must be familiar with and follow the instructions for using the applications.

After completing the AR tasks, it is important to organise a discussion to identify which technology helped achieve the learning objectives and what new knowledge or understanding was gained.

Methodological aspects of virtual reality (VR) integration. VR technology provides unique opportunities for immersive practice and the development of complex professional skills for future teachers. The methodology for using VR should consider the specifics of full immersion and potential challenges.

We suggest considering examples of VR usage methodology. Using platforms to practise strategies for responding to the behaviour of virtual students, as described in studies of analogues such as TeachLivE or Mursion (Mursion, 2025), applying different styles of interaction, and obtaining feedback (Yang et al., 2025); (Pellas et al., 2024).

Conducting fragments of lessons in a virtual classroom, applying various teaching methods and techniques in a virtual audience (Yang et al., 2025).

Simulating problematic situations with parents, students, colleagues; practising public speaking in virtual auditoriums (Yang et al., 2025).

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The use of VR simulations helps students with special educational needs gain experience in developing empathy and understanding their needs (Pellas et al., 2024).

Visiting virtual museums, historical locations, conducting safe experiments in virtual science laboratories (Labster, etc.), which broadens the horizons of students and their subject preparation (Maro & Prosper, 2024).

During the preparatory stage, it is essential to formulate the goal and provide instruction (safety rules and equipment use).

When working in a VR environment, the optimal time frame is 15-30 minutes, which will not lead to cybersickness.

An important stage is receiving explanations: reflection, discussion of experience, analysis of actions, connection with theory, and planning further steps (Pellas et al., 2024). During these stages, the teacher monitors the educational process, helps students comprehend the experience, formulates questions for reflection, and provides feedback.

It is important to choose VR simulations that are realistic, pedagogically sound, and relevant to the learning objective. Interestingly, some studies demonstrate the advantages of not only realistic but also 'imaginary' virtual spaces that allow one to distance oneself from everyday life. Collaboration with teachers during the development of VR applications increases their value and relevance to needs (Pellas et al., 2024).

It should be noted that virtual practice is not intended to replace real pedagogical practice, but rather to complement it, enabling students to prepare for it in a qualitative manner and practise specific skills before working in a real classroom.

The correct use of AR and VR in the training of future teachers, from a methodological point of view, is aimed at developing the professional competencies necessary for successful work in a modern school. Among them, we highlight:

- The ability not only to use, but also to critically evaluate, select and create content for AR/VR, understanding the principles of their operation and pedagogical potential.
- Deepening professional knowledge through visualisation and virtual experiments; practising teaching methods in VR simulations.
- Developing classroom management, communication, and conflict resolution skills, as well as understanding the individual and age characteristics of learners through VR practice.
- Developing empathy and readiness to work with children with special educational needs.

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- Readiness to experiment, innovate, and use technology to create interactive learning environments.
- Ability to analyse one's own experience (especially after VR sessions), evaluate the effectiveness of one's actions and adjust them.

Virtual and augmented reality technologies have significant didactic potential for modernising the training of future teachers. They provide opportunities for immersive, interactive and exploratory learning.

Our practical experience shows that VR/AR has a positive impact on increasing the motivation of higher education students, reducing anxiety before practical training, improving specific teaching skills, and bridging the gap between theoretical training and school reality. VR simulations have proven to be particularly effective for practising responses to complex situations in the classroom.

The implementation of VR/AR also has certain difficulties, such as high cost, technical problems, the need to train teachers, ensuring the pedagogical relevance and scalability of solutions, and the development of high-quality educational content.

For the effective integration of VR/AR into the teacher training system in Ukraine, it is necessary to consider foreign experience, develop our own scientific and methodological developments, create the appropriate infrastructure in educational institutions, and ensure the proper training of both teachers and future educators in the use of immersive technologies in their professional activities.

Augmented and virtual reality are powerful tools for transforming the training process for future teachers. Their effectiveness largely depends on the methods used to integrate them into the educational process. The key methodological aspects are clear goal setting, contextuality, active involvement of students, ensuring a safe space for practice (especially in VR), organising reflection and debriefing, and developing relevant competencies in both students and teachers.

We see prospects for further research in studying the impact of VR/AR on the formation of teachers' professional competencies, comparative analysis of the effectiveness of different VR/AR platforms and scenarios, and the development of methods for integrating immersive technologies into various disciplines of the pedagogical cycle.

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2.3. PRACTICAL EXPERIENCE IN PREPARING STUDENTS FOR PROGRAMMING UNMANNED AERIAL VEHICLES FOR EDUCATIONAL PURPOSES

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The rapid development of technology and the digital transformation of all areas of life, without exception, require a rethinking of approaches to education. In today's world, where innovation is a key driver of progress, it is particularly important to prepare students to work with advanced technologies, in particular, unmanned aerial vehicles (UAVs) or drones. A decade ago, these devices were an element of science fiction, but today they are an integral part of many industries, from agricultural technology and environmental monitoring to logistics, cartography, and security.

The drone industry is developing quickly every year. The areas in which drones are used to solve various tasks are expanding. Due to the dynamic development of artificial intelligence (AI), companies are conducting research and testing innovative technologies, such as unmanned taxis, courier drones, rescue drones, etc. (Brain, 2023). At the same time, in recent years, there has been an increased use of drones in the military sector, with training of FPV (First Person View) drone pilots and scouting drone pilots; they are studying various modifications for drones (both hardware and software), etc.

In such conditions, the introduction of UAVs into everyday life and various fields of professional activity is accelerating. This creates a demand for specialists who are skilled not only in operating drones but also in programming, maintaining, and integrating them into complex systems. The relevant competencies are becoming an integral part of the digital and technical literacy of specialists. Thus, training modern youth to work with educational UAVs, in particular to program them, is in line with the strategic goals of human capital development and is a step towards forming a generation ready for the challenges of the fourth industrial revolution.

In Ukraine, the demand for training young people to work with UAVs has increased due to their use in defence operations (Servetnyk & Snizhko, 2023). The number of educational initiatives aimed at training operators and developers is constantly growing: specialised courses are appearing on various platforms (e.g., Drone School, Dronarium, Prometheus, Kyiv Drone Pilot Academic Programmes, UA Drone School, etc.), combining theory, simulation, and field exercises. Certain aspects of training specialists in the field of design, programming, and practical application of UAVs on a civil and military scale are also being implemented in higher education institutions. In particular, in 2024-2025, the Kyiv School of Economics, NaUKMA, and Kharkiv National University of Air Forces developed and are implementing relevant engineering programs.

Given the current realities and the undeniable relevance of the need to use drones and develop the appropriate skills to operate them, a logical question arises: can drones be used in the educational process to prepare students to work with educational UAVs? The purpose of this study is to highlight the practical experience of training students to program educational UAVs, as well as to identify effective approaches for developing the relevant competencies in students.

An analysis of studies by Giernacki et al. (2022), Petrovič & Verčimák (2023), Balabukh & Balyk (2024), García et al. (2024), Ivanov (2024), Kryvonos (2024), and publications on the programming of educational drones has shown the relevance of this topic in both foreign and Ukrainian educational institutions. Ukrainian researchers and practitioners consider drone programming as a component of STEM education, proposing to study the basics of the drone hardware and software and conduct relevant training (i.e., Balabukh & Balyk (2023), Hansel & Svinnykh, (2024)). Foreign experts are studying both the experience of using drones in education (for example, in robotics classes, for various competitions, etc.) and the development of complex applications that demonstrate the operation of drones using modern technologies but are not adapted for use in the educational process. The studies reviewed suggest using the DJI/RYZE Tello drone model, as this model supports many programming languages, which facilitates its implementation in the educational process in accordance with the programming language used by the teacher.

To avoid ambiguous interpretations of the basic concepts used in this study, let us clarify their definitions. Various practitioners and scholars use terms such as 'drone,' 'UAV,' etc. in relation to this topic, but their studies do not always specify the meaning in which these concepts are used. Therefore, it is worth paying special attention to what is meant when the terms UAV, educational UAV, and drone are used, as these terms can apply to several areas that cannot be used in the educational process.

In the context of this study, the term 'UAV' refers to an unmanned aerial vehicle, namely an aircraft that has no pilot on board and is controlled remotely by a human operator. The term 'drone', in turn, is a fairly common name for UAVs in the civilian sphere. Given the variety of uses, each industry can interpret what a UAV is in its own way. When using drones in the educational process to develop relevant skills that can then be used in a civil, research, or other context, the term 'drone' or 'UAV' will refer to a quadcopter, or a UAV that has four propellers, and in some cases, a hexacopter with six such propellers.

Among the main areas of application for drones, the most prominent are:

- Civilian: aerial photography and video recording, rescue operations, delivery of items, etc.
- Scientific: collection of various data that will then be used in research, for example, research in ecology, meteorology, geology, etc.
- Agricultural: hexacopters are mainly used here, given the need to move around with a large tank for spraying. Currently, drones are actively used in this field and not only help speed up the process of treating plants from pests but also help collect various data on the condition of plants and the field in general.
- Military: drones are mainly used for reconnaissance, target detection, and other tasks that minimise human casualties.

When considering drones in an educational context, it should be noted that they can be used as a platform for developing programming skills while simultaneously exploring the specifics of drone control, the limitations of their hardware and software characteristics for performing certain tasks and studying the issue of expanding drone functionality. Currently, the use of drones in education is possible because more companies are beginning to pay attention to educational drones and develop this area. One such company is DJI, which, in collaboration with RYZE, produces the RYZE/DJI Tello series of drones, the main feature of which is their programmability.

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In the context of education, educational drones are considered robotic systems whose purpose is the practical application of programming to solve specific tasks. This approach allows students to consider various approaches to creating an application for working with a robotic system, try to optimise their code to improve the application's performance, and gain experience working with documentation and various additional services that can extend the application's functionality. In the process of this study, the DJI Robomaster Tello Talent training drone (third-generation DJI Tello) was used, which has the most advanced functionality compared to previous models in the series.

Compared to other quadcopters for civilian use, educational UAVs do not have powerful technical characteristics, but these characteristics are sufficient enough for training, since the main task of educational drones is to teach students how to control a drone and demonstrate the practical application of programming by developing applications for drones. It is this focus on the educational component that makes educational drones relatively affordable compared to professional ones, which have better cameras, more powerful motors, advanced software features, etc. For clarity, let's look at the characteristics of the drone used in this study, specifically the DJI Robomaster Tello Talent (Fig. 1):

Figure 1. UAV DJI Robomaster Tello Talent
(Source: URL: https://ek.ua/ua/DJI-ROBOMASTER-TT.htm)

- Weight: 87 g.
- Camera: 5 MP.
- Photo/video quality: 720p/750p.
- Maximum flight altitude: 30 m.
- Maximum flight range: 100 m.
- Maximum speed: 8 m/s.
- Maximum flight time: 13 minutes.
- Maximum flight time with expansion module: 8.5 minutes.
- Sensors: infrared altitude detection, barometer, downward view sensor.

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As for programming languages supported by the drone, there are no restrictions. A prerequisite for operation is the ability to create a server that will work with the UDP (User Datagram Protocol). The most common programming languages for this drone are Scratch, Python, web development languages (HTML/CSS/JS/Node.js), Swift, and Kotlin.

Analysing the mentioned characteristics and comparing them with other drones, such as DJI Mavic or Air, we can conclude that the most important characteristics of an educational drone are support for programming languages (or programming environments) and the availability of various sensors, which can be used to obtain the necessary data for programming corresponding events. Support for different programming languages allows teachers to adapt the curriculum to the programming language that students have previously studied.

One of the most common educational tasks in drone programming is creating a drone control application. This task can be adapted to the age group of students and the programming language they are learning. For example, for grades 5 and 6, block programming using Scratch can be used; for grades 7 to 9, it can be the Python programming language; for grades 10 and 11, it can be the development of a web application using HTML/CSS/Javascript web technologies. In addition, a major advantage of the Tello series of educational drones is the availability of a drone control app from the manufacturer, which allows students to familiarise themselves with the basic functions of drone control before moving on to developing their own application.

To develop and improve the skills of drone control application development, students of the Kyiv Junior Academy of Sciences (Kyiv, Ukraine) who studied the course 'Computer Engineering. Software Engineering' section during 2022-2024 offered the following projects:

- Project 1. Development of a basic web application for drone control.
- Project 2. Development of a module for drone control using a gamepad (studying documentation for working with relevant technologies, working with services for configuring the gamepad, implementing new functionality in the basic web application).

Project 1.

The goal of this project is to teach students how to develop a basic web application for controlling a drone. The project consists of the following stages:

- development of the client and server sides of the application;
- control panel;
- video streaming from the drone.

During the development of the application, students learned the basic steps for creating a server using technologies and libraries such as node.js, express.js, and socket.io. The latter library is a key technology that serves as a 'bridge' between the client and the server for sending commands to the drone. On the client side, students work with standard web technologies, namely HTML/CSS/Javascript, creating the application interface using modern markup technologies (flexbox and grid), adapting the application to different screen resolutions.

Special emphasis is placed on the client side on processing commands for further execution by the drone, which is then sent to the server. The project involves the creation of various JavaScript modules that show students how to optimise program code using special HTML element attributes. In addition, keyboard control support is provided, approaches to working with various data entry fields that can be accepted as arguments to the drone command are proposed (for example, setting the colour of the extension module's light, adjusting the drone's speed, etc.), and a function for taking pictures from the drone's camera is additionally implemented. As a result of their work on the project, students develop a basic web application for controlling a drone, which may look like this (Fig. 2):

The students used laptops to develop the educational UAV control application. Desktop computers can also be used, but the main requirement is the presence of a Wi-Fi module, which is necessary to connect to the drone's access point. In terms of the choice of technologies for developing the drone control application, web technologies were chosen, namely HTML/CSS/Javascript for the client side and Node.js for the server side. Throughout the learning process, students gradually improved the application interface, each time adding new functionality, such as a control panel for the expansion module (available only for the DJI Robomaster TT model), video streaming from the drone, and more.

Given the specifics of working with the DJI Tello drone, students can examine the architecture of the application, which consists of client and server components. The chain of interaction between the drone and the control device (in this study, it is a laptop or computer that must have a Wi-Fi module) looks like this: when the drone is turned on, the built-in Wi-Fi access point is launched, to which the control device must connect. Next, an application with a server and client part must be launched on the control device.

The application is divided into these two parts in order to separate the functions for working with the drone and more efficient code management, where the client

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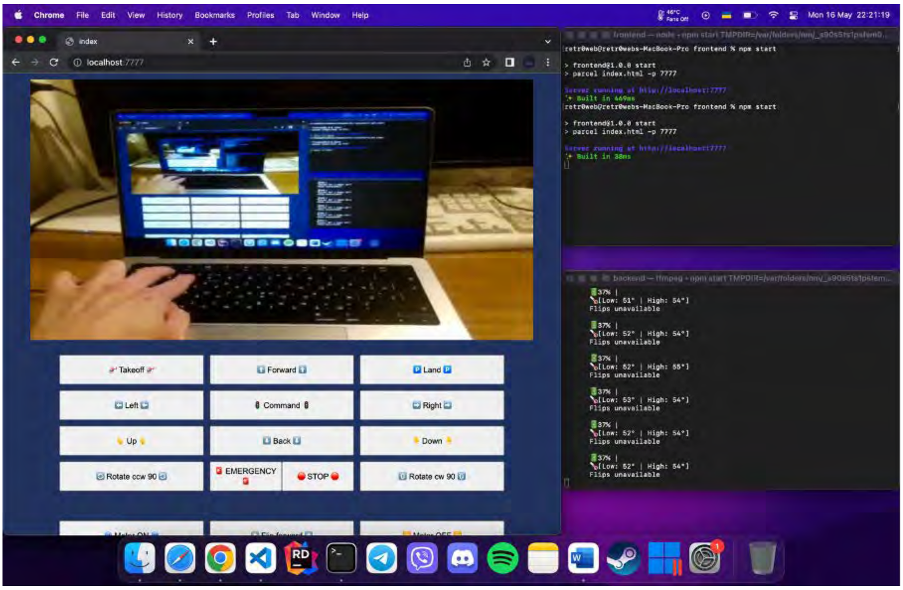

Figure 2. Example of the interface of the developed application for drone control (Sourse: own elaboration)

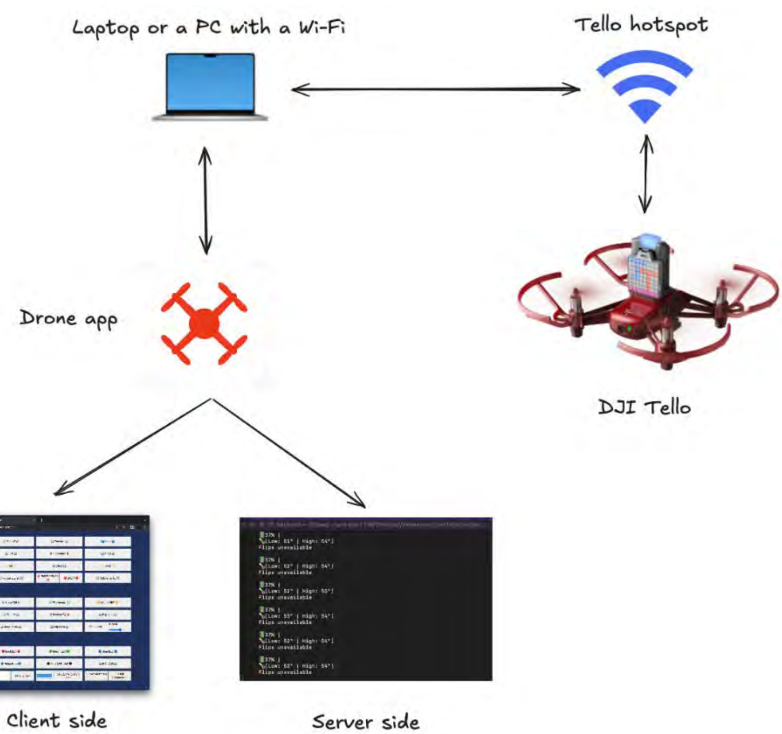

Figure 3. Diagram of the application's operation using a drone (Source: own elaboration)

side can be customized to the student's needs, in a way that is convenient for the student to use. For example, the control panel may have a block with buttons that execute certain commands (movement, special modes, speed modes, etc.), and the server side will receive a command from the client side and send it to the drone (Fig. 3).

At the end of the project, students are expected to have developed the following skills:

- Create the client and server sides of a web application for controlling a drone.
- Create a control panel and configure it to use the corresponding commands.
- Implement alternative control methods (e.g., using a keyboard).
- Create a server for streaming video from the drone and use a library to display the video in the client part of the application.

Project 2.

The goal of this project is to teach students how to use specific hardware to improve the functionality of a drone control application. The project consists of the following stages:

- Studying the documentation for working with the gamepad and the web application.
- Working with services for debugging the gamepad.
- Developing and implementing new functionality (module) in the basic web application for drone control.

This project provides students with the opportunity to familiarise themselves with documentation and services that will help them develop a module for an application that uses a special controller to control a drone. The proposed control method is similar to the control method used for civilian drones, such as the DJI Mavic series. This control approach provides students with the relevant knowledge and skills that are used for almost all types of drones, even FPV drones.

To control the educational drone, we suggest using a gamepad (Fig. 4) as a special controller, such as the controller for the PlayStation or Xbox game console, since these devices can be connected to a web application. In addition, they have a sufficient set of buttons, each of which can be assigned a corresponding command to control the drone.

While working on developing a module for connecting a gamepad to the app, students explore how to program a gamepad to work in a web application based on studying the relevant documentation (MDN Web Docs, 2025) and also learn how

Figure 4. Xbox Wireless Controller (Gamepad)
(Source: URL: https://www.xbox.com/en-gb/accessories/controllers/xbox-wireless-controller)

to use services to check the correct operation of the gamepad using the Gamepad tester website (Hardwaretester, 2025). After familiarising themselves with these resources, students will be able to create a module that can be configured with the proper control parameters and assign the corresponding commands to the buttons (for example, button A - drone take-off, button Y - drone landing).

The drone will be controlled using two sticks with two coordinate axes, which will be used as values in a specific drone command. This control method addresses a certain drawback of the DJI Tello, specifically that commands intended for movement are executed sequentially, which limits the simultaneous execution of certain actions. However, using the command and values from the sticks as parameters for this command allows the drone to perform complex manoeuvres. At the end of the project, students are expected to have developed the following skills:

- Study documentation on web technologies to expand the functionality of the drone control application.
- Use services to configure and test the gamepad.
- Connect and use the controller with the drone control application.
- Configure commands for the gamepad buttons according to the needs.

Modern technologies are constantly evolving, so there will be more and more ideas for developing drone control applications in the process of solving applied problems every year. Currently, there is also rapid development in the field of artificial intelligence, which can also be used in the process of programming drones in accordance with the technical specifications for application development.

Thus, teaching drone programming not only demonstrates the practical application of programming skills but also allows for the implementation of problem-based learning principles, which contributes to the formation and development of the following in students:

- Algorithmic and logical thinking (in the process of developing algorithms for the drone to perform specific tasks).
- System analysis skills (in the process of understanding the interaction of UAV hardware and software components).
- Creativity and innovation (in the process of finding non-standard solutions, for example, to optimise the operation of drones).
- Teamwork skills (in the process of joint project development and exchange of experience).

These skills are fundamental for a successful career in future professions related to the use of drones, such as UAV operator, drone development and programming engineer, unmanned systems integration specialist, drone data analyst, and many others.

Given the current challenges and technological developments, drones will be increasingly used in various industries, which will ensure demand for educational drones and, in turn, stimulate their use in the educational process.

This study shows that training students in programming educational UAVs is not only expedient but also necessary. This will contribute to the development of technical education, increase the level of competence in STEM areas, and strengthen the state's potential in the development and use of innovative technologies.

At the time of this study, the authors did not find any generalised approaches to building a course structure for teaching students to program UAVs, nor did they find any systematic information on which modern approaches to drone programming can be used to teaching school students to explore and use relevant services and libraries that will help them solve drone control tasks and contribute to solving complex problems in this field (e.g., the use of computer vision technologies). Thus, this area of further research is important and promising.

Based on the results of the study, the authors developed and proposed a module for teaching students how to control drones using modern programming approaches, which can be used in a school programming course (Movchan, 2022; Movchan, 2023). In addition, teaching materials have been prepared that can be used by teachers to organise and implement complex projects with students using modern approaches to drone programming (Movchan, 2022; Movchan, 2023). Such projects allow students to acquire knowledge and develop skills in working with various documents and services, which will further improve the functionality of existing drone control applications. Prospects for further research include involving students in the development and implementation of projects such as:

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- Programming a swarm of drones, researching the specifics of developing an application to control different numbers of drones to perform specific tasks, such as drone shows.
- Simulating rescue operation scenarios, where students can become more familiar with event programming and the application of computer vision technologies.
- Creating applications for autonomous drone control. An example of such an application is a program for controlling a drone that captures video and focuses on a specific object or person and constantly follows it.
- Creating an application using Internet of Things technologies, which can be implemented with another robotic system from DJI, namely the DJI Robomaster S1 system.

Despite the promising prospects for the development of this industry as a whole, the following issues remain controversial:

- The choice of the age group of students who should be taught to program drones, which also depends on their previous programming training.
- The selection of technologies for programming drones depends on the age category of students (for example, whether it is appropriate to use the Python programming language as the main language for programming drones in middle school (grades 6 to 9), etc.).
- The possibility of applying the acquired knowledge and skills to other platforms.
- Whether it is necessary to introduce drone operation and programming training in general education schools or only in schools (classes) with a natural science, mathematics, and/or engineering profile.
- The goals and content of teaching students how to work with drones and program them (which also depends on the answers to the previous questions).
- Whether it is necessary to introduce topics related to working with drones and programming them into the training of future teachers and in which specialties (depending on the answers to the previous questions), etc.

However, the relevance and the timing of introducing drone operation and programming training into Ukrainian schools is beyond doubt. The above emphasises the importance of integrating educational UAV programming into the curricula of educational institutions. This will not only provide students with the necessary knowledge and skills for their future professions but will also contribute to the development of Ukraine's innovative potential as a whole. Further research by the authors will be directed towards resolving the issues outlined above and related issues.

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2.4. USING VIRTUAL REALITY IN COMPUTER SCIENCE LESSONS ON THE EXAMPLE OF DRONE CONTROL EMULATORS

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Virtual and augmented reality technologies are increasingly being used in the educational environment, opening up new opportunities to improve the learning process and enhance the quality of knowledge acquisition. Their introduction is primarily aimed at creating conditions in which students are not limited to theoretical material but can learn knowledge through active practical activities, which is extremely important for modern education. Virtual and augmented reality provide immersion in a learning situation by simulating real-world conditions, which greatly facilitates the understanding of complex topics and helps to develop professional skills.

The successful implementation of such technologies requires coordinated action by all participants in the educational process. Students are the main consumers of educational services, who, as members of the digital generation, are accustomed to the constant presence of technology in their everyday lives. For them, the integration of modern digital tools into learning is not only attractive, but also quite expected. They want to see innovative solutions in the educational environment that meet the challenges of the times.

At the same time, teachers play an extremely important role as they are the leaders of innovation in the learning process. The effective use of virtual and augmented reality requires them to have appropriate methodological training and a willingness to change teaching approaches. It is teachers who have the necessary experience and understanding of the specifics of perceiving educational material, which allows them to reasonably determine the feasibility of using interactive technologies at certain stages of learning. Their active participation in the implementation of digital educational tools is the key to the effectiveness and efficiency of educational changes.

It is also necessary to take into account the position of educational institutions that play a key role in expanding the use of virtual and augmented reality in education. They should not only implement these technologies at the experimental level, but also integrate them into curricula at the systemic level. It is important to create the conditions for the widespread use of such solutions, in particular through the purchase of the necessary equipment, the development of training courses and staff training. In order to achieve high quality education, it is important not only to ensure access to the latest technologies, but also to effectively integrate them into the learning process, making them an integral part of educational practice.

Particular attention should be paid to the role of hardware, software and technology solution providers. They shape the market for educational technologies, determining the direction of their development. Innovative devices, software products, and interactive platforms they create directly affect the effectiveness of virtual and augmented reality in the educational process. Specialised events, the development of new products, and the improvement of existing solutions help to expand the possibilities of digital learning.

However, the most important aspect of implementing these technologies is not the devices or software products themselves, but their role as tools to improve the learning process. The main purpose of using virtual and augmented reality is not only to introduce innovations, but also to increase students' knowledge, facilitate the learning of complex topics and promote their professional development. The educational process is dynamic and constantly changing, so the integration of the latest technologies should be aimed at creating conditions for high-quality and effective learning that meets the current challenges and requirements of society.

The relevance of the study is due to the rapid development and integration of virtual reality (VR) and unmanned aerial vehicles (drones) technologies into various spheres of life, including education. Modern students expect to use the latest technologies in the learning process. At the same time, the study of computer science requires practice-oriented approaches, and drone control is becoming an increasingly popular skill. The relevance of the study lies in the need to find effective, safe, and cost-effective methods of teaching drone control. The use of VR emulators can solve the problems of the cost of real equipment, the risk of damage, and space limitations, providing a realistic environment for practicing piloting skills and understanding the principles of UAV operation as part of school computer science lessons.

An analysis of scientific sources shows a high level of interest in the introduction of augmented reality in the educational process, which is confirmed by numerous studies both in Ukraine and abroad. In particular, the work of Lucena-Anton et al. (Lucena-Anton, Fernandez-Lopez, Pacheco-Serrano, Garcia-Munoz, & Moral-Munoz, 2022) confirms that the use of augmented reality technologies activates students' cognitive activity, creating an exciting, playful and comfortable learning environment. Such technologies help to establish effective interaction between students, encouraging them to solve problems together, conduct reasoned discussions and develop critical thinking. Students note that augmented reality is an effective tool for learning, particularly in pedagogical disciplines, as well as for modelling and resolving conflict situations.

Similar results are presented in the works of Singh et al. (Singh, Kaur, & Gulzar, 2024), where it is noted that augmented reality allows for an organic combination of digital content with the real world, which greatly facilitates the understanding of complex concepts. In addition, these technologies provide teachers with the opportunity to diversify teaching methods, increasing student engagement and motivation to actively participate in learning. Scientists note that the use of augmented reality helps to build confidence in one's own knowledge, a positive attitude to the educational process, and an increase in the overall level of satisfaction with learning. The integration of augmented reality into the teaching of natural and technical subjects, such as physics, mathematics, biology, and history, is particularly effective, where visualisation plays a key role in learning.

Ukrainian scientists also recognise the prospects of using augmented reality in education, although the number of domestic studies in this area is still inferior to international ones. In particular, S. Lytvynova, O. Burov, and S. Semerikov (2021) emphasise that the flexibility of this technology allows it to be used both for individual learning and in group work, which contributes to the personalisation of the educational process in accordance with the needs of individual students. Augmented reality can be successfully applied at all levels of education, which is evidence of its universal nature.

Scientists note the particular value of AR technologies in distance learning, as they provide access to educational material regardless of the location of students. The systematic implementation of augmented reality contributes to the development of digital literacy and the formation of key professional skills required in the modern digital society. Integrating AR into educational materials not only expands the content of educational content but also increases its didactic effectiveness. This is especially important when studying complex scientific concepts, historical processes, or natural phenomena, as it promotes deeper learning.

A study (Semerikov, Lytvynova, & Mintii, 2020) on the domestic experience of introducing augmented reality into the educational process confirms its significant potential for increasing motivation to learn, developing cognitive abilities and learning in the format of interactive interaction. The study analysed modern AR/VR platforms, in particular, the feasibility of using Unity, Visual Studio, Google VR, and Vuforia tools for educational purposes. Particular attention is paid to the development of an optional course dedicated to virtual and augmented reality. This course aims to familiarise students with both the theoretical foundations of AR and the practical skills of creating innovative educational products.

The curriculum covers a wide range of topics, from building user interfaces to setting up geo-positioning systems and creating educational materials using platforms such as Vuforia. Feedback from participants showed a high level of interest in augmented reality technologies, their desire to continue their studies in this area, and confidence that the knowledge they acquired would be useful in their future professional activities.

Among the suggestions for improving the course, the most frequently mentioned was the need to increase the amount of practical training, which would allow students to better master the material through real-life projects. The expediency of integrating the course with STEM disciplines was also emphasised, which would provide a link between theoretical knowledge and engineering and scientific practices.

According to L. Tarangul and S. Romaniuk (2022), augmented reality is becoming particularly important in the field of information technology. Unlike virtual reality (VR), which completely immerses the user in an artificial environment, augmented reality (AR) combines the real world with digital objects, creating a new level of interactive educational experience. This approach contributes to the formation of a personalised interaction between the student and the learning content that corresponds to the individual style of knowledge acquisition.

The researchers point out that the lack of need for specialised laboratories makes learning with AR applications mobile and accessible anywhere with a smartphone or tablet. Modern mobile devices have sufficient technical characteristics to support

AR applications. There is a wide range of platforms on the market, including Vuforia, ARToolKit, Kudan and other libraries that provide tools for creating educational AR solutions, combining various multimedia elements and supporting work on most popular devices.

In addition, as shown in other studies, augmented reality technology can be an effective tool for modelling various practical actions and techniques. This opens up the possibility of practicing professional skills in a safe and controlled learning environment.

The purpose of this paper is to study the theoretical foundations and practical aspects of using virtual reality, in particular drone control emulators, as a teaching tool in computer science lessons, as well as to justify the feasibility of their implementation in the educational process.

Virtual reality is a modern trend in the use of computer technology that allows the user to immerse themselves in an artificially created world that exists only in the memory of a machine. However, true VR is not just a 3D image or 360-degree video, but a complex system that simulates reality through full sensory immersion. Just a few years ago, such systems were only part of experimental laboratories, such as NASA Ames, where the first immersive environments with primitive vector graphics were demonstrated in 1987. However, even then, they conveyed the key principle of VR - the feeling of being in another world, regardless of photorealism.

In general, the term “virtual reality” refers to an interactive technology that gives the user a sense of real presence in a simulated space. This is achieved not only through visual effects, but also through the synchronisation of movements, spatial sound and tactile feedback. For example, early systems such as the Placeholder project (1993) used wing movements to move as a virtual crow, and in the Osmose installation (1995), participants controlled the environment with their breath. Such solutions emphasise that VR is primarily about action, not passive observation.

The main hardware element of a VR system is a high-performance personal computer, but specialised devices play a key role. Modern VR helmets, such as the Oculus Rift or HTC Vive, do not just display stereo images - they provide binocular vision (stereopsis), where each eye sees slightly different frames, simulating depth perception. In addition, gyroscopes and accelerometers track even micro-movements of the head, and spatial sound adapts to the user’s position. For example, if a virtual sound source is on the left, when you turn your head to the right, its volume and timbre automatically change to maintain the illusion of localisation.

Tactile devices, such as touch gloves or suits, expand the boundaries of interaction. The Placeholder project used prototypes of trackers for both hands, as the one-armed Dataglove limited the feeling of full embodiment. Today, technologies such as haptic feedback allow you to feel the "touch" of virtual objects, such as resistance when you press a button or vibration when you hit it. Even systems that simulate temperature or pressure are being developed, although this is still an experimental area.

The prospects for VR go far beyond gaming. In medicine, virtual environments help train surgeons or treat phobias through immersive therapy. In education, students can "visit" historical events or study molecules in 3D space. Engineers use VR to design complex structures, and in the future, virtual offices may completely replace physical workplaces. For example, Microsoft Hololens technology (developed by graduates of the Art Centre College of Design) shows how AR/VR hybrids can integrate digital objects into the real world for collaborative work.

The most revolutionary may be neural interfaces that allow you to control VR without physical devices. Experiments with BCI (Brain-Computer Interface) have already demonstrated the ability to move in virtual space with the power of thought. This opens the door for people with disabilities, as well as for fundamentally new forms of art and communication.

Virtual reality is not just an "extended screen" but a new medium that redefines the concept of presence. From the primitive vector worlds of the 1980s to modern multi-sensory systems, VR continues to evolve, combining technology, neuroscience and creative design. And while today we wear helmets, in the future VR may become an extension of our consciousness.

Virtual reality (VR) is becoming a powerful tool in modern education, transforming traditional teaching methods and opening up new opportunities for students and teachers. One of the key benefits of VR is its ability to provide visualisation and interactivity, making learning more engaging and effective. Through virtual simulations, students can explore complex concepts such as cell structure, cosmic phenomena, or historical events in detail in three dimensions, which greatly improves their understanding of the material. For example, instead of passively reading about the solar system, students can "visit" it with a VR helmet, making learning more vivid and memorable.

In addition, VR helps to increase students' focus and engagement, as the virtual environment minimises external distractions. This allows learners to be fully immersed in the learning process, actively interacting with the content. For example, apps such as Google Expeditions allow you to take virtual tours of museums or historical sites, and Labster allows you to conduct complex laboratory experiments without the need to use real equipment.

An important advantage of VR is also safety, as virtual simulations allow you to model dangerous or expensive situations without any risk. Students can conduct chemical reactions with hazardous substances, practice flying an aircraft, or even find themselves in conditions that cannot be recreated in the classroom, such as the middle of a volcano or on Mars. This not only keeps them healthy, but also pushes the boundaries of the learning experience.

Studies show that VR improves memorisation and understanding of material through the effect of "learning by doing". When learners become participants in events or experiments, the information is better absorbed and retained in the memory for longer. This is especially useful for learning complex topics such as molecular biology, physics, or history, where abstract concepts can be visualised and "felt" in practice.

VR also opens up access to unique learning opportunities that would otherwise be unattainable. Students from anywhere in the world can visit famous museums, take part in virtual archaeological excavations, or observe rare animals in their natural environment. This is especially true for schools with limited resources, where organising real-life excursions or experiments is often difficult.

In addition, VR allows you to adapt learning to the individual needs of students, including children with special educational needs. For example, students with autism can practice social skills in a controlled virtual environment, and children with disabilities can "visit" places that would otherwise be inaccessible to them.

The interactivity and gaming elements of VR also increase student motivation, making learning a fun experience. Apps such as Minecraft Education or HistoryMaker VR allow students not only to observe but also to actively participate in the creation of content that develops creativity and critical thinking.

However, to fully implement VR in education, a number of challenges need to be overcome, such as the high cost of equipment, the need for teacher training, and the development of high-quality educational content. Nevertheless, Ukrainian schools are already taking the first steps in this direction by testing VR technologies in classrooms and libraries.

Virtual reality significantly expands the boundaries of traditional education, making learning more interactive, safe, and accessible. It not only improves the quality of learning, but also prepares students for life in the digital world, where technology plays a key role. The future of education will undoubtedly be closely linked to VR, and it is worth investing in its development now to provide students with the most advanced learning opportunities.

Table 1.

Advantages and opportunities of VR in education

Advantage	Specific opportunity	Example
Visualisation	3D visualisation of complex concepts and processes	Learning anatomy through 3D organ models, travelling through the solar system
Interactivity	Direct interaction with learning content	Virtual experiments in Labster, «touching» historical artefacts in digital museums
Safety	Modelling dangerous or expensive situations	Chemical experiments with toxic substances, evacuation training
Memorisation	The effect of «learning by doing»	Simulation of historical events as a participant, VR excursions to ancient civilisations
Accessibility	Overcoming geographical and physical limitations	Visiting the Louvre or the Great Barrier Reef without leaving the classroom
Individualisation	Adaptation of content to the student's level	Personalised simulations for children with special needs
Motivation	Gamification of learning	Mastering the material through the InMind 2 game (modelling emotions)
Practical skills	Training of professional actions without risks	Virtual medical operations, pilot training
Creativity	Ability to create your own virtual projects	Designing 3D models in Tinkercad VR, creating virtual exhibitions
Interdisciplinarity	Integration of knowledge from different subjects	The Volcano project (geography + chemistry + physics) in the VR environment

Drones are not only entertaining, but also become a powerful tool for studying various disciplines, from science to art. They help broaden students' horizons, motivate them to learn and make lessons more interactive. The use of modern technology in the educational process has long been a necessity, as young people live in a world where technology is developing at a rapid pace, and education must adapt to these changes.

One of the main advantages of drones at school is their ability to demonstrate complex concepts. For example, in physics classes, the laws of aerodynamics, gravity, and flight control principles can be taught. Students have the opportunity not only to observe the processes, but also to experiment by changing flight parameters and analysing their impact. This approach makes the learning process more engaging and helps students better understand how physical laws work in real life. In addition, the use of drones in the educational process can help to increase students' interest in technical sciences and motivate them to pursue further studies in engineering and aviation.

Geography and biology also benefit from the use of drones. Students can explore landscapes, analyse environmental features, and even conduct nature observations. Drones can be used for mapping, studying rivers, forests, and other ecosystems. For example, as part of environmental projects, students can assess the state of the environment and identify pollution problems. This helps to develop ecological thinking and a responsible attitude towards nature. Many modern environmental problems require detailed analysis and monitoring, and drones can become an indispensable tool in this process.

Computer science classes get another interesting opportunity - drone programming. By learning the basics of coding, students can learn how to create algorithms for automatic flight control. This not only develops logical thinking, but also introduces them to real-world technologies used in robotics, artificial intelligence and aviation. Thanks to such tasks, children acquire practical skills that can become the basis for a future career in the IT field. Programming drones helps to understand the basic principles of artificial intelligence and automated systems, which is extremely important in today's digital world.

Even the humanities can be made more interesting with drones. For example, history classes can conduct virtual tours of historical sites using aerial footage. Literature or art classes can also include creative assignments involving video projects or artistic imagery using drones. For example, students can create documentary videos about places of interest in their region or experiment with cinematic techniques. This allows them to combine technology with creativity, developing both analytical and creative thinking.

In addition to academic disciplines, drones promote teamwork and critical thinking. Collaborative projects, where students work together to plan tasks and analyse results, help strengthen collaboration and problem-solving skills. This is especially important in today's world, where teamwork is a key skill. In addition, the use of drones can develop leadership skills, as students have to take responsibility for certain aspects of a project when working in teams. In many fields of activity, the ability to work in a group, coordinate the efforts of different people, and solve problems together is now valued.

However, introducing drones into the school process requires some preparation. Appropriate guidelines for teachers, curricula, and safety rules need to be developed. The use of drones requires adequate space, and schools should be able to organise flights without risking students. The cost of such devices should also be taken into account, although with the development of technology, prices for basic models are becoming more affordable. To overcome financial barriers, you can use grant programmes or cooperate with local companies that are interested in developing STEM education.

Attracting additional resources and partners can help to speed up the introduction of drones into the educational process.

In summary, drones open up great prospects for education. They make learning fun, promote the development of technical and creative skills, and allow you to apply the knowledge gained in practice. Thanks to , with the right approach, their use in schools can become not just an interesting addition, but an important element of modern education. Further improvements in technology and teaching methods will only expand the possibilities of using drones in the learning process, contributing to an interactive and dynamic educational environment. As technology continues to evolve, drones can play an even greater role in educating future generations, building the skills needed for a successful career in the modern world.

An unmanned aerial vehicle is lifted by the rotation of propellers, which generate lift. One of the most common types of drones is a quadcopter.

A quadcopter is an aircraft equipped with four engines with propellers attached to their shafts. Their rotation generates lift, which allows the drone to take off.

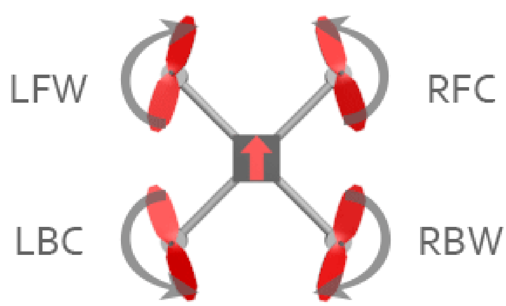

Fig.1 Direction of rotation of the screws and location of the motors.

The quadcopter is controlled by changing the power of the motors. To move forward or backward, the speed of the front and rear propellers changes. For example, to move forward, the power of the rear motors increases, and the front motors slow down, which also causes a slight tilt of the drone.

Turning works on a similar principle. When tilting to the left, the right motors rotate faster and the left motors rotate slower. To turn around, it is enough to change the speed of the diagonally spinning propellers.

Modern quadcopters are equipped with additional sensors and detectors, such as a barometer, GPS, or cameras for obstacle detection. This allows you to program the flight depending on the surrounding conditions.

The presence of sensors and special obstacle detection sensors significantly helps both beginners and experienced pilots avoid accidents. You won't find such sensors on budget models, but their presence in expensive equipment is more than justified. Depending on the settings and number of these sensors, the drone can either fly around an obstacle or stop at a safe distance from it.

Quadcopters usually support at least two flight modes: manual and autopilot.

Manual mode - in this mode, the control of the quadcopter is completely dependent on the operator, none of the internal systems stabilise or control the quadcopter. This is the most difficult mode, recommended for experienced users.

Stable Flight Mode/Space Orientation Mode - this mode uses an accelerometer to help stabilise the quadcopter. This mode is suitable for most beginners who are just starting to learn the basics of flying a quadcopter.

Altitude Hold Mode - In this mode, the quadcopter automatically maintains a set altitude using a barometer or other sensors. This simplifies control and allows the operator to focus more on the direction of flight rather than altitude control. The mode is useful for aerial photography and flying in difficult conditions.

Stabilisation with GPS - quadcopters with built-in GPS can use this mode. It is designed to capture high-quality videos and photos, as it allows you to keep the quadcopter in place. With the help of GPS, you can also perform autopiloting, holding the altitude and direction of flight.

As for how they can be controlled, there are a variety of ways to do so, allowing them to be used in a variety of areas - from entertainment and amateur filming to military and scientific purposes.

One option is to use a remote control that works on radio frequencies or WI-FI. The remote control is convenient via for real-time operational control, but it has a limited range, and in conditions of radio interference, the connection may be lost.

The most advanced control method is a fibre-optic connection. This method is used in professional and military drone models because it provides extremely fast data transmission speeds, minimising signal delay, and allowing the drone to respond instantly to changes in control, which is critical for complex flights. Another advantage is that it is not subject to electromagnetic interference and it is almost impossible to intercept data transmitted via fibre optics.

The main disadvantage of fibre optic control is its limited mobility. Since the quadcopter must be physically connected to the operator by a cable, this makes it impossible to use this method for long-distance flights. However, in certain conditions, for example, when exploring dangerous objects or in underground tunnels where radio communication does not work, this method is indispensable.

As for software, it is an important component of unmanned aerial vehicles (UAVs), as it guarantees autonomy, stability and efficient performance of tasks. The most popular drone control platforms include PX4 and ArduPilot (Colomina, & Molina, 2014).

PX4 is an open-source flight software stack that is primarily maintained by the Dronecode Foundation. It is known for its emphasis on accuracy, reliability, and modularity. Among the main features of PX4 is its modular architecture, which allows users to customise and extend the stack's functionality. Developers can create and integrate their own modules, sensors, or control algorithms, making it highly adaptable to different platforms and drone use cases.

The PX4 also provides advanced autopilot functionality, including support for multiple flight modes, obstacle avoidance, and even GPS-free navigation. These features make the PX4 an ideal choice for professional applications such as surveying, mapping, or search and rescue.

The PX4 is widely used in the commercial drone industry and is trusted by leading manufacturers. Its stability and accuracy have made it a popular choice for companies that need reliable software for their drones. The drone APIs allow you to write code to control and integrate with PX4-based vehicles without needing to thoroughly understand the vehicle and flight stack details or think about critical safety behaviours. In particular, our work has considered two of them in more detail.

ArduPilot, in turn, is another open source flight software stack that focuses on versatility and strong community support. It has been in development since 2007, and during this time, a large and active community of users has formed around it.

ArduPilot is compatible with a variety of drone hardware, including fixed wing aircraft, multirotors, and ground vehicles. This versatility makes it a popular choice among hobbyists, researchers, and professionals alike. This software has extensive documentation and is supported by an active online community. Users can find tutorials, guides, forums, and other resources to help them complete their drone projects.

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It also includes a user-friendly ground control station (GCS) called Mission Planner. This intuitive interface makes it easy to set up a flight stack and plan missions.

The above programs work using MAVLink (Micro Air Vehicle Link), a protocol developed in 2009 that allows you to send commands to the flight controller firmware. The protocol is distributed under the LGPL licence as a module for the python programming language.

Thanks to this protocol, both programs provide high-level APIs that allow you to autonomously control the drone using the programming language of your choice.

For ArduPilot, the DroneKit package is particularly popular. It's considered a powerful tool because it allows you to control your drone using simple functions without diving into the specifics of low-level hardware management. The downside is that it is considered somewhat outdated.

In PX4, the main high-level interface for vehicle management is the MAVSDK. It functions similarly to ArduPilot's DroneKit. And it is better in almost all respects: features, speed, support for programming languages, maintenance, and so on.

It is recommended to use MAVSDK because it is more intuitive, easier to learn, and supported on more operating systems, including less productive hardware.

However, if you already have experience with ROS or can use its out-of-the-box integrations (for example, for computer vision tasks), this option may be preferable. In general, ROS is usually the best choice for applications that require extremely low latency or deeper integration with the PX4 than is possible with MAVLink.

Drone control is a complex process that combines theoretical knowledge, technical aspects, and practical skills. It is based on the integration of hardware components, software, and flight modes that ensure stability, manoeuvrability, and mission accomplishment. It is important not only to understand how they work, but also to be able to adapt their use to specific operating conditions, taking into account weather factors, obstacles and possible external influences.

Each drone consists of several key components. The flight controller is the "brain" of the drone, which processes sensor data and regulates the operation of the engines for stabilisation and navigation. Modern controllers have advanced features such as autonomous navigation, environmental adaptation, and intelligent power management to improve energy efficiency.

Sensors include gyroscopes, accelerometers, barometers, magnetometers, and GPS modules. Gyroscopes and accelerometers help determine the speed and direction of movement, while magnetometers are used to adjust the orientation relative to the Earth's

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magnetic field. GPS modules allow to determine coordinates with high accuracy, which is especially important for drones performing mapping or aerial photography tasks.

Motors and propellers generate lift and provide manoeuvrability. They can be either brush or brushless, and each type has its own advantages and disadvantages. Brushless motors, for example, offer greater efficiency and durability, making them ideal for professional drones.

The battery is the power source that determines the flight duration. The capacity and type of battery play an important role in a drone's performance. Lithium-polymer (Li-Po) batteries are the most common due to their high energy density, but they require careful maintenance and proper charging to prevent overheating and failure.

The communication system transmits commands between the drone and a control panel or ground station. It can use Wi-Fi, radio waves, satellite, or fibre optics to ensure a stable connection. Some modern models support a real-time video transmission system that allows operators to better monitor the drone during flight.

The drone is controlled by a remote control equipped with two joysticks. The left joystick adjusts the flight altitude and rotation of the drone, while the right joystick controls horizontal movements. The combination of these movements allows you to perform complex manoeuvres. In addition to traditional controls, some drones support mobile app or gesture control, which makes it easier for beginners to use.

Fig.2 One of the drone control panels

Flight modes. Modern drones have different flight modes. In Manual/Stabilised mode, the operator has full control over the drone without automatic stabilisation. This is the most difficult mode and requires a high level of training.

Altitude Hold mode automatically maintains the altitude, which makes it much easier to control, especially for beginners or when taking aerial photos.

Position Hold mode allows the drone to hold its position using GPS, which is useful when shooting video or working in difficult conditions, such as windy weather.

Headless Mode allows you to control the drone regardless of its orientation, making it easier for inexperienced users to navigate.

Follow Me mode allows the drone to follow the operator or a selected subject, which is useful for dynamic shots such as cycling, running, or road trips.

The Return to Home mode allows the drone to automatically return to the take-off point, which is especially important in cases of loss of communication or low battery power.

In addition to these basic modes, some drones are equipped with additional features such as automatic obstacle avoidance, flight on predefined routes, and intelligent power management, which increase efficiency and safety.

These modes simplify operation and make flying safer and more efficient, allowing beginners and experienced operators alike to get the most out of their drones.

Drone emulators are special software packages that create a virtual environment for training, testing and debugging unmanned aerial vehicles. They simulate physical flight conditions, including aerodynamics, weather effects, control parameters, and sensor signal processing.

The main components of the emulator include: a physical engine that simulates the laws of physics, such as gravity, air resistance, inertia, and wind effects,

Aerodynamic engine - responsible for simulating drone flight, including changes in altitude, pitch, speed, and stabilisation.

Sensor modelling - simulates the operation of GPS, gyroscopes, accelerometers, barometers, cameras, and lidars.

Application Programming Interface (API) - allows you to interact with the simulation through code in Python, C++ or ROS.

Graphics engine - visualises the environment to ensure realism.

Modern simulators use highly accurate modelling algorithms, such as computational fluid dynamics (CFD) methods, to more realistically reproduce the air movement around the drone.

The advantage of emulators is their safety, as they allow you to learn without the risk of damaging a real drone. They provide flexibility by allowing you to simulate different weather conditions and flight scenarios, allowing you to practice your skills in a wide range of situations. Their scalability allows a large number of variants to be tested at no additional cost, making them an effective tool for research and training. Moreover, they are characterised by accessibility, as they do not require physical resources other than a computer, making them a convenient solution for both beginners and professionals.

Today, there are many emulators that help to master the skills of drone control. Emulators take into account all the technical characteristics of a winged machine - from engine power, weight, and wind force to the specifics of fuel distribution in the wings, aerodynamic advantages and disadvantages, and stall conditions. The same simulators are used by novice navigators in maritime schools. Controlling a copter in the simulator is quite different from real life experience - instead of a special remote control, a joystick is used. If you use a smartphone or tablet, then control will be limited to a few buttons and tilting the device. In a real flight, drone control requires a completely different level of precision and coordination. Nevertheless, it is still useful to learn basic skills in an emulator, as it helps to avoid costly mistakes. In addition, this approach can be useful in computer science classes, helping students to better understand the principles of drone control, algorithms of their work, and develop programming and technical modelling skills. Switching from a joystick to a remote control will take some time, but it is much safer than trying everything out on real drones and risking damage. The main area of application for drones is teaching photo and video shooting. Shooting from drones opens up new opportunities for creativity, allowing you to get unique angles and shots that are impossible to make with a regular camera. In addition, drones are actively used in journalism, cinema and the advertising industry.

However, their use is not limited to filming. Drones play an important role in agriculture to monitor fields, in rescue operations to search for people, and in construction and inspections of hard-to-reach facilities. Thanks to advances in technology, the scope of drones is constantly expanding, making them an indispensable tool in various industries.

Fig.3 Drone sprayer at work

Having analysed modern emulators in detail, we will compare them based on their key advantages and disadvantages:

Fig.4 Litoff emulator logo

Liftoff by Immersion RC . This game is a leader on the Steam gaming platform in terms of content and the number of active users. It is equipped with a drone editor, pre-configured models, and integration with the Workshop, which provides access to a variety of drones, tracks, and settings created by other users.

The project has a wide range of maps, each of which contains several options for speeding through. A freestyle mode is available that allows you to perform trick manoeuvres with the accrual of points. The game progression system includes the accumulation of experience, opening cases, and unlocking visual customisations.

There is an option to fly in FPV mode for both experienced pilots and beginners. A mode with dynamic objects is also available, but it is implemented as a separate paid add-on.

Realistic control is ensured by extended support for various radio controllers and compatibility with FPV glasses.

Fig.5 Uncrashed emulator logo

Uncrashed: FPV Drone Simulator. This simulator is characterised by a lower content saturation, but it allows you to fully customise it. The peculiarity is that unlike Liftoff, where changing components affects the characteristics of the drone, in this simulator, the user directly changes the control parameters.

The latest update has significantly expanded the functionality, including the addition of a tool for creating custom maps in a convenient editor. This makes the simulator an effective tool for learning the basics of flying.

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Users have access to a free map with interactive, moving objects. An important advantage is the variety of locations, including stadiums, abandoned car parks, parks, etc. In addition, the simulator allows you to configure a much wider range of parameters compared to similar applications, including gravity, aerodynamic drag based on air density and pressure, and propeller efficiency depending on gas levels.

Any joystick can be used to control the virtual drone, but the simulator works exclusively on PCs or laptops running the Windows operating system. There is currently no mobile version of the application.

Fig.6 Tryp emulator logo

TRYP FPV. The simulator is characterised by high quality graphics, which requires powerful hardware. For comfortable use on the recommended settings, you need a graphics card of at least RTX 2060, 16 GB of RAM, 26 GB of free disk space, and Windows 11.

The game offers the possibility of joining a specialised community on Discord, where users can discuss ideas and share experiences. Before the start of the race, the system offers to calibrate the joystick by performing simple manipulations at . The drone's characteristics can be adjusted by replacing its components.

At the initial stage, the user has access to four maps: winter mountains, desert, forest, and summer mountain landscapes. During the game, you can observe moving objects, such as climbers, cyclists, and racing cars, as well as practice manoeuvres in a complex landscape, including abandoned construction sites.

The popularity of the simulator is explained by its wide functionality, affordable price and high quality graphics, which ensures realistic visual perception.

For a more detailed analysis, a comparative table showing the main features of different simulators is provided below. This will allow you to assess their differences and determine the best choice according to the individual needs of the user.

Table 2.

Comparison and characteristics of emulators

Name of the simulator	Advantages	Disadvantages
Liftoff	High quality graphics and the ability to customise UAVs. Provides deep immersion in FPV flight. Compatible with FPV goggles and radio transmitters, which increases the realism of control. Relatively low cost. Easy to use, which makes it convenient for beginners.	Insufficiently realistic physics, which makes the simulator more like a video game. Limited applicability for FPV filming and drone racing.
Uncrashed: FPV Drone Simulator	Easy to set up. A large number of tracks and locations, including parks and abandoned car parks. Wide range of physical settings, including propeller efficiency depending on the throttle pressure. High flight realism.	High system requirements that require powerful hardware. Relatively high cost compared to other simulators. No support for Apple devices.
TRYP FPV	High quality graphics. A large selection of dynamic objects that can be observed (cars, motorcycles, bicycles, climbers, runners, etc.). The ability to practice stunts. The most realistic physics among the presented simulators. Affordable price.	High system requirements.

Training in drone control and programming can be carried out both on real devices and in emulators, and from a financial point of view, the use of emulators is much more cost-effective, especially at the initial stages of training. The cost of training with real drones is much higher, as you need to buy the drone itself, with prices ranging from $300 to $1,000 for basic models and from $2,000 to $10,000 for professional ones. Added to this are the costs of repairs, as beginners often make mistakes that lead to damage, and replacing screws can cost $20-50, while camera or body repairs can cost $100 to $500. In addition, additional equipment such as FPV goggles, controllers, batteries, and charging stations can add another $500 to $2,000 to the total cost of training. The limited flight time, which averages 10-30 minutes on a single battery charge, also requires the purchase of additional batteries or charging costs, and flying in special zones may require the rental of sites, which creates additional costs. In comparison, simulator training is much more affordable, as most emulators cost between $20-100, do not require any repair costs, additional equipment, and allow for unlimited attempts without risk of damage, making them a cost-effective training solution for both beginners and professionals.

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Drone racing is the latest form of eSports that has emerged on the border of virtual reality and aeromodelling, which is a small quadcopter racing competition on a specially equipped track. The track at the Kyiv Palace of Children and Youth is marked with ribbons and chips. The track is looped, the start coincides with the finish, there are specially set up obstacles, is equipped with devices for timing and systems for broadcasting the video stream of participants to a large screen.

Ukraine hosts various drone racing competitions for children and young people. One of the centres of such competitions is the Kyiv Palace of Children and Youth, which regularly organises aerial robotics tournaments. In particular, in 2023, the Palace Cube Drone Racing competition was held, where participants demonstrated their ingenuity and skill in flying drones. Such events help to promote drone racing and engage young people in technical creativity.

An exciting drone flying competition was held in Zhytomyr. It was attended by 40 schoolchildren from 17 educational institutions of the city. The youngest participant was only 10 years old, and the oldest was 17. The competition was held in three categories:

Simulator operation - a virtual race where participants demonstrated their drone control skills in a digital environment.

Overcoming obstacles - a challenging trajectory that had to be completed using real drones.

Labyrinth - participants competed on the simplest quadcopters, overcoming difficult routes.

The organisers of the competition prepared an impressive prize fund. The winners of the individual championship received drone control panels worth about UAH 6 thousand. The competition was also supported by sponsors and the Education Department of Zhytomyr City Council.

The winners received remote controls for their drones, and the best participants were invited to continue their education in specialised clubs.

Participation in such competitions allows students to better understand the principles of aerodynamics, the structure and functioning of unmanned aerial vehicles. This contributes to the development of engineering thinking and technical literacy, which are important components of modern education. For example, in Zhytomyr, there is a robotics club called RoboticsZT, where children learn to pilot drones, starting with simple models and moving on to more complex FPV drones.

Conclusions . Based on the study, it can be argued that virtual reality (VR) opens up significant prospects for modernising the educational process, providing a high level of immersion, interactivity and visibility. This contributes to a better understanding of complex topics and increases student motivation. In this context, drones are emerging as a relevant interdisciplinary tool that combines knowledge of physics, computer science, geography and other fields. However, their direct implementation in school practice is associated with financial and security challenges. Drone control emulators, as a specific VR application, effectively overcome these obstacles by providing a safe, accessible, and cost-effective environment for learning piloting skills, studying the principles of UAV operation, and simulating various flight conditions without the risk of damage to real equipment.

The use of VR emulators such as Liftoff, Uncrashed, or TRYP FPV in computer science classes not only teaches the basics of drone control, but also develops important competencies: spatial thinking, problem-solving skills, understanding of software and hardware interaction, the basics of algorithmisation, and even programming through appropriate APIs (e.g. MAVSDK). The availability of various simulators allows you to choose the best tool depending on your learning objectives and technical capabilities. The practice of holding drone racing competitions confirms the high motivational potential of this area. Thus, the integration of VR drone control emulators is an appropriate and effective step to modernise computer science lessons, making learning more practice-oriented and preparing students to interact with advanced technologies.

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Chapter 3.
STEAM EDUCATION AND EDUCATIONAL ROBOTICS

3.1. STANDARDIZATION OF STEM EDUCATION IN UKRAINE: SUSTAINABLE DEVELOPMENT IN TIMES OF CRISIS

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In the ever-changing landscape of education, the role of STEM has been the subject of extensive debate and research. STEM-based learning methods that integrate engineering design, mathematical thinking, scientific research, and technological literacy are crucial to harnessing the achievements of past industrial revolutions and preparing a workforce capable of addressing problems and challenges associated with uncertainty. These arguments point to the need to rethink STEM education for 21st century citizens who are focused on the prospects of 2050. Compelling arguments for STEM education today place it at the center of 21st century skills development and the "holy grail of our time," the Sustainable Development Goals" (Jakfar et al., 2024). STEM education has become a cornerstone of global political and economic priorities. This has sparked considerable debate and research by various actors who view it as an apolitical tool and an economic and educational life jacket (Razi & Zhou, 2022). It is advisable that this rethinking of STEM education as a factor of sustainability leads to its standardization based on national frameworks to promote STEM-based strategies and programs in all sectors and at all levels of education.

Ukraine has been in a deep crisis for a long time, caused by a number of factors, including military aggression, which has led to terrible human losses, human capital drain due to external migration, infrastructure destruction, and the emergence of essential challenges for all spheres of public life, including education. In these conditions, when traditional approaches to education are becoming ineffective, STEM education, an interdisciplinary approach that integrates natural sciences, technology, engineering, and mathematics and is a powerful tool for training a generation of future highly qualified professionals capable of innovative thinking in solving complex problems, actively contributing to the country's recovery and development, and implementing projects in critical sectors of science and economy, including transport, is becoming especially relevant. The STEM competencies of Ukrainian citizens are critical to overcoming the consequences of the crisis and building a sustainable future.

However, in order to fully realize the potential of STEM education, its standardization is necessary, as the lack of common approaches to curriculum development, pedagogical methodology, assessment of STEM learning outcomes, and determination of the current structure of STEM competencies can lead to a loss of quality of STEM education in different educational institutions and regions of Ukraine. This, in turn, deepens inequalities in access to quality education and reduces the effectiveness of investments in STEM education at the state and local levels. Standardization of STEM education is a complex but essential process that involves the development of clear frameworks and criteria for assessing key aspects of the educational process. Its components are: definition of key concepts; normalization of the idea of what STEM education is, as it is understood; development of approaches to content; pedagogical strategies; assessment of learning outcomes; uniform requirements for infrastructure, material and technical base, formation of the STEM education ecosystem; professional standards applied to teachers, quality of education management, etc. It is important to establish a link between all components of standardization.

Currently, there is a lack of research on the components of STEM education standardization, which determines the authors' choice of the topic of the publication.

In this paper, we want to analyze the role of STEM standardization in ensuring the sustainability of education in times of crisis, supporting innovative development and the recovery of Ukraine. We will review the international experience of STEM education standardization; analyze the current state of STEM education in Ukraine; assess the challenges to its development, opportunities for applying international experience and ways to adapt it in Ukraine, and offer specific recommendations for implementing an effective system of standardized STEM education in Ukraine.

Purpose of the study: to analyze the role of STEM education standardization in ensuring the sustainability of education in times of crisis, supporting innovative development and restoring Ukraine. Objectives: to review international experience, analyze the current situation in Ukraine, identify challenges and develop recommendations.

1.International experience of STEM education standardization

Countries leading the world economy in the global North and South have long perceived STEM education as a strategically important educational sector, as their developed industries require a constant replenishment of STEM specialists. National STEM development policies mostly include measures to: a) improve science and mathematics education; b) enhance cooperation and social dialogue between stakeholders and educators; c) expand opportunities for girls and vulnerable populations, equal access to STEM education; d) develop and promote innovative STEM learning and teaching programs based on a transdisciplinary approach; and e) recruit, retain, recognize, train, and develop STEM teachers.

Review of documents reflecting the national policies of STEM leading countries: Finland, Germany, the United Kingdom, the Netherlands, Australia, and the Global South, lead to the conclusion that their successful experience is based on an early start in STEM and the integration of STEM concepts into the educational process from preschool and primary school. Long-term studies by PISA and the OECD, which assess the quality of national education systems, note that the quality of a teacher's work, his or her deep knowledge of subjects, and mastery of effective pedagogical methods are the second, no less important, factor of success. This is a critical dimension of every effective education system around the world. The most successful European countries according to PISA, Estonia and Finland, require a master's degree to become a teacher. Others, such as Singapore and Canada, have rigorous selection and training programs and provide ongoing professional development opportunities. A broad research base recognizes the strong relationship between teacher quality, preparation, qualifications, professional development, and improved student outcomes - especially for disadvantaged groups of students (see also Darling-Hammond, 2010; Hattie, 2012; Montt, 2011; Un, 2018).

It encourages the implementation of STEM educational projects that are designed to solve real problems of the community and the country and allow students to apply their knowledge in practice; as well as cooperation with STEM companies and scientific institutions, which gives students practical experience.

In the United Kingdom, the STEM Concept focuses on human capital development, commitment to an effective scientific entrepreneurial and innovative investment system. A comprehensive STEM education ecosystem, the STEM Learning Ecosystem, is being developed, including schools, universities, businesses and public organizations. Initiatives such as the STEM Learning Network and Industrial Cadets provide support to teachers, offer resources and facilitate the exchange of best practices, and provide students with work experience at STEM enterprises, which increases their motivation and understanding of career opportunities. There are a number of initiatives aimed at attracting girls and students from low-income families to STEM, increasing diversity and supporting universal design.

In contrast to the UK, where STEM is integrated into the national curriculum through individual subjects with considerable autonomy for schools to implement it, some European countries have a more centralized approach to developing and implementing STEM education through national curricula or strategies that closely regulate the content and methods of teaching. It is important to note that even in countries with a more centralized system, schools have academic freedom, exercising flexibility and variability in implementing standards and model programs and adapting them to local needs. However, the overall structure, content, and goals of STEM education are largely determined at the national level. For example, Finland has a National Core Curriculum that serves as the basis for all basic education. Although STEM is not taught as a separate subject at all levels, the curriculum clearly defines the goals and content of learning in math, science, technology, and computer science. The state plays a key role in developing this program and updating it. The concept of STEM in Finland is implemented through integration and interdisciplinarity, a competency-based approach, as cross-cutting gives better results than isolated teaching. Focus on Inquiry and Problem-Solving pedagogical strategies are used to guide students to ask questions, research, experiment, and find ways to solve problems through collaboration. The connection between Real-World Relevance STEM and the application of acquired knowledge in real life, work, and solving social challenges, as well as building strong partnerships between schools, higher education, and employers are crucial. Highly qualified teachers have a high level of scientific literacy and methodological culture, possess relevant pedagogical strategies, and have the autonomy to adapt programs to the local context and the needs and interests of children. Technology is seen as a powerful tool that should be used to make learning simple, accessible and understandable. Finnish education policy aims to ensure equal access to quality STEM education for all students, regardless of their background.

Educational standards and STEM programs in Finland. The Finnish National Agency for Education (Opetushallitus) develops the National Core Curriculum, which provides the basis for basic education, including STEM. This curriculum emphasizes broad goals and competencies and allows municipalities and schools, through academic freedom, to create their own local curriculum based on the national curriculum, taking into account local needs and priorities, adapting it to local conditions. Despite integrated approaches, the curriculum traditionally has a subject-oriented structure, with math and science as the core subjects. Technology and engineering are often embedded in the natural sciences and arts. The science curriculum (natural science) for basic secondary school often integrates biology, physics, and chemistry. The emphasis is on both content and scientific inquiry, on achieving a balance between acquiring knowledge of scientific concepts and understanding the nature of science, and mastering scientific methods. There is a growing trend towards the integration of the arts (STEAM) to develop creativity and innovation along with STEM disciplines[1][2][3]. The National Strategy for STEM Development in Finland aims to ensure a high level of STEM competencies of citizens to promote socially, environmentally and economically sustainable well-being and growth through improving teaching methods, monitoring the quality of education and developing the STEM ecosystem, and extensive communication with stakeholders. The strategy emphasizes lifelong learning, the development of STEM skills throughout life, and ensuring a sufficient number of STEM experts in Finnish society by 2030. It promotes the study of STEM disciplines at all levels of education, with equal encouragement for all genders and population groups to ensure diversity and accessibility.

The MINT-Initiative, a national initiative in Germany, aims to promote STEM among young people, improve the quality of teaching, and foster cooperation between schools, universities, and industry. Experimental centers and laboratories have been set up

1 Finnish National STEM Strategy and Action Plan (2021-2030): https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/164953/OKM_2023_22.pdf

2 Finnish National STEM Strategy and Action Plan. Experts in natural sciences, technology and mathematics in support of society: https://julkaisut.valtioneuvosto.fi/handle/10024/164953

3 National Core Curriculum for Basic Education https://www.oph.fi/en/education-and-qualifications/national-core-curriculum-primary-and-lower-secondary-basic-education

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in many states where students can conduct hands-on research and experiments; the dual system of vocational education is developing rapidly, combining education in vocational schools with on-the-job training at enterprises and providing qualified technical personnel.

The Dutch National STEM Platform (PTvT) implements the National Technology Pact (formerly the Dutch National STEM Strategy) in the flagship program Katapult. This national network supports public-private partnerships in higher education and vocational training. In the Netherlands, a network of Technasium schools has been created that offers a specialized STEM program for high school students based on project work, interdisciplinarity, and cooperation with business. Science centers, such as SciTech Center Delft in Delft, are examples of successful cooperation between university, business, and schools in STEM education, offering a variety of educational programs and resources1. The Technasium network of schools is not a separate type of school, but rather a specialization within regular secondary schools. The key characteristics of the Technasium STEM program are: Project-Based Learning (PBL) as a central element of the program; interdisciplinarity; collaboration (students work on projects in teams); reliance on real customers and context (working on projects for real customers gives authenticity to learning and shows students the practical application of STEM knowledge in the real world. Feedback from customers is a valuable experience. Technasium's learning process focuses on developing 21st century skills such as critical thinking, creativity, problem solving, communication, collaboration, digital literacy, and independent learning. Students learn to present their projects, negotiate, and take responsibility for their own educational progress. Cooperation with companies and organizations provides insight into various STEM professions.

The Technasium program usually lasts for all years of high school. Each year, the complexity of the projects increases, and students gain more independence. During the first 3 years, they learn the basics of STEM through small projects, develop basic design and collaboration skills. In high school (the last 2-3 years, depending on the level), projects become more complex and longer, require deeper knowledge and skills, and have the opportunity to specialize in certain STEM areas.

Technasium is a vivid example of a structured and effective approach to STEM education, specialized training for young people to enter STEM professions, and preparing them for future challenges.

1 https://www.technasium.nl/

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Spain. At the national level, the Ministry of Education and Training sets general educational standards and frameworks. Regions, as autonomous communities, develop their own curricula based on them. Therefore, there are certain national benchmarks for STEM subjects, but their specific implementation may vary from region to region.

Turkey. The Ministry of National Education develops and implements national curricula for all levels of education, including STEM subjects. There are clearly defined curricula in math, science, technology, and engineering that are mandatory for all schools.

Israel offers STEM courses at the primary and secondary levels and includes STEM training during compulsory military service.

In Australia, the national STEM education strategy was developed in 2016 until 2026[1]. It aims to coordinate the efforts of stakeholders in promoting STEM education. The Australian government has many good programs, such as the National STEM School Education Resources Toolkit to support schools and businesses in creating new initiatives, forming partnerships and implementing best practices[2]. For example, the National STEM Strategy 2019-2023 (Engineers Australia) program focused on training future engineers to join the country's workforce (Xu, L., Fang, S. C., & Hobbs, L., 2022).

The states of the Gulf Cooperation Council (Middle East) are taking the same approach (Kayan-Fadlelmula, 2022).

China hopes to improve the competitiveness of STEM education. The country prioritizes a strong, innovative STEM workforce (Yan et al., 2024). Comparative studies (Kamsi et al, 2019), (Yan et al., 2024) show FIR-STEM (fundamental integrated and adaptive STEM) in China, echoing the view (Joseph, 2018) of the importance of human capital, equipped not only with skills but also with knowledge, experience, creativity and motivation.

Often compared to Finland, Singapore has a strong emphasis on integrated STEM education, where subjects are taught in a way that emphasizes their connection to real life. This approach is evident in their national curriculum, which promotes the use of project-based learning and encourages teachers to collaborate across disciplines (Brand, 2021).

1 National STEM School Education Strategy 2016–2026: https://www.education.gov.au/national-stem-school-education-strategy-2016-2026

2 National STEM School Education Resources Toolkit: https://www.stem.edu.au/resources/national-stem-school-education-resources-toolkit

Attention to human capital development is outlined in the Science, Technology and Innovation Strategy for Africa, which is enshrined in the African Union's Agenda 2063 (African Union Commission, 2015). To achieve technical competencies, which are a fundamental requirement of the Fourth Industrial Revolution, member states are expected to take systematic measures.

Comparative studies of STEM education in the Global North and South (Mudaly and Chirikure, 2023 and Wolff et al., 2022) have found that the success, sustainability and recognition of STEM education is much higher in high-income countries, developed countries, G7 countries, compared to developing and underdeveloped countries with low GDP. High levels development of economic countries are characterized by advanced technologies, high living standards, and a significant share of the tertiary and quaternary sectors of the economy, have a steady need for skilled workers with a high level of STEM competencies, have sufficient financial resources, and systematically develop and support STEM education for the projected training of such specialists.

The preliminary review makes it obvious that countries with actively developing STEM education have already developed and are implementing strategic national frameworks and policies in the field of STEM. They ensure massive involvement, standardization, and create space for centrally managed and funded programs, including reform of educational content at all levels and new teaching standards.

General trends that can be traced in successful STEM education concepts (European Commission, 2025) are a systemic approach (successful countries consider STEM education as part of the overall strategy for education and economic development); active role of the state (the state plays an important role in policy development, financing and coordination of STEM education initiatives) involvement of business and science (cooperation with enterprises and scientific institutions is key to ensuring the practical orientation of STEM education and familiarizing students with modern technologies and career opportunities); support for teachers: (providing opportunities for continuous quality training, professional development, and resource updates); and systematic evaluation and research (evaluating the effectiveness of STEM programs, conducting research to continuously improve concepts, policies, and programs) (European Commission, 2019,2025 & EU STEM Coalition, 2025). Each country that has achieved some success in implementing STEM has its own unique context and approaches that are worthy of a deeper study, which is beyond the scope of this study. The study of these successful cases can provide valuable information

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and ideas for improving strategies for standardization and mass implementation of STEM education in Ukraine.

It is worth noting that global concepts of STEM education are constantly evolving and, based on political, economic, environmental, social, demographic, and technological contexts, outline a framework for developing effective STEM policies and strategic plans to strengthen competitiveness in the face of technological transitions. In addition to studying local features, it is worthwhile to make a brief overview of the evolution of approaches to STEM implementation, which have changed over time and apply to almost all countries for which STEM is part of national policies to strengthen competitiveness and human capital development, overcome the challenges of technological leaps and the reskilling revolution.

At the first stages of their formation, these concepts were focused on the development of educated STEM specialists in certain fields of S-science, T-technologies, E-engineering, M-mathematical modeling, as these are the ones that support the innovative development of the country's economy and make the largest contribution to GDP. However, at the end of the twentieth century, researchers realized the limitations of narrow disciplinary discourse and isolated approaches in STEM (Piaget, J, 1970) calls for "...rising above the narrow interests and interaction of researchers concerned with solving highly specialized problems...", moving to metacognition through transdisciplinarity. Later (Sanders, 2009; Scholz, 2011; Hwang et al., 2024) substantiate the movement from an isolated to an interdisciplinary approach, preferring methods where different subjects are "fused". Trans-disciplinarity in science and education ensures the transition to a new meta-level, the achievement of a certain meta-structure. Interdisciplinary integrated STEM education combines different cognitive strategies, theory and practice, and overcomes the limitations of disciplinarily organized classical science. Some researchers noting that integrated STEM classes encourage students to combine ideas from several disciplines around one artifact (Bybee, 2010; Hwang et al. 2024; Lee, 2024, Rumjaun et al.). The synergy of disciplines united under the banner of STEM, the so-called iSTEM (integration of STEM), multiplies their power and creates a more powerful and effective learning experience (Razi, 2022).

The last decade of the 21st century saw a significant shift in the STEM paradigm towards a post-nonclassical understanding and its extension beyond the integration of the "four pillars", making this educational innovation open to combining with humanities, economics, entrepreneurship, art, healthcare, design, linguistics, and even sports. As a result, a number of derivatives of the basic acronym have emerged: STEAM (STEM and art), STEMM (STEM and medicine), STEAMED (STEM, art, education and design) (Jolly, 2017) and STREAM (STEAM with robotics or reading), among others (Belbase, 2022; Ilhan et al., 2019; Kocabas et al., 2020; Lyons, 2018). The synergy of disciplines in STEM is capturing more and more new territories and encourages young people to develop STEM competencies through various activities, taking into account interests and hobbies, providing many opportunities for the formation of STEM identity based on experience, practical results, and recognition. The "fusion" of art and STEM, its transformation into STEAM, contributes to the development of creativity, which, along with artistic skills, forms 21st century competencies, such as logic, reasoning, problem-solving, design thinking, research skills (Ritz, J. M., & Fan, S. C., 2015; Correia, 2024).

STEM programs with a focus on coding and robotics (STREAM, C-STEM) help students develop practical problem-solving skills based on computational thinking and expand access to modern technologies for different social groups (Wright, 2024). C-STEM-PBL (Community-STEM Project-Based Learning) engages math and science teachers in project-based learning, taking into account the capabilities, voice, and needs of the community. The emphasis on community involvement makes STEM education impactful in the local context (Nava & Park, 2021).

E-STEM (Environmental STEM) emphasizes the importance of sustainable development (Jasrai & Kaur, 2024) and the connection of environmental education with STEM disciplines to enable students, teachers, professionals/experts, and researchers to collaborate in green STEM activities and gain authentic learning experiences (He et al., 2024). Similarly, ESD-STEM STEM combines STEM education with ESD principles of sustainable development, and STEM-FEM programs for girls and women overcome inequalities and develop gender-sensitive approaches to learning (Gao, 2024).

The openness of STEM education contributes to a flexible response to the requirements for the competencies of XXI professionals and a focus on solving real social problems faced by STEM professionals and achieving the Sustainable Development Goals.

Despite the successful practices developed over the decades, there is a problem of choosing theoretical and conceptual frameworks for standardizing STEM education. The above studies show that fragmented policies do not reflect systemic or holistic approaches to STEM education development and are not sufficient to equip current and future generations with the STEM competencies needed to replenish labor capital and maintain a competitive edge in a globalized world.

The current discourse focuses on the development of standards, the formation of national policies to achieve deep-STEM, and deepening the understanding of STEM competencies as central to the structure of key characteristics of a person of the 21st century. It is a well-founded belief that STEM education will help people of all ages to have more chances for success today and in the future, when innovations and technologies once again change the labor market, destroy jobs, turn economic sectors into deserted ones, and require rapid retraining and acquisition of new qualifications. The European Qualifications Framework defines STEM competencies as extremely important for responsible citizenship, which is based on their desires, needs, and the achievement of the social well-being (EU STEM Coalition, 2025).

2. Analysis of the current state of STEM implementation in Ukraine

In 2025, Ukrainian STEM education celebrates its tenth anniversary. 10 years separate the present from the time when the community of scientists and educators began to get acquainted with this educational trend, which was still new to most. During this period, not many events have taken place that correspond to the stage of formation of STEM education in Ukraine, but they allowed us to move quite rapidly and quickly from the stage of early innovators to the stage of standardization and mass implementation, from the first conceptual documents to specialized state model STEM curricula, enshrined in the educational standard.

Among the key documents regulating the implementation of STEM education in the country are the following.

1. Foresight of socio-economic development, where STEM was first mentioned as a trend necessary for the development of human capital capable of supporting the development of economic drivers (mechanical engineering, transport, IT, nanotechnology, earth science, metallurgy, agricultural engineering, etc. (ZgurovskyZ et al, 2015)

2. The Presidential Decree “On urgent measures to reform and strengthen the state” of 08.11.2019, where in paragraph 6, regarding measures in the field of education and science: development and approval of the concept of development of science and mathematics education (STEM education); updating the State Standard of Basic Secondary Education; updating the Basic Component of Preschool Education (President of Ukraine, 2019).

3. The Concept for the Development of Science and Mathematics Education (STEM Education) (MES of Ukraine, 2020) and the Standard List of Teaching Tools

and Equipment for Classrooms and STEM Laboratories, which introduced the concepts of STEM education, STEM competencies, and STEM laboratories into Ukrainian scientific circulation (MES of Ukraine, 2020) defined the mission and philosophy of Ukrainian STEM education, as well as its levels and types. The list, updated in 2020, made it possible to re-equip educational institutions and replenish them with modern STEM equipment in the period from 2020 to 2025, despite the pandemic and war crisis: digital measuring complexes, 3-D printers, digital machine tools, mechatronic and robotic systems, energy efficiency and Internet of Things designers, media studios, and maker tools.

4. From 2021 to 2024, the introduction of STEM in the Ukrainian educational space is ensured by the relevant provisions of the Model Educational Program for Grades 5-9 of general secondary education institutions, where the interdisciplinary integrated course "STEM" has found its current place in the list of subjects and integrated courses, among others. In 2021 and 2024, the teams of Ukrainian researchers consistently propose model STEM curricula for the adaptation (grades 5-6) and subject study cycle (Grades 7-9), providing a wide range of opportunities to implement STEM approaches in each general secondary education institution of their choice.

5. Model curriculum for 10-12 Grades of general secondary education institutions that provide specialized secondary education in an academic field, where STEM is one of the leading clusters (MES of Ukraine, 2025).

A general description of the progress of Ukrainian STEM education shows that it has absorbed the positive experience of leading countries. The state concept is based on trans-disciplinarity, competency-based approach, project-based methods, and problem-based learning; attention to teacher development and building partnerships based on social dialogue. The theoretical framework takes into account the educational, social, and economic contexts of Ukraine, its opportunities, challenges, and prospects, shortcomings in understanding STEM concepts, structural and crisis constraints, and allows to manage the transition to mass adoption of STEM education through its standardization.

For our study, it is important to assess the context against which the introduction of STEM education in Ukraine is unfolding. We will rely on analytical materials on the analysis of the current situation in the national education system, published in the period 2022-2024 by the Ministry of Education and Science, the Center for Education Quality Assurance, governmental and non-governmental organizations, including SavEd. They address issues of infrastructure destruction, access to education,

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classrooms, availability of technical capabilities for online learning and teaching, educational losses, etc. (MES of Ukraine, 2022, 2023, 2024: SQE, 2024: IEA of the MES of Ukraine, 2023).

Prior to the full-scale Russian invasion in 2022, there were 13,991 general secondary education institutions of various types and forms of ownership in Ukraine, where 4.23 million students were educated. As of the end of the 2022/2023 academic year, there were 12,930 schools with about 4.04 million students enrolled in various forms of education [((MES of Ukraine, 2022). According to the representatives of local governments who participated in the study, some schools in the communities are unsuitable for education. For the most part, the number of such schools in a community is about 6%. However, there are four communities where a significant proportion of schools are identified as unfit for learning: Barvinkivska community (Kharkiv region) - 18%, Nikopol community (Dnipropetrovsk region) - 40%, Kharkiv community (Kharkiv region) - 64%, Kherson community (Kherson region) - 95% (IEA of the MES of Ukraine, 2023).

As of January 20, 2023, 3051 educational institutions were affected, 420 of which were completely destroyed. Almost half of them are secondary schools: 1619 schools were damaged and 223 were completely destroyed1 [59]. There are 894 general secondary education institutions in the temporarily occupied territory along with their branches (as of May 21, 2023) (IEA of the MES of Ukraine, 2023).

The material and technical base that contributed to the development of STEM education has been lost. In particular, in the physics, chemistry, biology, and geography classrooms of 176 schools, 10,815 units of teaching aids were damaged, destroyed, or are considered missing, namely 969 pieces of laboratory equipment, 1684 computers, 91 interactive whiteboards, 219 projectors, 287 TVs, 7565 pieces of other electronic equipment, including 1534 pieces of equipment purchased to implement the NUS reform in recent years (IEA of the MES of Ukraine, 2023).

The development of STEM education and professions in times of crisis has its own peculiarities, both challenges and opportunities. The main challenges for STEM development in the crisis are the destruction of infrastructure and limited physical access to education, especially for experimental and practical classes, which are key to STEM.

Population displacement (both internal and external) affects STEM students and teachers, disrupting the continuity of the educational process, creating a shortage

1 Education under threat, https://saveschools.in.ua/

of qualified STEM teachers as they may be forced to leave their places of residence or change their profession, and creating challenges to adapt to new conditions. The crisis often leads to a reduction in funding for education, especially for "expensive" areas such as STEM, which requires special equipment, laboratories, and materials. This may be due to changes in budget priorities in times of crisis. The stress, trauma and uncertainty caused by the crisis can negatively impact students' and teachers' ability to learn and teach, especially in challenging disciplines such as STEM. And more globally, in times of crisis, education systems may focus on basic needs such as security and humanitarian aid, putting STEM education on the back burner.

On the other hand, there are new opportunities for STEM development in the crisis: there is a growing need for STEM professionals to address crisis issues and solve complex problems, which emphasizes the importance of STEM professionals (e.g., for vaccine development, infrastructure restoration, data analysis); the COVID-19 pandemic has already accelerated the introduction of distance and hybrid learning. This has spurred the development of new online platforms, interactive resources, and virtual laboratories, making STEM education more accessible and flexible. Students and young people can apply their skills to develop innovative solutions to local and global challenges and complex problems. Attracting international assistance and partnerships to attract new resources and expertise. Society is better aware of the importance of science and technology in overcoming challenges, which leads to greater support for STEM and increased interest in these fields.

In the context of a full-scale war in Ukraine, the development of STEM education faces all of the above challenges (destruction of schools, displacement of population, lack of resources). At the same time, the war emphasizes the vital importance of technology and innovation for the country's defense and recovery. This creates a demand for engineers, programmers, and cybersecurity specialists, and in turn, stimulates the development of STEM education and research despite the difficulties. Thus, the crisis is a challenge for STEM development, but also a catalyst for innovation, rethinking approaches, and increasing the value of these important fields of knowledge.

For the successful development of STEM in crisis conditions, it is necessary to focus on: flexibility and adaptability (development of curricula and methods that can be adapted to changing conditions); digitalization of STEM education, implementation and improvement of online tools and resources to ensure sustainability; psycho-social support for children and adults, and building resilience. Standardization ensures a stable level and positive dynamics of STEM education implementation in crisis conditions, when there are significant resource constraints. It maintains a sufficient level of implementation even while ensuring equal access to quality STEM education for all students, regardless of their socioeconomic status, place of residence, or other factors.

Standardization of STEM education plays an important role in ensuring the sustainability of educational innovations and society itself. Young inventors are already offering their solutions in the areas of energy security, climate change, healthcare, and other challenges.

244 million children and young people are currently affected by armed conflict, climate-related natural disasters, political or economic crises, and related forced displacement, including the refugee crisis. Crises dramatically affect the long-term investments needed to transform education systems and ensure their resilience to future changes1.

The role of sustainability in STEM is becoming increasingly apparent given the crisis environment. Due to rapid technological development and transformation, it is more important than ever for STEM education to prepare students and teachers for the challenges of an unstable, uncertain, complex and ambiguous (VUCA) social and professional environment to ensure sustainable learning and innovation in a changing environment. On the one hand, resilience can influence the academic performance and professional achievement of STEM learners, and factors such as adaptability, self-efficacy, self-control, optimism, and perseverance are key protective elements. Resilience is a multifaceted concept that encompasses the ability of an individual or community to withstand, adapt, and recover from adversity and difficult situations and reflects dynamic processes that include the interaction between personal characteristics, social networks, and environmental factors (Sung, E, 2024)2 . Importantly, resilience is not only about returning to a previous state, but also about the potential for growth and transformation in response to disruptive and challenging events. Resilience as the ability to maintain or restore a state in a crisis. From a sociological point of view, resilience goes beyond individual attributes and processes of resilience to social systems and structures. It can be achieved through collective action, social support networks, and institutional measures that mitigate the effects of crises. The level of resilience of a community is often measured by

1 Education in Crisis Situations | #LeadingSDG4 | Education2030

2 Sung, E., Liu, L., & Kuang, K. (2024). Cultivating resilience in science, technology, engineering, and mathematics education. Engineering Education Review, 2(2), 66–71. https://doi.org/10.54844/eer.2024.0630 (Original work published September 12, 2024)

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the extent to which it can prepare for, respond to, and recover from various shocks, such as natural disasters, economic downturns, or social crises.

A focus on resilience that is built up can be particularly useful in an educational context. By focusing on these communicative processes, educators can create a supportive atmosphere that not only improves academic performance, but also provides students with the necessary discursive resources to navigate challenges, adapt to change, and thrive in diverse learning and teaching environments in STEM fields. In recent years, scholars have called for more important milestones and research on sustainability in STEM education (Aldrich DP, 2012).

STEM education has the greatest impact on the economy through the labor market channel, reducing costs and increasing investment. European countries have recognized STEM education as an integral component of creating qualitatively new human capital.

Ukrainian educational scientists are conducting painstaking research work on the creation of STEM educational centers (Institute for the Modernization of Educational Content, n.d., 2023). In favor of the need to teach young people to recognize the real-world application of STEM, it is argued that new jobs in a victorious Ukraine "... will be mostly related to innovative technologies in science, engineering and mathematics with an emphasis on IT, robotics and programming" (Pukhovska et al., 2020).

3. Specialized model curricula for intersectoral integrated STEM courses at the New Ukrainian School. A step towards standardization of STEM education.

As part of the state educational reform known as the New Ukrainian School, Ukraine is developing and implementing model STEM curricula that are enshrined in the current state standard of basic secondary education in the ideas of intersectoral integration, cross-cutting in the formation of key competencies and cross-cutting skills, and in the Model Educational Programs for grades 5-9 and for specialized schools (vocational and academic lyceums). As of 2025, the following programs have been developed:

- "STEM. Grades 5-6 (intersectoral integrated course)" by authors: Buturlina O. V., Artemieva O. E. (Recommended by the Ministry of Education and Science of Ukraine, Order of 12.07.2021 No. 795) (Buturlina O. & Artemieva O., 2021).
- "STEM. Grades 7-9 (intersectoral integrated course)" by authors: Buturlina O. V., Artyomieva O. E. and others (Recommended by the Ministry of Education and Science of Ukraine, Order of the Ministry of Education and Science of Ukraine of August 14, 2024, No. 1138) ((Buturlina O. et al, 2024).

- "STEM. Grades 7-9 (intersectoral integrated course), authors: T. M. Zasekina, O. V. Korshunova, et al. (Recommended by the Ministry of Education and Science of Ukraine, Order of the Ministry of Education and Science of Ukraine of August 14, 2024, No. 1138)) (Zasekina, O et al, 2024).
- "STEM. Grades 5-9 (intersectoral integrated course), authors: Levchenko F., Ozarchuk A., Rohosa V., Skulatov O., Sipiy V., Tyshkovets M. (Recommended by the Ministry of Education and Science of Ukraine, Order of the Ministry of Education and Science of Ukraine No. 1138 of August 14, 2024) (Levchenko F et al, 2024
- "Robotics. Grades 5-6" (intersectoral integrated course), authors I. Sokol, O. Chencov. (Recommended by the Ministry of Education and Science of Ukraine Order of the Ministry of Education and Science of Ukraine of 12.07.2021 No. 795) (as amended by the Order of the Ministry of Education and Science of Ukraine of 29.09.2021 No. 1031) (Sokol I, & Chencov O., 2021)
- "Robotics. Grades 7-9" (intersectoral integrated course) authors I. Sokol, O. Chencov. (Recommended by the Ministry of Education and Science of Ukraine" (Order of the Ministry of Education and Science of Ukraine of 10.09.2024 № 1279) (Sokol I, & Chencov O., 2024)

In our study, we will focus on programs for grades 7-9 of the interdisciplinary integrated STEM course, which is implemented in the second cycle of basic secondary education, in the cycle of subject study. What unites all three of these programs is their interdisciplinary nature, practical use of the knowledge acquired by the applicant from various STEM fields to solve complex problems, reliance on problem-based learning, active work, and involvement of the applicant's subjectivity (agency). programs are aimed at developing key competencies required in the modern world and cross-cutting skills. All programs have a modular structure, which allows them to be flexibly adapted to the needs of a particular educational institution and the interests of students. They have a common goal of developing students' key STEM competencies. They differ in emphasis, structure, and approaches to implementation. Buturlina's and Zasekina's programs are more focused on knowledge integration and research activities. The Levchenko program additionally emphasizes entrepreneurship and innovation, as well as sustainable development goals. The choice of a particular program depends on the needs and capabilities of the educational institution, the readiness of teachers, and the availability of resources. It is important to consider the potential risks and drawbacks of each program and develop strategies to overcome them.

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Table 1.

Comparative analysis of STEM model curricula. Grades 7-9 (interdisciplinary integrated course)

Model curricula STEM. Grades 7-9 (interdisciplinary integrated course)		
Authors: Buturlina O. and others	Authors: Zasekina T. and others	Authors: Levchenko F. and others
stem-7-9-kl-buturlina-ta-in-27082024.pdf	https://mon.gov.ua/static-objects/mon/sites/1/zagalna%20serednya/Navchalni.prohramy/2024/Model.navch.prohr.5-9.klas-2024/27.08.2024/03/stem-7-9-kl-zasyekina-ta-in-27082024.pdf	https://nddkr.ukrintei.ua/view/ok/58d555875e14b-d7823838819759a1fc9
Objective		
Formation of STEM-identity of students, development of STEM-competencies, increase of motivate motivation to study natural sciences, technologies, engineering and mathematics. preparation of students for future professional activities in STEM-areas. Implementation of interdisciplinary STEM projects aimed at achieving the Sustainable Development Goals. Development of design thinking, support for invention, entrepreneurship and scientific and technical creativity	Personal development of students, who have certain skills in nature study, are able to assess the impact of sciences, engineering and technology on sustainable development of society and possible consequences of human activity in nature, confidently use digital tools and technologies to solve educational and practical problems, and are capable of independent and team problem solving, decision making, critical thinking and creativity.	The program clearly defines the goal of STEM education as the development of a personality capable of entrepreneurship and innovation, critical thinking, problem solving, and responsible activities in society. The program offers a wide range of learning activities, including discussion, research, design, modeling, experiments, and presentations.

Content lines		
Module topics (7th Grade)		
1. 1. Human-Society "Diversity of food" 2. Human-Technology "Green transition of the Blue Planet" 3. Human-Nature "How do they breathe?" 4. Human-Sign "Millions underfoot" 5. Human-Image «Techno Park»	1.Artificial intelligence. 2.Energy and movement. 3.Technical solutions. 4.Ecology. Systems.	1.Society's needs and sustainable development. "Human needs" 2. Health and personal development. "Nutrition". 3. Ecosystems and human impact on the environment "Helping animals". 4. STEM Science "Observation of natural phenomena". 5. STEM Technology "Souvenirs". 6. STEM Engineering "Mechanical robots". 7. STEM Mathematics «Mathematics and art»
Assessment. Groups of learning outcomes.		
1. Research capacity (phenomena, objects, problems, information). Investigates nature, phenomena, patterns 2. Digital literacy Works with information and data. Searches, investigates, analyzes, critically evaluates, interprets, generalizes, uses safely, creatively uses, creatively transforms. 3. Creativity. The ability to create product (material/informational) to solve problems, satisfaction of personal and social needs and creative self-realization.	1.Identifies problems, develops strategies, action plans to solve problems.	1. Gaining experience in problem solving (individually and in cooperation with others).

4. Vision of the future. Entrepreneurship, The ability to plan for the future based on their strengths, talents, abilities, interests and needs of the society, investigate types of professional activities. 5. Presentation and performance. The ability to present the results of his/her activities, express his/her own opinion.	2.Creates information and material products for effective problem solving and creative expression. 3.Effectively uses equipment, technologies and materials without harming the environment. 4.Demonstrates entrepreneurship.	2. Development of critical and systemic thinking, creativity, initiative; gaining experience of cooperating with others. 3. Awareness of the role of science, engineering and technology in ensuring sustainable development of society; assessment of factors and activities that pose a threat to personal and social life, health, and well-being.
Advantages		
1. Clear cross-cutting content lines: The program structures the content by cross-cutting content lines, such as "Human and Nature", ""Human and Society", ""Human and Technology". This is the basis for real integration and a focus on practical application. Students explore the problems faced by professionals in various fields of human activity. 2. Emphasis on developing "systematic thinking": The program clearly states the development of "systematic, critical, logical thinking" through "the application of systems analysis tools". And it provides a methodological basis for achieving this goal.	1. Focus on forming a holistic picture of the world and complex problem solving: "Formation of a holistic picture of the world and gaining experience in solving problems that require the integrated application of knowledge and skills from different educational fields." The student will be able to understand how everything works together in real life, not just in textbooks.	1. The program is generally well aligned with the goals and objectives of STEM education, focusing on the practical application of knowledge and the development of key competencies.

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3.Active role of the student in the learning process, agency. Buturlina's program explicitly defines the role of the teacher as one who "creates conditions," "guides," and "helps students realize their own responsibility." This is in line with modern pedagogical approaches and encourages the development of their own facilitation skills. 4.Detailing of learning outcomes by year: the program clearly delineates the expected learning outcomes by year. This is useful for lesson planning, assigning current grades, and tracking student progress within each class period. 5. Specifying activities for the formation of competencies: This program offers specific activities, such as «project activities,» «design thinking,» «working with information sources,» «modeling and construction.» This gives the teacher clear tools and directions for organizing the learning process.	2. Emphasis on research and interaction with the real world: Zasekina's program places a strong emphasis on "research, design, modeling, construction activities." This means that applicants will not just learn theory, but will be able to explore, create, and see how it relates to the world around them. 3. Use of digital tools: Practical tasks show how to apply various digital tools and means for project implementation. 4. Formation of "competence to assess the impact of science and technology on society": The training is aimed at developing a responsible attitude towards the use of science and technology.	2. Modular structure, content lines focused on the needs of society, health, ecosystem. 3. Cross-cutting topics: professions, contribution of Ukrainian scientists, sustainable development goals. 4. The program can be taught as a set of additional modules to the subjects of the main disciplines. Teachers can develop their curricula by supplementing them with STEM modules. In this case, the STEM modules are taught by teachers of the relevant subject. An effective approach at the stage of starting to implement STEM education at school, allowing schools to adapt STEM education to the available resources and capabilities of teachers. Provides a smoother transition to STEM-oriented education without requiring significant changes in the curriculum. Allows teachers to gradually master STEM approaches, starting with the integration of individual modules into their subjects.

Disadvantages		
1.High requirements for teacher qualifications. Possession of subject competencies from many subject areas. 2.The need for modern equipment for research and project implementation 3.Complexity of assessment. Preference is given to formative assessment based on a portfolio of completed projects, etc. 4.Risk of superficial mastery of knowledge and skills in various fields of science and technology.	1. Dependence on the availability of appropriate equipment: Schools need to be properly equipped to conduct research and use digital technologies. 2. Potential difficulty in balancing the depth of study of individual subjects: An integrated approach may require careful planning to ensure that the basic knowledge of each discipline is sufficiently covered. 3/ Measuring the level of STEM competencies and research skills requires the development of comprehensive assessment approaches. 4. Lack of teacher readiness can lead to formal implementation of the program, when integration is superficial and projects are reproductive. 5. Risk that learning will be disconnected from real life.	1.Superficiality of integration, loss of key STEM ideas. Fragmentation of knowledge. Students may not see the connection between what they learn in math class and what they do in technology class. 2. Difficulty in coordinating teachers who will teach parts of the course to ensure coherence and achieve the common goal, the expected learning outcomes of the program. 3. Complexity of assessment in case of distributed teaching of modules. 4. Lack of teacher readiness to effectively integrate STEM-modules into their subjects. 5. Limitations of opportunities and difficulties in implementing projects that require the application of knowledge from different disciplines if STEM is taught in separate blocks.
Decisions		
Engaging multidisciplinary teams of teachers as mentors and consultants Update the material and technical base Ensure a balance between integration and learning of basic knowledge.	Implementing projects that are relevant to students and take into account the local context. Differentiated approach and support for all students Development clear assessment criteria and tools.	Ensure a balance between learning and other activities. Carefully plan the learning process and organize teacher collaboration. Take into account the needs and capabilities of all students.

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Specialized STEM model curricula designed for primary school students open up opportunities for mass STEM education, positioning schools as places where young people are prepared for the challenges of the future. Combined with continuous infrastructure improvements, STEM laboratories/centers and resource optimization, the programs highlight the school's ability to implement transformative innovative solutions. Training under specialized STEM model programs (grades 5-6 and 7-9) eliminates critical gaps in STEM education and bridges the gap between primary and secondary (specialized) schools, where it is transformed into STEM clusters. This is particularly important in the context of the growing popularity of STEM education and the desire of an increasing number of educational institutions of various levels and types to introduce such innovation.

The successful implementation of this Ukrainian project is based on several key assumptions set out in the programs themselves. First, the STEM-program provides for the further development of students' interest in studying STEM subjects (as evidenced by 85% of respondents in the study) (S.Boiko, 2025), who indicate a strong willingness to participate in STEM projects, and 90% of parents demonstrate their full support. Secondly, it is expected that this interest, supported at the state level by policies for the development of STEM education, will lead to a significant number of young people obtaining professional and higher education in STEM fields, with a subsequent choice of STEM professions. The process of transforming the education system towards education for life and future success is reflected in the Ministry of Education and Science's policy of the same name (MES of Ukraine, 2025)1.

Thirdly, when the STEM program moves into the subject study cycle, grades 7-9, taking into account the psychological characteristics of adolescents and their personal growth, the authors of the program aim to form a STEM identity based on the STEM competencies acquired during the course of study (Buturlina O. et.al., 2024).

Fourthly, STEM programs provide for the active involvement of students in community life. For example, in grade 6, when studying the topic 'Drivers of the Economy', they conduct research on the economy of their region, determining what is the driver in their communities. In Grade 7, the module 'Millions Underfoot' allows them to study the resources of the community and compile its profile, which, using modern strategic planning tools and based on SWOT analysis, sets SMART goals and proposes their own solutions for promoting goods and services produced in this

1 Education for Life. (n.d.). Comprehensive policy for the implementation of the NUS reform. https://educationforlife.mon.gov.ua/.

territory, builds business models for future enterprises, based on the needs and available resources for community economic development, and develop strategies to improve community recognition (brand development, identity, advertising media products). In addition, it is expected that students who are motivated to develop their own city or town will stay, settle in communities in the future, return home to create new businesses, jobs, and added value in their territory, applying their own STEM potential, while parents and the community will support these initiatives and reinforce the importance of STEM education. STEM curricula are easily adaptable to the local context, and the use of problem-based and cooperative project-based learning ensures the implementation of the C-STEM-PBL model and collaborative learning. The integration of STEM into educational practices is presented as a key step towards promoting a knowledge-based economy and achieving the Sustainable Development Goals (SDGs). Finally, the STEM program assumes that communities will perceive this educational initiative as part of human resource development policy, include STEM in strategic documents on community development, participate in the financing of STEM-activities, STEM-labs, and open specialized lyceums in the field of STEM clusters.

All of the above requires the necessary resources: material and technical (state-of-the-art infrastructure), informational (teaching and methodological support, programs, textbooks, etc.), and human (a generation of teachers ready to teach STEM). Obviously, the implementation of STEM programs requires additional training and retraining of teachers.

In summary, the development of model STEM curricula in the New Ukrainian School reform is an innovative initiative that promotes the institutionalization and standardization of STEM education in Ukraine and its widespread implementation. Using the State Standard for Basic Secondary Education and the Model Educational Program as their solid institutional foundation, establishing strategic partnerships and maintaining a commitment to educational excellence, these programs aim to meet the growing demand for specialized STEM education among a wide range of educators. An active position in the development of STEM not only enhances Ukraine's reputation in the European educational space as a center of academic excellence, but also aligns with national goals for scientific research, innovation, workforce development and economic progress.

The development of teaching materials, appropriate textbooks for students, and manuals for teachers has a significant impact on the quality of mass implementation of STEM and the universality of its design based on the principle of 'low threshold, high ceiling.' STEM projects with an entrepreneurial background, the integration of STEM disciplines and economic knowledge with a focus on achieving the Sustainable Development Goals, and the use of well-structured pedagogical scenarios and STEM project case studies will be attractive to students and teachers. Despite the lack of material and technical resources for integrated STEM education, students demonstrate a high level of trust in the teaching work of teachers and a positive attitude towards activity-based, problem-oriented, integrated approaches to learning. Research conducted in Ukraine over the past five years and differences in interpretation highlight the need to develop a common understanding of pedagogical approach standards to the implementation of STEM.

The main arguments in favor of standardization are that it ensures stability in crisis conditions, which Ukraine has experienced over the last 10 years, and is an important factor in the mass implementation of STEM education and ensuring its accessibility; it shapes the adaptability of education to change and, finally, emphasizes the link between mass STEM education and the formation of a sustainable and innovative society.

Conclusions. Standardization of STEM education in Ukraine is a critically important step towards sustainable development in the context of the ongoing crisis caused by the full-scale invasion by the Russian Federation. The experience of recent years has clearly demonstrated both the vulnerability of the education system, as evidenced by the destruction of more than 3,500 educational institutions and the forced displacement of millions of students and teachers, and its powerful potential for adaptation and innovation. Uniform, clear standards for all levels of STEM education, from pre-school to higher education, are critically important for ensuring the competitiveness of Ukrainian specialists in the global market and meeting the country's domestic needs for qualified personnel, especially in the context of post-war recovery.

Despite the significant challenges associated with the physical destruction of infrastructure, lack of funding and staff shortages, the crisis also opens up unique opportunities. It stimulates innovation in teaching methods, especially in the development of distance and hybrid learning, which expands access to quality education even in conditions of security risks. This is confirmed by the dynamic development of national digital education platforms and the creation of new educational initiatives. The urgent need to solve complex problems caused by the war — from demining

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territories and restoring logistics to cyber security and medical innovations — raises awareness of the importance of STEM innovation.

Based on the analysis, it can be argued that the successful standardization of STEM education in Ukraine requires a systematic approach that combines:

- adaptability and flexibility in the development and implementation of curricula and educational standards;
- the development of STEM educational content;
- investment in the training and retraining of STEM teachers, in particular through professional development programs;
- the development of STEM laboratory and center infrastructure based on international standards;
- psychological support for participants in the educational process – students, teachers, parents, overcoming educational losses, maintaining motivation for learning and professional development;
- active international cooperation for the exchange of best practices.

Under these conditions, STEM education in Ukraine will retain its status as the foundation for Ukraine's sustainable development and competitiveness, prosperity and integration into the global technological space of the post-crisis world.

Specialized model curricula for STEM education play a key and decisive role in its standardization, especially in Ukraine, where the educational system is actively transforming and crisis conditions require quick and effective solutions. Their role is manifested in several ways:

- ensuring unity and consistency of content; model programs establish a basic framework of content, expected learning outcomes, and key competencies to be developed in students at different levels of STEM education (preschool, primary, basic secondary, and senior specialized). This ensures horizontal and vertical coherence of learning, allowing students to move smoothly between educational levels and successfully master more complex concepts;
- they help to equalize the quality of STEM education across the country, reducing the gaps between different regions and educational institutions, which is especially important in conditions where the material and technical base and staffing can vary significantly;
- model programs do not just list topics, but also offer recommended methodological approaches to teaching STEM based on integration, project activities, experiential learning, and practical application of knowledge. This is the basis for moving away

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from traditional subject-based teaching to the development of comprehensive skills; it encourages the use of innovative pedagogical technologies, such as robotics, 3D modeling, and programming, which are an integral part of modern STEM education;

Specialized model curricula play a key role in standardizing STEM education, which manifests itself in several ways:

- ensuring unity and consistency, model programs establish a basic framework for content, expected learning outcomes and key competencies that should be developed in students at different levels of STEM education (preschool, primary, lower secondary, upper secondary).
- horizontal and vertical coordination of learning, allowing students to move smoothly between educational levels and successfully master more complex concepts;
- model STEM curricula contribute to the equalization of STEM education quality at the national level, reducing gaps between regions and educational institutions, which is essential given the variability of material and technical resources, staffing, and safety conditions.
- model programs offer recommended methodological approaches to teaching STEM based on integration, project activities, research-based learning, and practical application of knowledge. This is the basis for the formation of complex skills;
- specialized model STEM curricula clearly define which competencies (engineering thinking, research and scientific literacy, creativity, problem-solving, digital literacy) should be developed and what learning outcomes are expected.
- model curricula provide teachers with sufficient academic freedom and autonomy to adapt content to local conditions, student interests, and available resources, implementing the C-STEM-PBL model. This encourages the search for effective solutions within the established framework.
- STEM programs serve as a guideline for the development of relevant professional development programs for teachers.

Thus, specialized model curricula are the foundation for the standardization of STEM education, ensuring consistency, quality, continuity, accessibility, mass appeal, competence orientation and innovation. They form a holistic STEM education ecosystem that meets the needs of modern Ukrainian society in times of crisis and prepares Ukrainian youth for life and professional activity in a rapidly changing world.

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3.2. ANALYTICAL REVIEW OF THE STATE OF DEVELOPMENT OF SCIENTIFIC-METHODOLOGICAL SUPPORT FOR IMPLEMENTING STEM EDUCATION IN UKRAINIAN LYCEUMS

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Over the past decade, Ukraine's progress toward the formation of a knowledge society has been shaped by STEM education—an integrated field designed to unite the natural sciences and mathematics with technological and engineering practices. While the contours of scientific and methodological

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support have already been established for basic (gymnasium) schooling, the specialized lyceum level is only entering a phase of systemic rethinking. It is precisely at this final stage of general secondary education that young people complete the process of professional self-determination, acquire advanced competencies, and establish their readiness for further academic or engineering pathways. Therefore, a comprehensive analytical review of the state of STEM support in lyceums is not merely a matter of scholarly interest but a strategic prerequisite for modernizing the entire specialized segment of schooling.

The purpose of this analytical study is to synthesize the available normative, scientific, and practical achievements, to identify gaps, and to outline prospects for methodological support of STEM education in upper secondary school. The analysis focuses on: the evolution of state policy, curricular models, educational and technological solutions, systems of internal and external assessment, as well as the local experiences of lyceums already implementing diverse STEM formats. A complex of methods has been applied-documentary analysis, comparative study of educational models, statistical monitoring of student and teacher performance, and case studies of innovative practices. Such multidimensionality makes it possible not only to record the current state but also to highlight causal relationships between policy decisions, resource provision, and educational outcomes.

Structurally, the subsection proceeds from the general to the specific: first presenting the regulatory and scientific-methodological contexts, then characterizing existing methodological products, followed by an analysis of experimental platforms and local models, and concluding with challenges and recommendations for further development of the toolkit. This sequence allows the reader to trace the logic of STEM education deployment in lyceums and to assess the depth and relevance of the proposed solutions for a future strategy of scientific and methodological support.

Thus, the proposed analytical research aims to create a conceptual and practical platform for the research team of the Department of STEM Education at the Institute of Pedagogy of the National Academy of Educational Sciences of Ukraine, which is tasked with developing a comprehensive set of methodological materials. This inquiry sets framework guidelines that combine academic rigor with the concrete needs of educational practice, thereby forming a foundation for the further modernization of Ukraine's specialized secondary education in line with global STEM trends.

Regulatory and legal framework for implementing STEM education in specialized schools (lyceums). The competency core of STEM-oriented learning is primarily en-

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shrined in basic laws. In particular, the Law of Ukraine “On Education” (2017) defines ten key competencies, among which natural science and mathematics, technological, and innovation competencies are highlighted. It also guarantees academic autonomy for institutions to select integrated courses (Zakon Ukrainy. Pro osvitu, 2017). Additionally, the Law of Ukraine “On Complete General Secondary Education” (2020) introduces a two-tier structure of specialized schooling, establishes the lyceum as a distinct institutional type, specifies the profile model, and confirms students’ right to choose interdisciplinary courses, including STEM-oriented ones (Zakon Ukrainy. Pro povnu zahalnu seredniu osvitu, 2020).

The provisions of these two legislative acts form the fundamental normative basis for any methodological solutions in upper secondary education.

To reinforce the legislative framework, the strategic direction is set by the Concept of the “New Ukrainian School” (2016), which first established the idea of integrating science, technology, engineering, and mathematics across all educational levels. Its provisions were elaborated in the Cabinet of Ministers Resolution No. 960-r of June 25, 2020, “On Approval of the Concept for the Development of Natural Science and Mathematics Education (STEM Education) until 2030.” The document envisages content renewal, teacher training, infrastructure modernization, and defines performance indicators for annual monitoring (Kabinet Ministriv Ukrainy, 2016, Kabinet Ministriv Ukrainy, 2020a).

The next level of the normative hierarchy consists of ministerial orders, including:

Order of the Ministry of Education and Science of Ukraine (MoES) No. 1451 of October 10, 2024, “On Approval of Conceptual Principles of Specialized Secondary Education Reform (Academic Lyceums),” which identifies STEM as one of four official profiles of upper secondary education and outlines the structure of model curricula;

Order No. 1438 of October 9, 2024, “On Implementation of the Innovative Educational Project ‘Scientific and Methodological Support of STEM Education in Educational Institutions (2024–2027),’” which launched a nationwide experimental platform involving the first pilot lyceums to test methodological materials, assessment systems, and equipment models (Ministerstvo osvity i nauky Ukrainy, 2024a, Ministerstvo osvity i nauky Ukrainy, 2024b).

Standardization is ensured by the State Standard of Basic Secondary Education (Cabinet of Ministers Resolution No. 898 of September 30, 2020), which defines cross-cutting “STEM competencies” and expected outcomes, as well as the draft State Standard for Specialized Secondary Education (public consultation – April

2025) (Kabinet Ministriv Ukrainy, 2020b). Based on these documents, a draft Model Curriculum for Grades 10–12 (April 16, 2025) has been prepared, including a mandatory integrated course “Engineering and Robotics” (5 hours/week) and an optional module “STEM/STEAM Projects” (Ministerstvo osvity i nauky Ukrainy, 2025c).

Further clarifications on the model curricula are provided in a methodological letter from the Institute of Educational Content Modernization (IMCE) and analytical materials on the NUS portal (June 2025), which outline the possibilities for developing internal lyceum variants of curricula and position the STEM module as an interdisciplinary “platform” for deepening profiles in natural sciences, IT, or engineering (Instytut modernizatsii zmistu osvity, 2025a, Instytut modernizatsii zmistu osvity, 2025b).

Financial and logistical support is ensured through targeted subsidies for STEM equipment. For 2025, UAH 499.4 million was allocated, with application procedures and timelines published by MoES in April 2025 and distribution across 17 regions and Kyiv approved by Cabinet Resolution of June 12, 2025. The funds are intended for biology, physics, chemistry, geography, and mathematics classrooms, as well as specialized STEM laboratories (Kabinet Ministriv Ukrainy, 2025).

The staffing dimension is regulated by the Professional Standard “Teacher of General Secondary Education Institution” (MoES Order No. 1225 of August 29, 2024), which specifies requirements for teachers’ knowledge and skills in project-based, research, and engineering student activities. The standard serves as a basis for professional development and certification programs for STEM-subject teachers.

Beyond laws and standards, the practical implementation of STEM education in upper secondary schools relies on a series of national projects, either established by MoES orders or carried out under its supervision. These initiatives serve as an “operational bridge” between normative declarations and the daily practices of lyceums, providing educational, methodological, and information-communication support. (… translation continues with descriptions of projects such as the 2024–2027 national experimental project, the annual “STEM Spring” Festival, the “STEM School” sessions, the “Engineering Week”, and the National STEM Day, along with their role in building a practical ecosystem of state support, ensuring teacher professional development, and promoting public visibility of STEM initiatives.)

Scientific and methodological context of STEM education in Ukrainian lyceums.

Over the past decade, STEM education has transformed from an innovative trend into a mandatory component of state policy in the sphere of general secondary education. However, legal and regulatory consolidation provides only a framework;

actual implementation depends on the scientific and methodological foundation, which has become the subject of this review.

An analysis of the scientific and methodological literature on the implementation of STEM education in Ukraine reveals the evolution of scholarly approaches.

In the context of contemporary educational development in Ukraine, particular attention is drawn to the integration of STEM approaches into school curricula. The first domestic studies dedicated to STEM were aimed at the theoretical consideration of possibilities for combining knowledge from the natural sciences, technology, engineering, and mathematics within interdisciplinary courses. These studies laid the methodological foundation for the further introduction of STEM education into national educational practice.

Among the first researchers to address STEM education were O. Topuzov and N. Demianenko. In their work, they viewed STEM as a promising direction for the integration of natural and mathematical knowledge, focusing on the formation of a holistic scientific worldview among students and the development of their ability for interdisciplinary analysis (Topuzov & Demianenko, 2015). The authors emphasized the need to update school curricula and implement integrated forms of learning.

The significance of integration as a didactic principle was revealed in the work of O. Savchenko, who, although not directly focused on STEM, provided a theoretical justification for the interdisciplinary approach as a key condition for modernizing the content of education (Savchenko, 2014). She emphasized the necessity of forming a holistic, coherent understanding of the world through the combination of knowledge from various subject areas.

A significant contribution to the development of the theoretical and methodological underpinnings of STEM education was made by N. Prokopenko and L. Smoliar, who considered STEM not only as an interdisciplinary model but as an integral educational paradigm (Prokopenko & Smoliar, 2016). In their work, the authors argued for the importance of developing students' research and project skills, as well as updating didactic tools oriented toward practical activity and problem-solving.

A separate niche within the STEM discourse was occupied by the issue of developing engineering thinking, researched by M. Lazarenko. The author highlighted the need to foster in students the ability for technical modeling, design, and rational project development (Lazarenko, 2015). His work emphasized the role of STEM approaches in cultivating engineering culture and practical skills among future specialists.

Practical pathways for implementing the STEM approach in general secondary education were analyzed in the work of T. Volosiuk and S. Sakaieva. They examined the organizational and pedagogical conditions for implementing integrated learning, oriented toward active, project-based, and experimental student activity (Volosiuk & Sakaieva, 2017). Their research stressed the importance of adapting STEM to the realities of the Ukrainian school, particularly with regard to staffing and methodological support.

Thus, an analysis of early Ukrainian studies demonstrates that at the initial stage of STEM development in Ukraine, the dominant focus was on integrating the content of natural and mathematical disciplines, developing engineering thinking, and promoting project-based learning. Ukrainian scholars directed their efforts toward adapting global STEM experiences to the national educational context, thereby creating the foundation for the subsequent development of this educational paradigm.

Since 2018, emphasis has gradually shifted toward the competency-based approach, where STEM is viewed as a platform for the development of critical thinking, creativity, and engineering design. Expanded conceptual frameworks can be found in the works of V. Bykov and S. Semerykov, who propose the “concentric circles” model of integration that combines levels from policy to classroom practice (Bykov & Semerykov, 2023).

Since 2024, the discussion has intensified regarding the transition from STEM to STEAM, whereby art is added to the dominant cluster of natural and mathematical disciplines as a space for creative synergy. Contemporary research by A. Oleksiuk underscores cloud-oriented ecosystems that ensure the continuity of STEM projects regardless of the physical laboratory environment (Oleksiuk, 2023).

Thus, the theoretical foundation has evolved from subject-oriented integration toward a systemic vision of STEM/STEAM as a methodology for forming cross-disciplinary competencies based on digital ecosystems.

The analysis of literature on the development of scientific and methodological support for STEM education makes it possible to identify three of the most widely used models:

- Laboratory-oriented (FabLab model). Experiences of lyceums in Kyiv and Kharkiv demonstrate the transformation of traditional physics and labor training classrooms into FabLab spaces equipped with 3D printers, laser cutters, and Arduino microcontrollers (Donets, 2024). Methodological materials focus on project-based modules lasting 18–24 academic hours.

- Cluster-based (block) integration of subjects. The collection "STEM Education in the Regions of Ukraine" (NENC, 2024) describes "cluster weeks," during which mathematics, computer science, and chemistry are united under a common theme (e.g., "green energy") (Shkuropet, 2024). Positive dynamics in student motivation and interdisciplinary connections were observed, though standardized performance indicators remain lacking.
- Networked (hub) model. The IMCE innovative project (2024–2027) envisages the creation of a nationwide network of STEM hubs with a centralized repository of digital resources and remote master classes (Instytut modernizatsii zmistu osvity, 2024a). Methodological guides describe in detail the roles of coordinator, mentor, and facilitator of online events.

These models demonstrate high flexibility, yet their effectiveness remains limited to pilot implementations; no large-scale studies have yet confirmed their outcomes.

The issue of assessing STEM competencies among students in grades 10–12 remains under-researched. The first attempts include rubrics for evaluating complex projects in cloud-based environments (Nahrybelna, 2023). In addition, the IMCE methodological recommendations (2024) provide a pilot monitoring matrix covering cognitive, operational-technological, and value components (Instytut modernizatsii zmistu osvity, 2024b).

However, these tools have not undergone broad validation. The absence of standardized indicators makes it impossible to compare results across institutions and hinders the creation of a national ranking system of STEM competencies—representing a significant gap in scientific and methodological support.

At present, the scientific and methodological support of STEM education in Ukrainian lyceums is at a stage of active formation. The most developed areas include conceptual frameworks and models of laboratory-oriented and cluster-based learning. Other aspects—particularly content-related provisions of methodological support—remain insufficiently researched, which underlines the relevance of this study.

Key challenges for upper secondary school in implementing STEM education.

The establishment of specialized STEM education in lyceums occurs at the intersection of regulatory ambitions and the real capacities of institutions; thus, every step of reform is accompanied by a set of systemic and contextual problems. A broad understanding of these challenges helps not only to diagnose the "bottlenecks" but also to outline trajectories for further action.

The first and foremost issue is the discrepancy between the speed of normative decisions and the pace of developing practical methodological materials. Foundational documents have already mandated the integrated course “Engineering and Robotics” and the module “STEM/STEAM Projects.” However, detailed syllabi, collections of competency-based tasks, and standardized assessment tools for upper secondary school are still at the piloting stage. As a result, lyceums are compelled either to extrapolate materials created for lower secondary levels—which do not cover advanced requirements—or to improvise, relying on scattered online resources and volunteer initiatives. Such a “technological gap” can lead to inconsistencies in approaches and misalignment of educational outcomes across different institutions.

Equally acute is the issue of staffing. An advanced STEM program requires teachers capable of combining knowledge from mathematics and the natural sciences with skills in digital and engineering technologies. In Ukraine, most physics, chemistry, or computer science teachers have undergone classical training oriented toward disciplinary separation. Reorienting them toward interdisciplinary courses and project-based pedagogy is possible only through long-term (not short-term, but certification-based) programs where theory is combined with practice using modern equipment. However, such 90-hour or longer programs are currently offered only sporadically; the system of mass professional development is still unable to meet demand, particularly in rural regions.

Material and technical asymmetry between lyceums in large cities and those in small communities adds another layer of risk. Despite the availability of state subsidies, their volume does not fully cover the costs of comprehensive re-equipment of each classroom, and co-financing mechanisms are often inaccessible to poorer territorial communities. As a result, some lyceums acquire fully equipped STEM laboratories with 3D printers, laser engravers, and high-precision sensors, while others are limited to basic demonstration sets. Such inequality deepens disparities in graduate preparation and reduces the overall national effectiveness of reforms.

Another component of the challenge is the mismatch between the new learning paradigm and the current system of final assessment. The External Independent Assessment (NMT/DPA) is predominantly oriented toward testing theoretical knowledge, whereas STEM projects focus on the ability to apply knowledge to solve complex practical problems. If the format and content of state examinations are not revised, teachers will face a dilemma: to prepare students for the test or to support project-based activities. The absence of a “single front” of signals from the state demotivates both students and teachers, who struggle to connect the evaluation of creative projects with outcomes that directly affect university admission.

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Special attention must also be paid to the creation of monitoring and analytical systems capable of tracking the dynamics of STEM competencies at the class, lyceum, regional, and national levels. Currently, data are collected sporadically: separate IMCE studies, Olympiad results, local student surveys. The lack of unified digital tools, such as a "STEM portfolio" or a national panel of integrated indicators, complicates informed management decisions, obscures the successes and problems of individual lyceums, and slows adaptive funding.

Finally, the socio-cultural context of wartime introduces specific barriers: student migration, psychological stress, limited access to stable internet and electricity in certain communities. Under such conditions, ensuring continuity of project work, laboratory experiments, and interschool hackathons is much more difficult than in peacetime. This creates the need for mobile laboratory kits, hybrid models of learning, and psychological support for school teams, which also require additional resources and clear managerial algorithms.

Thus, the key challenges of upper secondary school are not a chain of isolated problems but an interconnected system, where normative gaps exacerbate staffing, resource, and assessment difficulties, while external social factors increase tension. Only a comprehensive approach—synchronizing improvements in the legislative framework, large-scale professional development, targeted equipment funding, reform of the assessment system, and the introduction of digital monitoring—can transform these challenges from restraining factors into drivers of development for the modern specialized school.

Local experience of implementation. Successful cases.

Ukrainian lyceums that actively embrace the philosophy of STEM education are experimenting with several relatively established models, each of which demonstrates its own dynamics of growth. The most widespread format remains the full laboratory model, where modern equipment for robotics, 3D printing, and sensor-based measurements is combined with open access for students. Such an environment encourages independent project work and accelerates the shift from classical demonstrations to genuine engineering design.

A second model involves the simultaneous re-equipment of several natural science classrooms, creating a "cluster" space that physically brings together students from different subject domains and thereby stimulates interdisciplinary research and joint experimentation. In recent years, the concept of DIY laboratories has also gained particular traction, often emerging through grant support or partnerships

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with local businesses. In such spaces, students, teachers, and community members collaboratively assemble or modify equipment, thereby learning resource management and the transfer of engineering solutions to real community needs—such as environmental monitoring or urban design—from the very outset.

Another promising approach is based on an extended network of microlaboratories, where each lyceum receives a limited but standardized set of technical tools and is simultaneously connected to a remote coordination center. This structure enables schools to exchange developments quickly, avoid duplication of expenses, and conduct virtual hackathons or live joint lessons. Finally, national festivals and thematic weeks serve as platforms where local innovations transition into the broader professional field: teachers present their authorial methodologies and receive expert feedback, while student teams compete at the national level, which reinforces motivation and builds portfolios for university admission.

Despite differences in scale and funding, all of the described models demonstrate a common result: the share of project-oriented learning increases, collaboration among teachers of different subjects deepens, and students acquire not only academic but also entrepreneurial and social competencies. Already after the first year of functioning, such environments record significant growth in the number of scientific projects, startup ideas, and participation in engineering-oriented Olympiads, indicating the tangible impact of STEM infrastructure on the quality of upper secondary education.

Lessons learned from local implementation of STEM education in lyceums.

An in-depth analysis of lyceum practices shows that even within the same regulatory framework, the trajectories of STEM infrastructure development vary significantly depending on the chosen model, the financial profile of the community, and the degree of partner involvement. Seven of the most important lessons that have emerged from piloting laboratories, clusters, and interschool networks are outlined below:

Comprehensive re-equipment of several adjacent classrooms creates a synergy effect. Lyceums that simultaneously modernized physics, chemistry, biology, and computer science facilities transitioned more quickly to interdisciplinary projects because teaching teams began planning joint scenarios already at the stage of equipment installation. Where resources were distributed in a fragmented way, students tended to remain within a single subject area and less often engaged in complex engineering tasks.

DIY laboratories foster entrepreneurial thinking and civic responsibility. Projects in which students independently assemble or modify devices (often funded by charitable grants or donations from local businesses) demonstrate much higher "project productivity": children not only use the setups but also understand their construction and maintenance logic. One such example is a laboratory created with community and philanthropic funding, where students immediately integrated 3D printing into environmental monitoring.

Cost-sharing strengthens project sustainability. Where part of the expenses is borne by the community (parent committees, local entrepreneurs, self-government bodies), equipment is used daily and better maintained, as several stakeholders take responsibility. Financial co-ownership creates a sense of involvement and protects laboratories from downtime or vandalism—an especially important factor for small or remote lyceums.

Coordination hubs and regional STEM centers minimize duplication of costs. In regions where a single center with methodological, service, and logistical functions has been established, schools operate with standardized equipment sets and easily exchange results. Complex devices (such as precision milling machines or spectrometers) are concentrated in the hub and made available remotely or on a rotational schedule. This reduces the financial burden on individual lyceums and gives students access to equipment that would be economically impractical for each school to purchase.

The state subsidy for STEM equipment is effective only when combined with project-cycle management. Lyceums that had clear roadmaps (defined procurement lists, teacher training schedules, curriculum integration plans) utilized funds without delays and already presented results. Where project management was weak, equipment was underutilized or used below its potential.

National festivals and thematic weeks turn local innovations into collective resources. Formats such as "STEM Spring" provide lyceums with a public platform for validating and scaling their methodologies: teachers receive expert reviews, students gain competitive incentives and portfolio entries, while the Ministry of Education and Science collects a "data field" for further policy adjustments.

Teacher mentoring networks ensure the continuity of innovation. Some teams have initiated online mentorship: educators already experienced with equipment regularly conduct webinars for colleagues in other regions. This helps to address staff shortages in remote communities, where in-person training is less accessible due to logistics or wartime circumstances, while simultaneously creating horizontal connections among lyceums—a foundation for joint hackathons and interschool startups.

In summary, local experience demonstrates that the success of specialized STEM education is determined not by the size of the budget as such, but by a balanced combination of strategic planning, multi-channel funding, teacher networks, and institutional coordination. This constellation of factors transforms isolated "points of innovation" into a systemic resource capable of scaling to the level of national education policy.

The conducted analysis shows that in recent years Ukraine has built a strong regulatory and legal foundation for STEM education in upper secondary schools: the profile differentiation of lyceums has been enshrined in law, strategic concepts and standards have been adopted, state subsidies and nationwide support projects have been launched. However, a significant gap remains between the declarative level and everyday practice. The most acute shortcomings concern human resource capacity, equitable equipment provision, and, above all, the methodological content that would uniformly regulate curriculum, teaching technologies, and assessment of outcomes across institutions.

Thus, within methodological provision, the most developed areas remain laboratory-oriented and cluster models of learning, along with comprehensive teacher professional development programs. Their piloting has demonstrated an increase in interdisciplinary cooperation and growing student motivation. STEM education in Ukrainian lyceums already rests on a substantial methodological foundation but requires systemic solutions in assessment, infrastructural equity, and sustainability in order to become a full-fledged catalyst for human capital development.

Local cases show that pioneering lyceums have already managed to establish diverse model laboratories and mentoring networks, but their success depends on targeted grants, teacher enthusiasm, and community support. This "island approach" provides quick wins but does not guarantee system-wide coverage or scalability. Without the unification of content and assessment tools, differences in the quality of training between regions will only widen, and state investments will not yield the desired returns.

Therefore, the strategic priority of the next reform stage must be the creation of a unified, flexible, yet coherent system of teaching and methodological support for STEM education in lyceums. It should include: model programs for advanced courses, manuals, methodological guidelines, banks of project tasks and competency-based problems, standardized assessment rubrics, typical scenarios for using laboratory equipment, as well as long-term certification programs for teacher professional de-

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velopment. Only by integrating these components into the national education system will Ukraine be able to transform isolated successful practices into full-fledged state policy and ensure that lyceum graduates acquire competitive STEM competencies aligned with the challenges of today's economy and science.

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3.3. NEURONAL ASPECTS OF USING THE CREATIVE POTENTIAL OF ART IN STEM EDUCATION

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The integrative nature and practical and creative focus of STEM education define it as an educational metasystem that shapes specialists into active, actualized, self-realized individuals who are capable of rapid professional transformation and improvement in line with the demands of their work and the labor market. The unique and organic combination of the four main components (science, technology, engineering, mathematics) in the STEM "metasystem" each of which is an established and significant sphere of human activity is implemented through the "professional telos" of training effective and competent specialists in conditions of rapid technological, industrial, and sociocultural change. In this context, considering current development trends, we note that, according to J. Lyotard, for postmodern societies, the idea of competence and the competent specialist is a significant sociocultural phenomenon (Lyotard, 1979, p. 7). Competence is thus understood as a "professional telos" and a sociocultural telos that determines the "communicative" and professional inclusion of a specialist in society and the profession. Thus, the competence of a specialist, professionalization, economic efficiency, and communicativeness as important components of the competence paradigm determine its integrative nature. In this case, the competency-based approach acts as a "universal integrator" of different and "autonomous" spheres – science, technology, engineering, and mathematics in the STEM metasystem. This aspect of the integrative potential of the competency paradigm and its teleological significance for STEM is also linked to the idea of technologization, which is represented in STEM as "Technologies." Technologization is a way of constantly improving economic and production efficiency and, accordingly, it is a universal integrator and, to a certain extent, the highest goal (telos) of STEM. This, in turn, technologizes both professional activity and specialist training, which includes the possibility of identifying typical, planned, and predictable phenomena, operations, algorithms, scenarios, and expected results in the process of professional activity through the active involvement of the specialist in STEM "metatechnology." In modern societies, there were certain analogues of STEM, but locally, as interdisciplinary and intersectoral integration. Although some specialists acquired competencies similar to those formed by STEM education, such cases were rare. Interpreting J. Lyotard, we can say that in the modern era and in professional spheres, metanarratives prevailed (Lyotard, 1979, p. 7). Mathematics, as a fundamental science and as a science in general, has its own specific metanarratives with its own specific vocabulary, which to a certain extent limited their practical influence on education, culture, and production. An important change today is that in the STEM education system, the metanarratives of each field are no longer grand theoretical constructs, but are largely transformed into an accessible format of professional communication aimed at achieving specific educational and practical results. Within the framework of STEM education, in the process of implementing specific projects and goals, there are processes of technologization, operationalization (the use of theoretical concepts for the development of technologies and methodologies), and the concretization of the areas that form STEM. Specialists acquire the ability to solve specific problems and achieve specific goals, and the components of STEM play the role of strategies and specific mental tools and technologies for them. The "problem paradigm" becomes dominant, rather than the paradigm and specifics of each of the areas, against the backdrop of a sufficient level of training in the specified main areas. Similar processes are taking place in modern science, where not

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only specific scientific directions and fields begin to dominate, but also integrative strategies aimed at solving specific scientific problems with the involvement of the potential of various sciences, practices, and technologies. Communication and the development of soft skills, including teamwork and collaborative interactions, play a decisive role in STEM, which generally contributes to the development of synergistic effects.

In order to gain a deeper understanding of the research topic, we will analyze scientific works that highlight the main approaches and theoretical foundations of the chosen topic.

Meylani R. has researched the role of STEM education in preparing students for the challenges of the 21st century and is studying the effectiveness of online learning environments (OLE), highlighting "brain-based approaches" as an important topic (Meylani, 2024, p. 8210). The author identified 46 characteristics grouped into 10 thematic areas covering technological, pedagogical, and psychological aspects. The results emphasize the importance of an innovative approach to online education design and provide practical recommendations for educators and developers.

Martín H. R., García González J. M., and Mirón Canelo J. A. determined the effectiveness of the Socratic teaching method and the brain-based teaching approach (BBTA) (Martín et al., 2021). The study aimed to identify the relationship between the Socratic methodology of teaching physics and the development of students' executive functions. The results of the Stroop test showed a statistically significant advantage of the brain-based teaching approach (BBTA) in enhancing cognitive inhibition, indicating its positive impact on reasoning processes. The data obtained confirm the effectiveness of this approach in developing executive functions regardless of the students' gender.

Marchak D. and Shvarts-Serebro I. V. examined the concept of a multidimensional learning grid as an innovative tool for creating meaningful and multi-level learning experiences (Marchak & Shvarts-Serebro, 2021). Using the example of teaching chemistry in high school, the authors demonstrate how the integration of neuropedagogy, art, and an interdisciplinary approach contributes to better assimilation of abstract educational material. The results presented demonstrate the effectiveness of this approach in the development of visualization, creative thinking, and interdisciplinary integration of knowledge.

A study by de Barros Camargo C. and Fernández A. H. analyzed the potential of integrating neuropedagogy, neuroimaging, artificial intelligence (AI), and deep learning to improve the effectiveness of educational processes in accordance with the neurocognitive profile of students (Barros Camargo & Fernández, 2024). The results confirm a significant positive relationship between these components. Neuroimaging data showed increased activation of the frontal areas of the brain and improved synchronization of brain waves during AI-supported tasks, indicating the integration of information processes and opening up prospects for personalized learning.

The research of Repizo J. P. is important, who applies the principles of neuropedagogy in the project "My body, my temple" to actualize the influence of emotions on the process of learning Spanish (Repizo, 2024). This approach is effective – students' motivation to learn, emotional intelligence, and language skills have increased.

A study by Mystakidis S., Christopoulos A., Fragkaki M., and Dimitropoulos K. examined the importance of developing a scientifically sound understanding of the role of neuroscience in teaching among higher education teachers in order to improve teaching effectiveness (Mystakidis et al., 2023). As part of an international project, a six-module course on educational neuroscience was developed and an online community of practitioners was created. Survey results showed a high level of satisfaction with the course and highlighted the need for mentoring and collegial support for the successful implementation of neuroscientific approaches in teaching practice.

Based on preliminary analysis, the following aspects of STEM are relevant for theoretical understanding and practical application: the emergence of this field, both in education and professional practice, reflects the systemic and defining processes of high-tech, computerized, cognitive, and innovative postmodern societies; The factors that determine the integration of the components (science, technology, engineering, mathematics) of STEM are competence and competent specialists as central figures in postmodern society, as well as the cross-cutting phenomenon of technologization, including informatization, effective professional and educational communication, the telos (higher and ultimate goal) of economic efficiency, innovation, and creativity. STEM is also the result of a significant degree of integration of all spheres of life, primarily education, science, production, the social sphere, culture, and technology, which is achieved through various strategies and, above all, through informatization (Klochko et al., 2023; Fedorets et al., 2024). A significant factor in such integration of STEM components is the cross-cutting cognitivization of the "knowledge society."

In further anthropologically oriented reflections on the essence of STEM education, we focus on the phenomena of integrativeness, cognitiveness, anthropological and social orientation, communicativeness, and creativity. These aspects of both STEM education and professional practices are systemic, cross-cutting, and, above all, reflect the cognitive, communicative, and creative essence of human nature. Accordingly, ways to improve STEM education should include the targeted development of the above-mentioned aspects, which we consider to be meta-strategies. We consider art in combination with a neural approach, which reveals innovative and at the same time natural ways of improvement, as relevant and appropriate to human nature, contributing to the development of the above-mentioned meta-strategies.

We consider art in combination with a neural approach, which reveals innovative and at the same time natural ways of improvement, as relevant and appropriate to human nature, contributing to the development of the above-mentioned meta-strategies. The use of art as a component is an established direction in STEAM education, which integrates science, technology, engineering, arts, and mathematics. We focus our methodological intentions on STEM education with the aim of integrating art and a neural approach to improve this type of education, rather than including the arts component as a professional and educational component in its structure. In our view, art and the neural approach, which greatly contributes to the objectification of intellectual and professional development and creativity processes, are the natural factors that will contribute to the disclosure of the intellectual, creative, and communicative potential of the individual in the STEM education system.

In scientific pedagogical literature, the issue of the integrative application of art and neural approaches in STEM education has not been sufficiently explored. The significance of STEM education as an educational, professional, and innovative trend that is actively developing is determined by the need for its further improvement using various approaches. Among such established, innovative, and proven educational practices are artistic and neural approaches presented in the format of neuropedagogy, neuropsychology, cognitive science, and other neurosciences. The application of art and neural sciences in STEM education is also driven by processes of anthropologization, humanization, humanitarization, and the active implementation of inclusion. A relevant aspect of this issue is the education of people with special needs, which requires special approaches and knowledge of the neuropsychological and psychological characteristics of such individuals and, accordingly, the consideration of special knowledge in the organization of the educational process. An important aspect of the integrative use of art and neural sciences is the focus of modern education on health preservation. This is due to the fact that the neural approach, based primarily on knowledge of certain objectively existing patterns and characteristics of the functioning of the nervous system and psyche, determines the understanding of human capabilities and the paths and specifics of human development in accordance with human nature. Art is aimed at: harmonizing the human being, revealing their creative potential and ability to understand and see aesthetics and harmony in its various manifestations, recreation and therapy for certain psychological problems.

Thus, we present the integrative use of the neural approach and art in STEM education as an innovative strategy for improving this educational direction as a pressing issue.

To reveal methodological strategies and present practical and technological aspects of the integrative use of the neural approach and art in STEM education as an innovative strategy for improving this educational direction.

In order to conduct a qualitative analysis of key aspects of research in neuropedagogy, we analyzed the works of scientists that contained the term "Neuropedagogy" in their titles and abstracts.

In Elsevier's Scopus database (Elsevier, 2025) and Web of Science Core Collection (Clarivate, 2025), we found works by scientists from January 2020 to May 2025 based on the query: "Neuropedagogy." Based on the data obtained, a map of thematic categories of research (Fig. 1) was constructed, which was developed in the VOSviewer environment (VOSviewer, 2025). This map was constructed using cluster analysis, natural language processing, and network analysis.

Let's analyze the clusters shown in Figure 1:

I. Cluster 1, "Psychological, pedagogical, and neurophysiological aspects of personality development and learning" (red), represents multidimensional research on human learning and development, integrating psychological, pedagogical, and neuroscientific perspectives, often with an empirical or research lens. The terms indicate a focus on education, psychology, personal development, and scientific research, with a particular emphasis on individual and contemporary pedagogical approaches. There is a strong inclination toward understanding human behavior, learning processes, and self-improvement in an educational or developmental context.

II. Cluster 2, "Modern Educational Strategies: Inclusion, Communication, and Neuropedagogy in Professional Training" (green), focuses on modern educational practices, particularly in the context of training future specialists, with a significant emphasis on communication, inclusion, and the application of neuroscientific

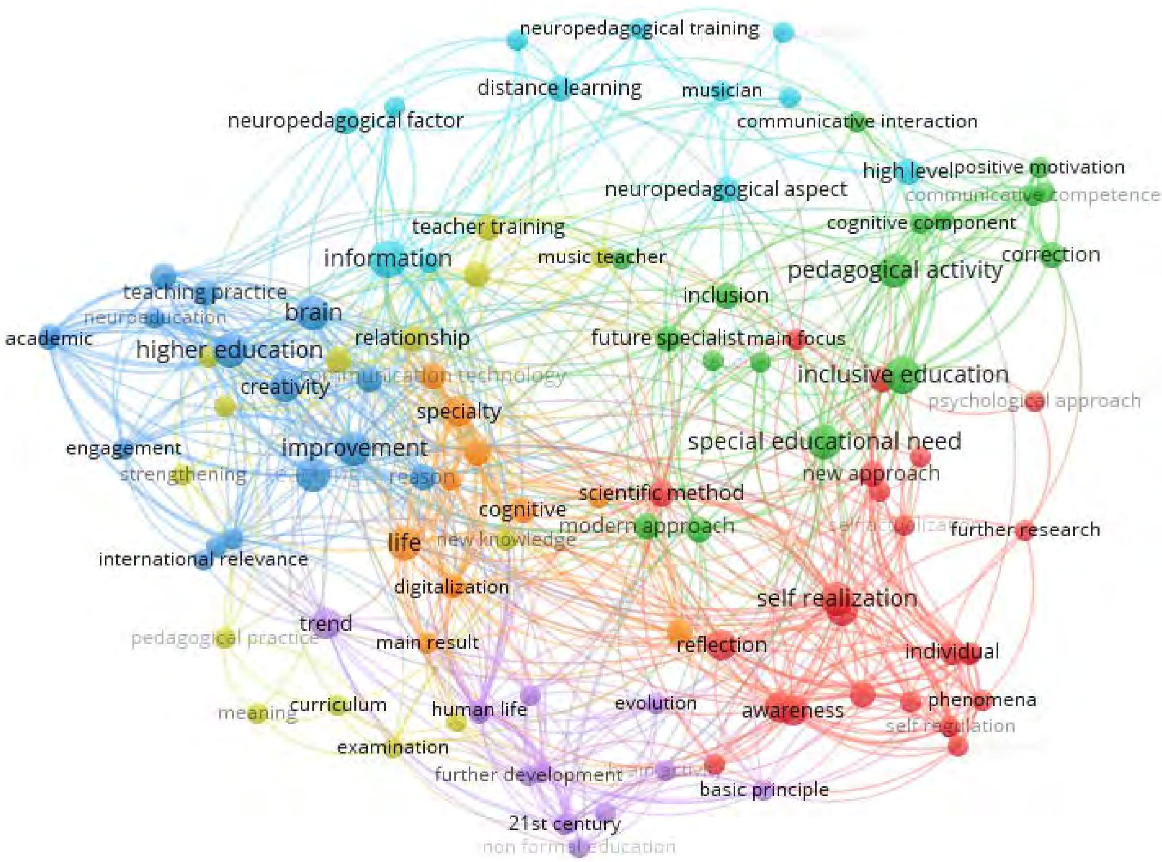

Figure 1. Map of thematic categories of research conducted by scientists from January 2020 to May 2025, developed based on search results for the term "Neuropedagogy" in scientific works.

(Developed by the author in VOSviewer (Elsevier, 2025) using data from Elsevier's Scopus database (Clarivate, 2025) and Web of Science Core Collection (VOSviewer, 2025).)

principles. The cluster reflects a modern, forward-looking view of education that prioritizes the holistic development of professionals. It integrates neuroscience knowledge and emphasizes practical skills, effective communication, and the crucial aspect of inclusivity to meet diverse learning needs. The presence of "correction" and "creativity" indicates a dynamic process of adaptation and improvement of educational programs.

III. Cluster 3, "Neuroeducation and Critical Thinking Development in Higher Education" (blue), focuses on higher education, emphasizing the integration of neuroscience into pedagogical practice for the development of critical thinking, creativity, and engagement, with the aim of academic improvement and international relevance. The cluster represents a modern, scientifically based approach to higher education.

It emphasizes the importance of using neuroscientific knowledge ("brain," "neuroscientific evidence") to improve teaching methodologies ("pedagogical method," "teaching practice") and the development of advanced cognitive abilities ("critical thinking," "creativity") and active participation ("engagement") among university students. The goal is to achieve continuous 'improvement' and ensure "international relevance" in academic activities.

IV. Cluster 4, "Neurodidactic Aspects of Teacher/Lecturer Training and the Development of Their Tolerance" (yellow), focuses mainly on teacher education and teaching practice, particularly for university and music teachers, with an emphasis on curriculum development, neurodidactics, and the development of positive qualities such as tolerance for future educational relevance. This cluster reflects a comprehensive view of teacher/lecturer training and their continuing professional development. It combines the practical aspects of curriculum development and its pedagogical application with the latest advances in neurodidactics. Emphasis is placed on acquiring knowledge and skills for imparting "new knowledge," conducting effective "exams," and building meaningful "relationships" with students. The inclusion of the terms "tolerance" and "future" indicates the goal of preparing educators for a diverse and changing educational landscape and improving their practical training.

V. Cluster 5, "The Evolution of Educational Practices in the 21st Century: Formal and Informal Approaches to Human Potential Development» (purple) represents the fundamental and evolutionary nature of education in the 21st century, in particular exploring its role in human life, including understanding brain activity and considering various forms of learning outside formal settings. The cluster presents a holistic view of education in the modern era, emphasizing its continuous "evolution" and 'progress' as a fundamental part of "human life," delving into the "basic principles" that guide "educational practice" and recognizing the importance of "brain activity" in learning. Most importantly, it expands the understanding of education beyond formal institutions to include "non-formal education" and "informal education," reflecting the 21st-century 'trend' toward diverse lifelong learning opportunities. The cluster presents contemporary "methodological approaches" for adapting to these changes.

VI. Cluster 6, "Online Education and Neuropedagogy" (turquoise), characterizes the connection between modern online and distance education and neuropedagogical principles, particularly in a scientific context, and potentially for specialized fields such as music. This cluster reflects a contemporary and specialized field of educational research and practice. It focuses on research that shows how the human brain

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learns and functions in the context of digital and distance learning environments. The emphasis on "neuropedagogical aspects," "factors," and "learning" reflects efforts to optimize online education based on scientific understanding. The mention of "specific problem" and "research area" implies ongoing research into specific challenges and achievements in this innovative field, potentially applicable to specific professional training, such as training for "musicians."

VII. Cluster 7, "Digitalization of Higher Education: Cognitive Aspects and Neuroscientific Approaches" (orange), focuses on the impact of digitalization and communication technologies on cognitive processes in higher education, particularly on the role of the human brain and neuroscientific approaches. The cluster reflects the modern view of higher education, which is adapting to the radical changes brought about by digitalization. It presents the direction of research by scientists who study how "communication technologies" and the enormous "information flow" they provide affect the "human brain" and "cognitive" processes. The goal is to apply a "neuroscientific approach" to ensure that "higher education institutions" can effectively prepare students with the necessary "qualifications" and "specializations" for a successful "life" in the digital age, leading to the desired "key results."

Let us consider the influence of art on STEM education (Fig. 2). Art is a manifestation of human nature. It also contributes to the disclosure of human essence, primarily spiritual, intellectual, aesthetic, ethical, cultural, and social. It is an ancient manifestation of anthropology and represents an integral part of culture, including everyday life. Art uniquely integrates knowledge, self-knowledge, reflection, images, creativity, and image formation. Art is characterized by cognitive, aesthetic, creative, ethical, reflective, developmental, recreational, projective, and constructive functions. Human beings are, by nature, carriers of art, which manifests itself in the understanding of humans not only as Homo Sapiens but also as aesthetic beings – Homo Aestheticus. An aesthetic person who understands harmony and is its carrier is a manifestation of true human essence, which is primarily formed through art.

Currently, there is not only an idea, but also a new anthropological trend that defines and, in essence, shapes the technological human (German: Technisierte Mensch) in a world where technology permeates reality and, in essence, humans become part of it. Technology penetrates both the human consciousness and surrounds it externally. To a certain extent, STEM education can be seen as a manifestation of this technological trend. At the same time, human nature is not technological in essence, but is primarily artistic, ethical, and aesthetic. In modern culture, there is a contextual and existential conflict between Homo Aestheticus and Technological Man. At the same time, this conflict is largely offset by the purposeful aestheticization of everyday life, education, and professional activity, which is achieved through the active and purposeful use of art, which revives and supports the ethical, harmonious, and aesthetic beginning in humans.

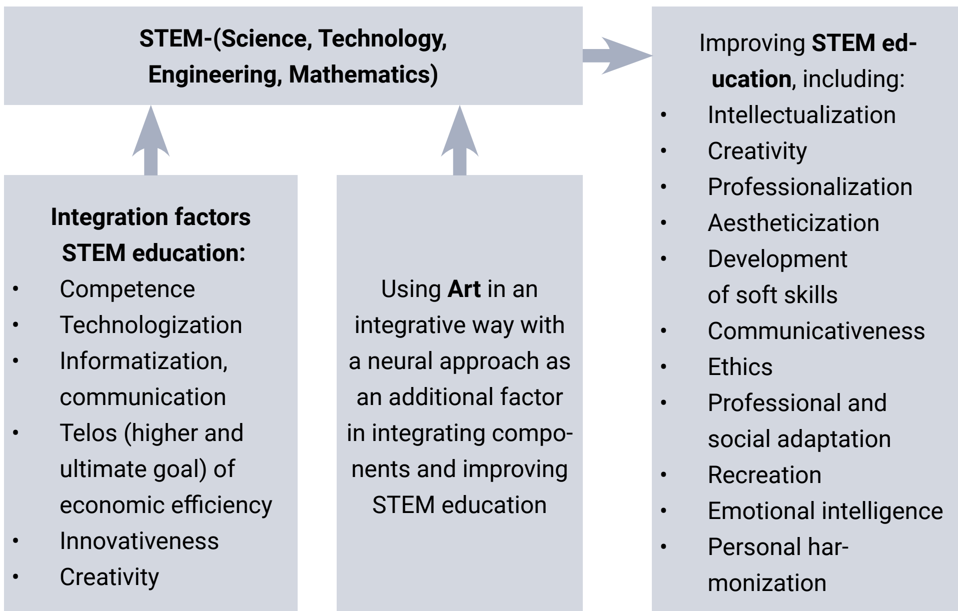

Figure 2. The impact of art on STEM education, including professionalization of specialists.

The peculiarity of aesthetics is that it lies at the heart of ethics and is a manifestation of life itself. Therefore, aestheticization is considered a manifestation and prerequisite for ethicalization and the disclosure of human vitality.

By holistically comprehending the phenomenon of art as a systemic manifestation of human nature, one can point to the significance of its application in STEM education with the aim of harmoniously forming both Homo Aestheticus and Technological Man and, accordingly, their holistic existence.

Let us consider the peculiarities of the influence of art on humans in the context of STEM education, applying the ideas, patterns, and phenomena revealed in the system of neuroscience.

The influence of art on brain blocks. Let us first turn to the concept of three functional blocks of the brain (Reynolds et al., 2007). The essence of this neuropsychological concept is that the brain, according to its functional characteristics, can be structured into three blocks (Reynolds et al., 2007):

- The first block is energy, which determines and maintains mental and nervous activity, including alertness.
- The second block is responsible for receiving, processing, and storing sensor information.
- The third block – programming, regulation, and control – is responsible for planning, organizing, and controlling mental activity.

Art can influence the first energy block of the brain as an activating factor, thereby increasing its potential, stimulating activity, and enabling the effective maintenance of sufficient alertness for a particular activity. At the same time, art, which is largely based on harmony as a meta-pattern of this world, together with the stimulation of activity, can harmonize and optimize the activity of this unit. This block is also largely related to the energetic aspect of motivation, goal setting, behavior, and soft skills in general, so the effect of art on this block contributes to an effective influence on them.

By influencing the second block of reception, processing, and storage of sensory information, art can contribute to the activation of both simultaneous and successive processing of sensory information. To clarify, simultaneous processing is associated with the instantaneous and rapid perception of a fragment of reality and with the parallel processing of information as a "picture" without much detail, while successive processing reflects perception in a temporal unfolding as a system of sequences, as well as further detailing and refinement of what is perceived. For example, when a person listens to something and responds or draws at the same time, this is simultaneous processing. When these processes are implemented sequentially, this is successive processing. These processes are also partially implemented by the third block of the brain.

The influence of art on the third block of programming, regulation, and control is associated with indirect stimulation of cognitive processes through the influence of images, metaphors, scenarios, and the reception and comprehension of typical algorithms of rhythms present in art. This is realized through the first and second blocks of the brain.

Art as a tool for forming images (auditory, visual, etc.) and metaphors. Art primarily shapes and activates images and, accordingly, develops imaginative thinking. Accordingly, imaginative thinking and imagination develop under the influence of art. A distinctive feature of an image is its integrity, completeness, and emotional richness. In the creative process, working with images is a relevant process. Often, in the process of creativity, a primary image of an action or object is formed, which, undergoing certain transformations, forms the basis of an engineering or scientific concept. For example, a specialist generally visualizes the appearance of the device he is designing, or comprehends it as a system of characteristics, formulas, and criteria, and in the process of further work, changes, improves, supplements, and details it. The creative process of forming and selecting images is energetically and emotionally intense. Significant in terms of creativity is the selection and selection of images, which can be effectively influenced by art.

Art as a way to activate metaphorization and mythological understanding of reality. Humans intellectually master reality, including virtual and imaginary things, through discursive-logical thinking based on language, signs, symbols, scenarios, algorithms, and logic, as well as through mythologization and mythological thinking, which is dominated by images, situations, and emotions. An important aspect of thinking is metaphorization, which underlies both mythological thinking and, to a large extent, discursive-logical thinking. These cognitive systems complement each other. Mythological consciousness and thinking dominate in archaic societies. In developed civilizations, rational consciousness, logic, and discursive-logical thinking prevail. A distinctive feature of the mythological aspect of consciousness (thinking, perception, etc.) is the experience and perception of certain problems, images, and situations in specific spatial and temporal formats, whether realistic or imaginary. When logical intelligence dominates, intellectual activity is experienced as a life scenario, but less emotionally intense and, to some extent, with less significance of temporal and spatial frameworks. In this regard, we recall René Descartes' classic maxim: Cogitoergosum (I think, therefore I am). The mythological dimension of thinking allows a specialist to deeply immerse themselves in the real or imaginary world, experience it, and understand it on an emotional level, and on this basis make comprehensive, fairly effective conclusions and predictions, almost without relying on logic. This mythological perception of reality is close to the ideas of E. Husserl's phenomenology (Husserl et al., 1964, 13-21), in which the world is perceived as a phenomenon of consciousness, which to a certain extent includes its comprehension and experience. In creativity, this mythological aspect of consciousness is present as something that generates images and determines intuitive paths of both cognition and construction. In the process of design, when modeling a specific problem, professional engineers can understand and even feel the characteristics of a particular device, structure, or situation on a mythological level of consciousness as if they were real, not imaginary. Both rational-logical and mythological consciousness, and above all its cognitive manifestations, exist simultaneously and complement each other, interacting in the stream of consciousness in the process of creativity. Mythological consciousness is largely associated with the first ("energetic") and second ("sensory") blocks of the brain. Discursive-logical thinking primarily concerns the third block of the brain – programming, regulation, and control. Art promotes optimal brain activation, including all of its blocks, which ultimately stimulates thinking and creativity.

Mythological thinking, stimulated by art, is connected to the archetypal level of consciousness, which is activated accordingly. According to C. Jung (Jung, 2014), an archetype is a certain typical stereotype of perception, image, algorithm of thinking, scenario, and actions that has been formed in the process of the historical development of humans as a species. An archetype has typical manifestations, is energetically charged, and can have a significant impact on human consciousness. For example, the archetype of Harmony, if it influences a person, gives them the opportunity to see and create beauty even without special training. The perception, understanding, and vision of Harmony as an Archetype, as a meta-strategy, defines Harmony for the specialist as a universal path, strategy, and specific mental tool in construction, analysis, study, and creativity. The actualization of the archetypal level of consciousness contributes to the development of intuition and the relatively quick obtaining of correct and optimal solutions to a particular problem. A certain design that is being projected, or the path of its construction, can "appear" in the specialist's consciousness in a fairly complete and perfect form as a holistic image, which subsequently only needs certain improvements. The problem of using the potential of the archetypal level of consciousness is revealed in such a direction of pedagogical science as archetypal pedagogy (Mayes, 2020).

Neural aspects of the influence of art on the emotional and motivational spheres. Art, by its very nature, is primarily aimed at influencing the emotional sphere, feelings, will, and personality, the essence of which is, above all, emotional and volitional. Currently, the limbic system is considered to be a set of neural (brain) structures that systematically and integrally ensure the realization of emotions (Buccilli et al., 2025, p. 679-704; Marunenko & Nevedomska, 2015, p. 5-7). This system consists of many structures of the brain: the olfactory sensory system: the olfactory bulb (Latin: Bulbus olfactorius) and tract (Latin: Tractus olfactorius); anterior perforated substance (Latin: Substantia perforata anterior); cingulate gyrus (Latin: Gyrus cinguli): parahippocampal gyrus (Latin: Gyrus parahippocampalis); dentate gyrus (Latin: Gyrus dentatus); hippocampus (Latin: Hippocampus): amygdala (Latin: Corpus amygdaloideum); hypothalamus structures (Latin: Hypothalamus); mammillary bodies (Latin: Corpus mamillare), reticular formation of the midbrain; anterior thalamic nuclei. An important component of the limbic system, which is primarily responsible for the emotional sphere, is Papez's circuit (Kamali et al., 2023, p. 371-389). These neural structures represent areas of the midbrain, intermediate brain, and telencephalon. These structures belong to the first energy block of the brain.

In general, art indirectly influences the human motivational system through the emotional and cognitive spheres, as well as the vital (life-important) complex of functions implemented by the limbic system, namely: behavior (relatively simple but vitally important behavioral reactions and stereotypes), learning, short-term and long-term memory, including spatial memory, the formation of orientational and search behavior, and the manifestation and development of communication. In addition, the limbic system plays a dominant role in the regulation of such basic and vitally important functions as sleep and sleep/wakefulness, smell, and regulation of internal organs. The functions regulated by the limbic system have a high degree of autonomy, but at the same time they are interconnected in a certain way.

Thus, the influence of art on the limbic system in the educational process will systematically affect a whole range of functions, among which the following can be highlighted as significant for human development: emotions, motivation, memory, learning, orientation, search, communication, sleep, and smell. With regard to learning and communication, the primary components are motivational and energetic, i.e., the desire to learn and work and the ability to maintain this state of interest and activity for a certain period of time. These functions are related to attention, which is generally also realized by the first energy block of the brain and other structures.

To sum up, we can say that the primary stimuli for learning, communication, and interest in the world are both hereditary and innate human abilities, which manifest themselves through interaction with the environment and, above all, through communication, as well as through the influence of art as a special “super-reality” created by humans. This was understood even in antiquity. In Ancient Greece, within the framework of the human-centered spiritual and educational system of paideia (Fedorets, 2019, p. 153-210), it was believed that human nature as intelligent, merciful, good, poetic, aesthetic, and ethical is revealed primarily under the influence of the muses – special spiritual entities. Art reveals human nature in a person, making them a spiritual, intelligent, aesthetic, harmonious, prudent (Greek: Σωφροσύνη – sophrosyne) and good being.

Conclusions. STEM education, as a modern educational and professional trend, is a complex technologically, cognitively, and anthropologically oriented educational system aimed at forming competent, intellectualized, and creative specialists capable of self-improvement. The factors of integration of STEM education components (science, technology, engineering, mathematics) are competence, technologization, effective educational and professional communication, intellectualization, professionalization, and innovation. We consider the possibility of applying art in integration with a neural approach to be a significant innovative aspect of the integration of these components of STEM education, as well as a direction for its further improvement.

Art is a special and attributive manifestation of human nature and a systemic phenomenon of culture. It represents a special "metaworld" and ontology of harmony, the interaction of which contributes to the disclosure of human potential – intellectual, creative, personal, communicative, aesthetic, ethical, existential, innovative, and the complete development of a person as a whole as a rational, ethical, and aesthetic being. The systemic and human-forming influence of art in the context of STEM education is revealed, objectified, refined, and improved through the integrative application of a neural approach.

An analysis of scientific publications from 2020-2025 containing the term "neuropedagogy" revealed seven key areas of research that reflect a comprehensive approach to integrating neuroscientific knowledge into educational practice. These studies cover a wide range of issues: from psychological and pedagogical aspects of personality development and learning to the implementation of neuropedagogical principles in modern educational strategies, particularly in the context of inclusion and professional training. Particular attention is paid to the application of neuroscientific approaches to the development of critical thinking in higher education and teacher training, including the formation of tolerance and adaptation to the digital educational environment. The identified trends underscore the growing importance of understanding brain function for optimizing learning processes in both formal and informal education, as well as for the effective training of specialists in the digital age.

From the perspective of the neural approach, the influence of art on the individual in the context of STEM education contributes to the manifestation and further development of creativity, the emotional sphere, including emotional intelligence, the ability and desire to learn, actively act and work, harmonizes behavior and social, educational, and professional adaptation of the individual, memory activation, imaginative thinking and intuition; intellect, including social and professional; orientational and search behavior, which underlies the intellectual sphere; the ability to perceive and form images; goal setting. Art also effectively influences: motivational, need-based, and behavioral spheres; the state of general activity and alertness; social behavior, as well as the rhythms of activity and rest, and has a recreational and stimulating function.

At the same time, we should clarify that the aforementioned influences, which are a priori considered positive, depend on the values and meanings, images, ideas, and scenarios that art brings, as well as on the dominant cultural and life contexts. In certain cases, the effects can be opposite if "infernal" art (in the sense of that which is below, like evil, primitiveness) is used, which stimulates aggression, hatred, and blocks the refined mind, etc.

The powerful creative potential of art contributes to the development of creativity, intellectualization, and professionalization of specialists, and is also aimed at their effective educational and professional adaptation and improvement. The creative, ethical, and aesthetic potential of art harmonizes the personality in the context of STEM education, shaping it as Homo Aestheticus and a Harmonious Person, which balances and limits the technologization of humans and their informational, psycho-emotional, and stress loads in the context of a "techno-informational civilization."

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3.4. EXPERIENCE IN IMPLEMENTING AN INTERNATIONAL PROJECT WITHIN THE ERASMUS+ JEAN MONNET MODULE PROGRAM (BASED ON THE STREAM PROJECT)

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Jean Monnet Programme is one of the European Union's (EU) educational programmes, which aims to raise awareness and knowledge of European integration within and outside the EU by promoting teaching, research on European integration, in particular EU relations with other countries, and interpersonal and intercultural dialogue. The programme is named after one of the founders of the EU, Jean Monnet.

Since 2007, the Jean Monnet programme has been integrated into the broader Lifelong Learning Programme alongside other educational programmes such as Erasmus Mundus.

As part of the Jean Monnet program, the EU allocates funds to universities to launch courses related to European integration and the development of scientific activity in fields according to the EU's research. The courses generally concern the development of the European community, European law, the European economy, European politics, the history of European integration, etc.

Since 2014, the Jean Monnet programme has continued its activities within the framework of the new EU education programme, Erasmus+.

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The main objectives of the programme are (European Commission, 2025):

- disseminating knowledge about European integration processes, raising public awareness by encouraging universities, departments, and lecturers to teach subjects related to European integration and conduct research;
- intensification of scientific and theoretical discussions and public debates on topical issues and problems, reflection on contemporary phenomena of European integration, interpretation of its past and search for its future through the organisation of scientific and practical conferences, public discussions and debates;
- support for educational and research institutions, associations, and networks specialising in European studies.

The Jean Monnet Programme has three main strands (Fig. 1):

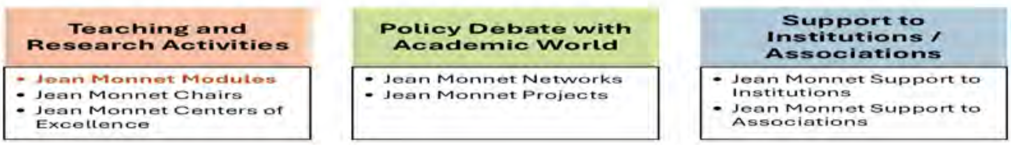

Figure 1. Jean Monnet Programme directions

The STREAM project "Best practices EU in STREAM education for pre-service teachers" (project number: 101098885 — ERASMUS-JMO-2022-HEI-TCH-RSCH-UA-IBA) was designed as a Jean Monnet Module under teaching and research activities of the Jean Monnet program. The project duration is 3 years (from 2022 to 2025), with Dragomanov Ukrainian State University (Kyiv, Ukraine) as the beneficiary.

The acronym STREAM stands for the integration of Science, Technology, Robotics, Engineering, Arts, and Mathematics. The STREAM project focuses specifically on education and the use of EU best practices in STREAM education.

The idea for the STREAM Jean Monnet Module project arose at the intersection of international education and the rapid internationalisation of the European educational space. Today's labour market needs specialists who are able to think globally, act locally, and at the same time function effectively in multicultural teams. The STREAM project responds to these challenges by integrating elements of international education through the involvement of teachers and students from different countries, the implementation of joint research initiatives, participation in academic mobility programs, including the use of blended learning formats.

One of the focuses of the STREAM module is the development of Global Citizenship Competences, which are formed throughout life through a combination of theoretical learning and practical experience to develop a mindset of caring for humanity and the planet and preparing individuals for responsible action for a more just, safe, and sustainable world. In this way, the STREAM project contributes to the development of an academic environment in which intercultural communication becomes an integral part of educational and research interaction, promoting a deeper understanding of global challenges and opportunities.

As Zalli (2024) emphasises, global citizenship implies an awareness of the interdependence of the modern world and a willingness to contribute to its sustainable development (Zalli, 2024). The STREAM module, aimed at developing Global Citizenship Competences, supports this goal through courses that combine a problem-oriented approach and analysis of EU international education policy cases.

The main objectives of the STREAM project are:

- to raise awareness among Ukrainian educators about the EU and EU best practices in STREAM education;
- to develop training programmes using EU best practices in STREAM education for the Ukrainian educational environment;
- to improve the training of highly qualified specialists in STREAM who are ready to work in a digital European society;
- attracting more people to the STREAM (Science, Technology, Robotics, Engineering, Arts, Mathematics) fields to overcome the future skills gap faced by EU countries and Ukraine;
- supporting gender equality in Ukraine and the EU by attracting girls and women to STREAM education;
- developing innovative teaching materials and tools to meet the needs of young people in order to promote a better understanding of the EU and its main policies and values.

The activities of Jean Monnet Modules projects, including the STREAM project, can be divided into the following components (Fig. 2):

Figure 2. Main components of projects under the Jean Monnet Modules programme

Let us briefly describe each of the components of the STREAM project. In order to define them correctly, we will note the target groups of the STREAM project. These include pre-service teachers and practising teachers. In addition, the impact of the project's implementation was also expected to extend to the wider educational community.

The '**Research**' section includes the following areas of activity: analysis of recent research in STREAM education (foreign and Ukrainian); development of surveys for target groups to identify their needs; development of the structure and content of the STREAM academic module, taking into account EU best practices in STREAM education for pre-service teachers; development of training courses for educators in this field; research visits to EU partners conducting research in STREAM education; annual updating of materials, taking into account current trends, experience gained and the current state of development of STREAM education, etc.

The '**Teaching**' section provides for the integration of the developed materials into the educational process of pre-service teachers. In particular, the STREAM project has developed a core course, 'EU best practices in STREAM education' (Strutynska & Morze, 2023), and optional courses for the STREAM educational block for MSc students studying under the 'Secondary Education (Computer Science)' educational programme:

- Digital technologies in STREAM education (Strutynska, 2023a),
- Robotics and computer design (Strutynska 2023b),
- Organization of project activities in STREAM education (Strutynska, 2024).

Certain topics and blocks of the STREAM academic module are also being introduced into the training of pre-service BSc degree teachers studying under the educational programme 'Secondary Education (Computer Science)'.

The '**Training**' section includes training courses developed for educators, namely three summer schools for practising teachers in the STREAM fields, as well as workshops for educators. The materials for the summer schools are available in the corresponding e-courses (Strutynska et al., 2023; Strutynska et al., 2024).

The general structure of the STREAM academic module is shown in Fig. 3:

During the project implementation, the STREAM academic module courses shown in Fig. 3 were developed (Figs. 4-8). Designing of the e-learning course "Summer School STREAM 2025" is now in progress.

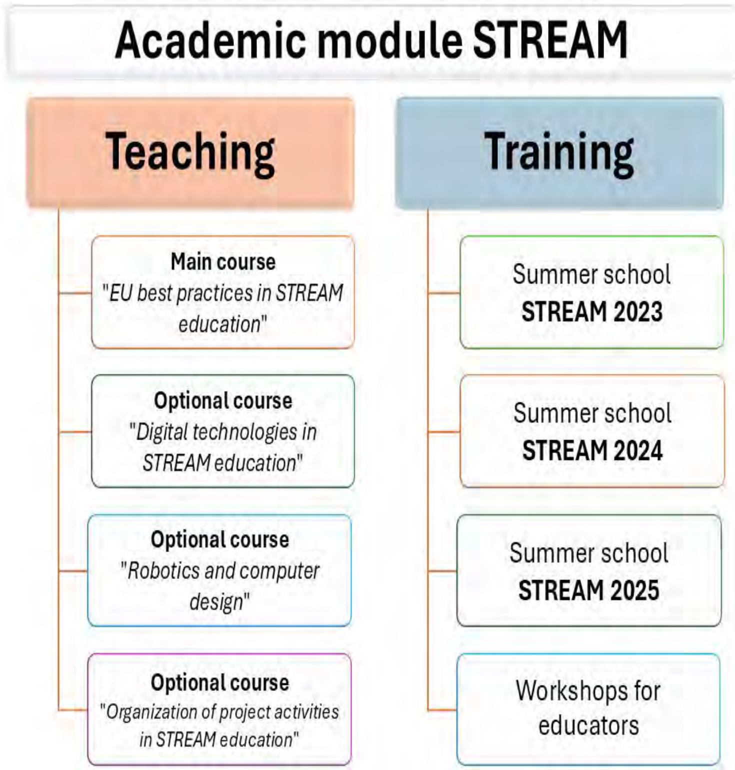

Figure 3. Structure of the STREAM academic module

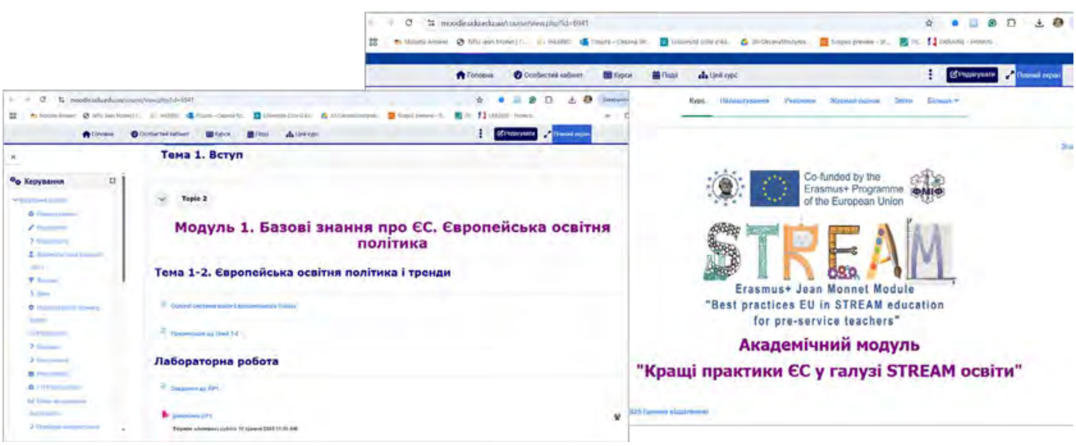

Figure 4. Home page of the e-learning course "EU best practices in STREAM education" (Strutynska & Morze, 2023)

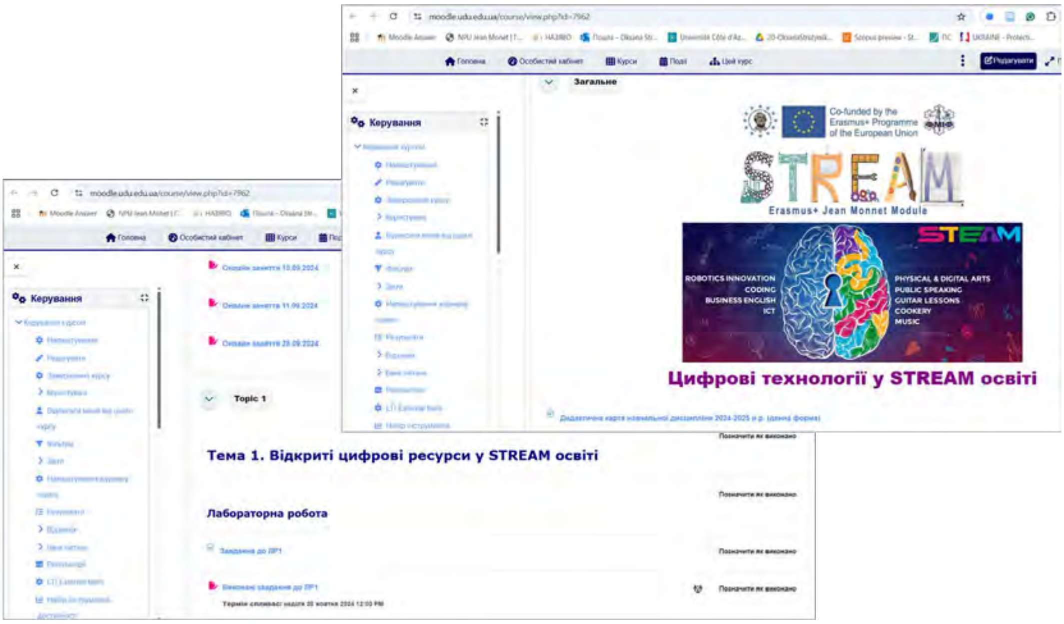

Figure 5. Home page of the e-learning course ‘Digital Technologies in STREAM Education’ (Strutynska, 2023a)

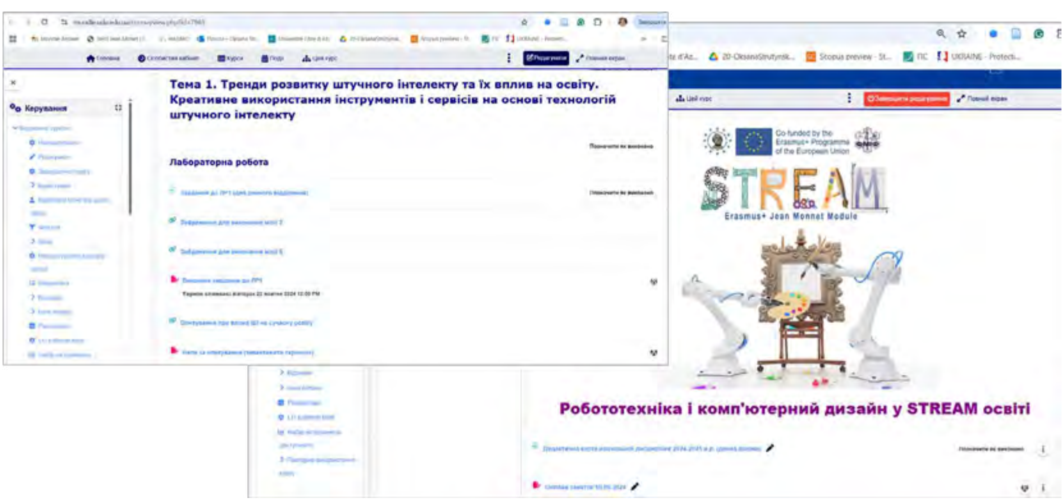

Figure 6. Home page of the e-learning course “Robotics and computer design” (Strutynska 2023b)

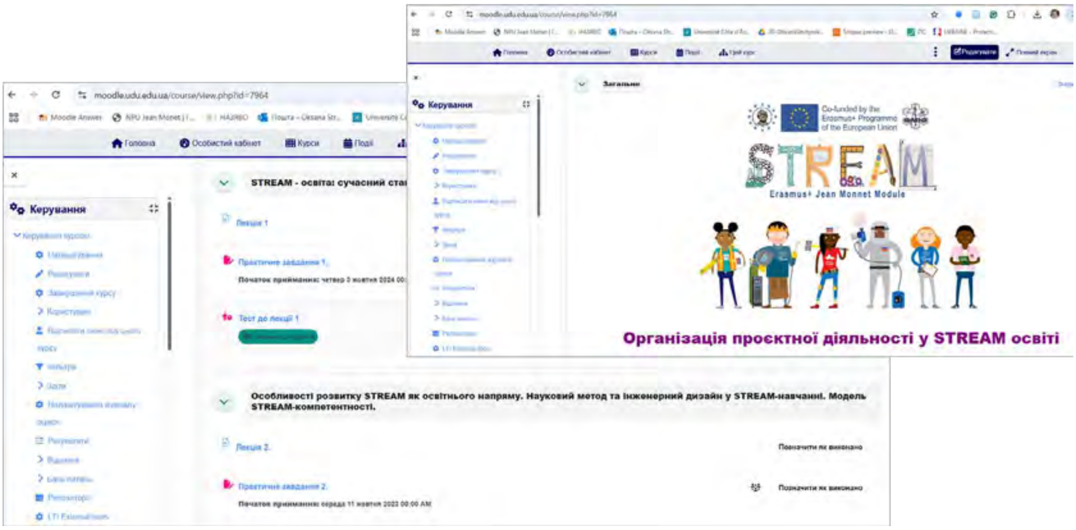

Figure 7. Home page e-learning course ‘Organising project activities in STREAM education’ (Strutynska, 2024)

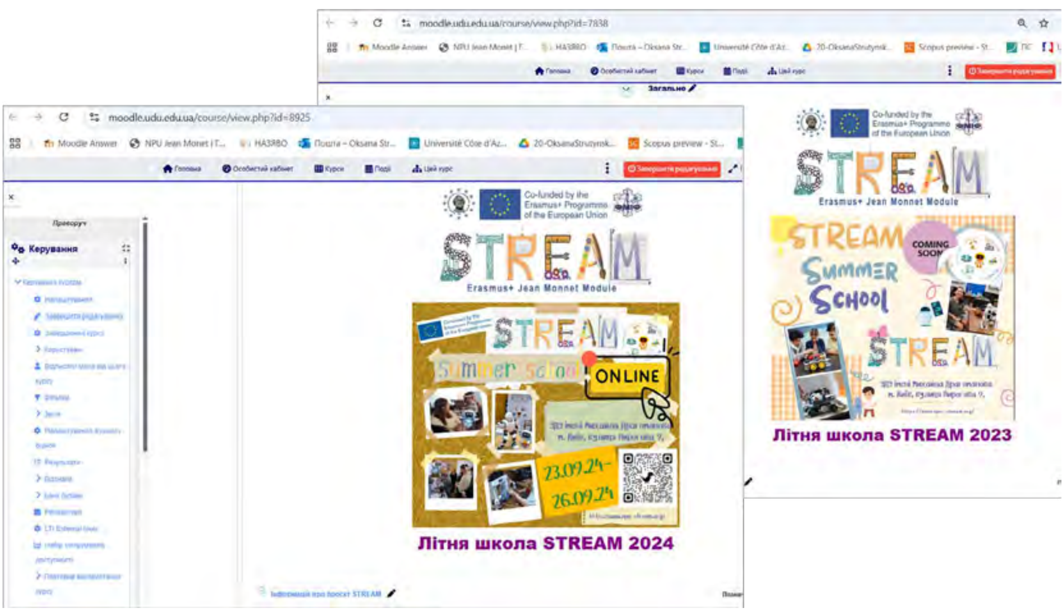

Figure 8. Home pages e-learning Summer Schools courses (Strutynska et al., 2023; Strutynska et al., 2024)

The 'Outreach' section is related to information and educational activities, namely the dissemination of project results and the involvement of the general public, in particular the educational community, in this issue. The STREAM project provides for the following types of activities in this area: holding information days to inform about the project's goals, objectives, expected results and its impact on the educational community; informing about project events through information channels (project website, social media pages, project YouTube channel); organising workshops on the project topic; holding an international conference; disseminating project results at conferences and seminars; publications on the project topic (Fig. 9).

Figure 9. Outreach activities of the STREAM academic module

The project STREAM Jean Monnet Module was launched in October 2022. Its implementation consists of the following main stages (Fig. 10):

- Preparation.
- Implementation.
- Evaluation.
- Follow-up and dissemination of experience.

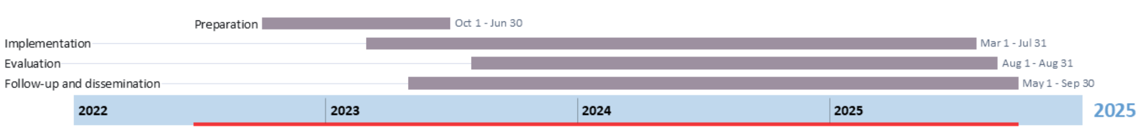

Figure 10. Timeline with stages of the STREAM project implementation

A brief description of the main tasks planned for each stage of the project implementation is shown below.

Preparation stage

- Formation of the project coalition (EU experts, STREAM experts, educational experts, and experts on engaging girls in STREAM).
- Development of a detailed plan-schedule.
- Development of case studies, practical and survey items.
- Designing the teaching content of the module, distance learning course, and Summer Schools: lectures, seminars, workshops, and discussions.
- Invitation of practitioners to STREAM education.

- Organization of workshops to present and discuss the Module with the participation of experts from the EU countries (using webinar technology).
- Designing a project website, pages on social networks, a project YouTube channel, and a social network community "Best practices EU in STREAM education for pre-service teachers" for information on the project events and dissemination of the project outcomes.
- Promotion of the institutionalization of the project at the home University.

Implementation stage

- Training students of the Bachelor's and Master's programs in the "Secondary school" specialty via the Module.
- Conducting seminars, discussion forums, and workshops for students enrolled in universities in Kyiv and the Kyiv region under the guidance of leading professors and practicing teachers in STREAM education.
- Participation of practicing teachers in Summer Schools.
- Participation of the target groups and the wider educator community in the final international conference.
- Initiation, development, evaluation, and selection of teachers' and students' STREAM projects developed according to the EU studies.

Evaluation stage

Internal monitoring (frequency – 1 per half year):

- design of survey with the following blocks: 1) number of classes (hrs.); 2) audience (number, sex, place of study/work, etc.);
- collection and processing of students' feedback;
- discussion;
- promotion;
- publications;
- operation of the website.

External monitoring (frequency – 1 per year):

- engaging external experts in the evaluation of projects;
- independent expert evaluation;
- experts' feedback;
- discussion;
- update of the module and distance learning course content.

Methods of evaluation: registration lists, questioning with the given scale (self-assessment) "input and output", statistical method (in particular, the efficiency of the website and community: number of authorized users, number of joined users, number of hits, number of downloads, etc.).

Follow-up and dissemination of the experience stage

- Organization of the workshop “Digital transformation and STREAM education” for University teaching staff, practicing teachers from different regions of Ukraine, and Partner countries;
- Vocational training of the target group.
- Integration of the academic module “EU best practices in STREAM education” and the e-learning course (Strutynska & Morze, 2023) into the University curriculum;
- Preparation of an analytical report with recommendations to the Ministry of Education and Science of Ukraine on the implementation of the Summer Schools summary and results as a part of the retraining practice teachers program;
- Publication of teacher guide on “Digital transformation and STREAM education” (Strutynska & Umryk, 2024).
- Publication of information materials of the project results in academic papers, a website (STREAM project website, 2022), and social media (Official STREAM project Facebook page, 2022; Official STREAM project YouTube channel, 2022).
- Sustainability: maintenance of contacts with school leaders, practicing teachers, and the association of STREAM girls and women; supporting the activity of the social network community “STREAM education” (STREAM community).
- During the project implementation, 99 students participated in the STREAM academic module courses:
- EU best practices in STREAM education - 99 students.
- Digital technologies in STREAM education - 43 students.
- Robotics and computer design - 68 students.
- Organization of project activities in STREAM education - 18 students.

322 people participated in training courses for educators, including summer schools (in 2023 and 2024):

- Training for Ukrainian practicing teachers to use EU best practices in STREAM education - 150 practicing teachers from the Shevchenkivskyi district of Kyiv, Ukraine (in October 2023).
- Summer School STREAM 2023 - 98 educators.
- Summer School STREAM 2024 - 74 educators.

Approximately 1,500 participants viewed the training videos published on the STREAM project YouTube channel (Official STREAM project YouTube channel, 2022), and more than 300 participants viewed the interactive teacher guide (Strutynska & Umryk, 2024), which may indicate the popularity of this topic among educators.

Following the training sessions, educators received certificates of professional development. The organisers and implementers of the STREAM project received positive feedback from training participants and students who completed the STREAM academic module, as reflected in the project report (Strutynska, 2025).

During the implementation project stages, the educational community and all those interested in STREAM education were involved in surveys related to the project's topics, namely a general survey on educators' awareness of the current state and prospects of STEM/STEAM/STREAM implementation in Ukraine; surveys on the learning outcomes of participants in the STREAM academic module (or its components); surveys on the results of training for practising teachers, etc. To date, nearly 700 educators have participated in the surveys (surveys were conducted from June 2023 to the present). The main information (educators' opinions on the development of STREAM education in general; on the content of the STREAM academic module and its components, etc.) obtained from the survey results is reflected in the project report (Strutynska, 2025).

In particular, it is worth noting the positive attitude of educators towards mastering STEM/STEAM/STREAM technologies (results of the survey 'STEM/STEAM/STREAM in Ukraine: current status and future prospects' (Strutynska, 2025)). In particular, the community of respondents considers practice and experimentation (93.5% of respondents), courses, training sessions, master classes (88.7% of respondents), as well as the exchange of experience and knowledge with other teachers (87% of respondents) to be the most effective for this purpose. 77.7% of respondents noted that online and/or online courses are also useful for improving qualifications in STREAM education, and 73% of educators believe that thematic webinars and conferences can be used for this purpose (Fig. 11):

Q.: What, in your opinion, will help teachers master STEM/STEAM/STREAM technologies?

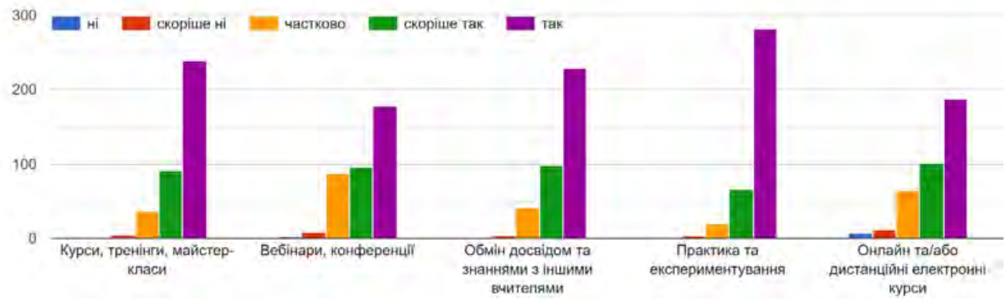

Figure 11. Educators' attitudes towards mastering STEM/STEAM/STREAM technologies (based on the results of a STREAM community survey)

In addition, 92% of educators note that STEM/STEAM/STREAM education develops creativity and an innovative approach to problem solving in students, allowing them to develop and prepare for future challenges in various fields, while 90% of them believe that using STEM/STEAM/STREAM principles in education helps students develop flexible skills (in particular, collaboration and communication skills), which is important for their future careers (Fig. 12):

Q.: What prospects do you see in the future for the use of STEM/STEAM/STREAM education principles in the learning process?

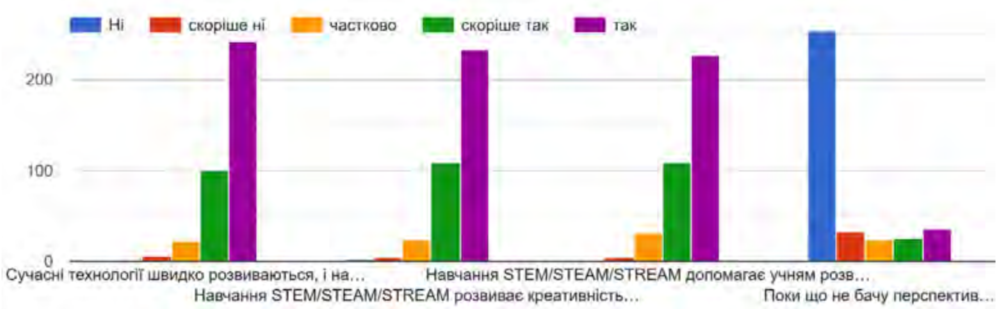

Figure 12. Educators' opinions on the possibility of using STEM/STEAM/STREAM education principles in the learning process (based on the results of a STREAM community survey)

At the time of writing, the project is in its final stage of implementation (until October 2025). The results of the STREAM community survey are reflected in the project report (Strutynska, 2025).

Overall, the STREAM project offers platforms for interdisciplinary discussions where participants have the opportunity to develop effective intercultural interaction skills. The COVID-19 pandemic has demonstrated the importance of digital and transnational cooperation. STREAM module training involves hybrid learning formats, ensuring the continuity of cross-border educational activities even with limited physical mobility, thereby promoting new standards of flexible, sustainable education.

Therefore, the implementation of the STREAM project is a strategic step towards increasing the university's competitiveness, deepening its international involvement, and preparing students to be responsible members of the global community. The project not only corresponds to current trends in internationalisation and globalisation, but also contributes to the formation of an educated and socially active generation focused on solving global problems and strengthening European values.

Thus, experience in participating in EU grant programmes and implementing similar projects will help Ukrainian educators to improve the qualifications of the educational community in particular and to understand the processes taking place in the EU educational space in general, which may have a positive impact on Ukraine's integration processes into the EU.

The research, the results of which are presented in the paper, was conducted as part of the Jean Monnet Module project 'Best practices EU in STREAM education for pre-service teachers' (STREAM) under the Erasmus+ programme (project number is 101098885 — ERASMUS-JMO-2022-HEI-TCH-RSCH-UA-IBA). The STREAM project is co-funded by the European Commission. The paper reflects the views of the authors. The European Commission is not responsible for any use of the information contained in it.

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Chapter 4.
ARTIFICIAL INTELLIGENCE AND ITS APPLICATION IN EDUCATION

4.1. ARTIFICIAL INTELLIGENCE TECHNOLOGIES AND DIGITAL TOOLS IN THE QUALITY ASSURANCE SYSTEM OF GENERAL SECONDARY EDUCATION INSTITUTIONS

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Digital transformation is significantly reshaping all spheres of social life, including the education system, emphasizing the implementation of innovative technologies, transformative educational practices, artificial intelligence, and digital tools. Under conditions of uncertainty, artificial intelligence technologies and digital tools serve as instruments that enhance the quality of

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education, improve the effectiveness of learning, enable the use of adaptive educational pathways for learners, support personalized learning, strengthen managerial decision-making, facilitate monitoring of the educational process, and promote the integration of modern digital teaching technologies (Vykorystannia shtuchnoho intelektu v osviti, 2021).

Each year, the penetration of Internet technologies into social life, including education, increases. According to the new Digital 2025 report, 67.9% of the global population are Internet users, of whom 37.6% use the Internet for educational purposes. In Ukraine, the number of active Internet users continues to grow and, as of February 2025, has reached 82.4% (DataReportal, 2025) (see Fig. 1).

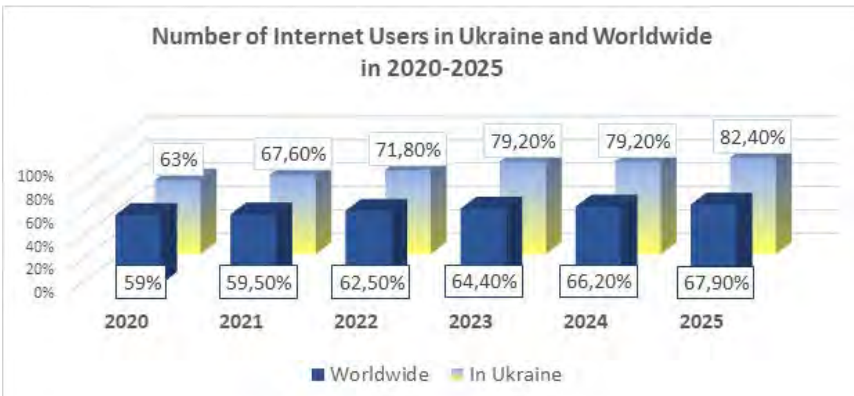

Fig.1. Number of Internet Users in Ukraine and Worldwide in 2020-2025 (DataReportal, 2025).

Artificial intelligence and digital technologies in the system of educational quality assurance have the potential to substantially transform educational processes, in particular by adapting educational content to the learning needs and knowledge level of each learner, thereby enhancing learning motivation and outcomes. Analytics and monitoring carried out through analytical platforms and artificial intelligence make it possible to track the learning dynamics and developmental progress of each learner. In addition, they enable the identification of educational gaps and the timely adjustment of pedagogical strategies as well as the provision of learner support (Topuzov & Alieksieieva, 2024a). Artificial intelligence and digital technologies make the educational environment more dynamic, interactive, and oriented toward twenty-first-century competencies, fostering the development of information literacy, analytical skills, and critical thinking.

Artificial intelligence technologies also contribute to the formation of ethical standards in education through the automation of assessment, algorithmic trans-

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parency, and data protection. This strengthens trust in educational systems and ensures equal opportunities for all participants in the educational process. The use of artificial intelligence and digital tools proves effective in educational analytics and constitutes a significant step toward ensuring the quality of education. The outcomes of educational analytics provide the foundation for building an effective quality assurance system in general secondary education institutions.

In this paper, we will analyze the quality assurance system of general secondary education institutions, assess the possibilities of applying artificial intelligence technologies and digital tools, outline key trends and challenges, and propose recommendations for their effective implementation in the context of educational policy transformation.

The Quality Assurance System of General Secondary Education Institutions

The effectiveness of educational and managerial processes determines the quality of education. Establishing an effective quality assurance system is a strategic priority of national educational policy.

The quality assurance system of general secondary education is described in the provisions of the Laws of Ukraine “On Education” (2017), “On Complete General Secondary Education” (2020), as well as in the Standards of Basic and Profile Secondary Education. Thus, the Law of Ukraine “On Education” (2017) stipulates that the quality of education is ensured through: (1) an internal quality assurance system within educational institutions; (2) an external quality assurance system; and (3) a system of quality assurance in the activities of governing bodies and institutions that provide external quality assurance. The quality assurance system of general secondary education is holistic and clearly structured. For instance, external monitoring of quality is coordinated by the State Service of Education Quality of Ukraine, which implements institutional audits in general secondary education institutions. During such audits, the internal quality assurance system of schools is assessed.

Let us consider some of its provisions in more detail. For example, the internal quality assurance system is regarded as an integrated mechanism that provides the foundation for sustainable development, institutional effectiveness, and educational innovation within an institution. The organization of an internal quality assurance system in general secondary education institutions enables systematic evaluation of the quality of educational content, teaching methods, and learners’ academic achievements. This approach allows for the timely identification of challenges in the educational process and the improvement of pedagogical practices. The internal quality assurance system enhances institutional capacity and fosters a culture of responsibility, professional development, and teamwork among participants in the educational process (Ministerstvo osvity i nauky Ukrainy, 2020). Internal data on learning quality serve as a basis for making informed managerial decisions, ensuring compliance with educational standards, developing institutional development plans, adhering to the principles of academic integrity, and protecting the rights of participants in the educational process, while also supporting transparency in assessment. The collection and analysis of information facilitate the identification of learners' emerging educational needs and trends, thereby opening pathways for the integration of modern pedagogical technologies and methods of digital didactics.

The Law of Ukraine "On Education" (2017) clearly regulates the main provisions regarding the internal quality assurance system in education. In particular, according to Part Three of Article 41 of this Law, each educational institution must develop a Quality Assurance Strategy and mechanisms for ensuring academic integrity. In line with the internal quality assurance system, schools are required to publish criteria, rules, and procedures concerning the assessment of students; the evaluation of pedagogical staff and their teaching activities; as well as the assessment of the managerial performance of school administrators (Verkhovna Rada Ukrainy, 2017). Overall, the internal system of general secondary education is oriented towards ensuring quality across four dimensions, namely: the educational environment; the student assessment system; the pedagogical activities of educational staff; and the managerial processes of the institution. These very dimensions serve as the basis for evaluating the educational and managerial processes of schools and ensuring the quality of education during institutional audits (which corresponds to Clause 6 of the Procedure for Conducting Institutional Audits of General Secondary Education Institutions, approved by the Order of the Ministry of Education and Science of Ukraine of January 9, 2019, No. 17, registered with the Ministry of Justice of Ukraine on March 12, 2019, under No. 250/33221 (Ministerstvo osvity i nauky Ukrainy, 2017)).

External evaluation of the educational and managerial processes of general secondary education institutions is carried out through an institutional audit, which is aimed at the comprehensive assessment of the quality of educational activities (Alieksieieva, 2025c). Institutional audit is an external evaluation of school performance, during which independent experts assess both educational and managerial processes, as well as the compliance of the institution with legislative requirements.

The audit represents a new procedure for Ukraine in the study of educational activities of schools, replacing the former system of state certification.

Summarily, let us note that strategies for improving quality in general secondary education institutions today are particularly relevant and are associated with the development of an internal quality assurance system, the formulation of a quality policy aligned with the strategic goals of the institution, the implementation of mechanisms of self-assessment and internal audit, and the engagement of all stakeholders in the process of analysis and improvement. A key element is ensuring academic integrity within schools, supported by transparent communication between teachers, students, and administrators, the establishment of electronic assessment systems, and mechanisms for preventing plagiarism. Increasingly important are strategies focused on adapting educational content to both local and global contexts, fostering an environment that addresses the needs of diverse groups of participants, and promoting linguistic, ethnic, and social diversity. Furthermore, collaboration with employers and academic institutions aimed at aligning education with labor market demands and the needs of local communities is of significant importance.

One of the most promising strategies for improving quality in general secondary education institutions is digitalization and the integration of artificial intelligence. The use of data analytics for monitoring student achievement, forecasting educational risks, automated assessment, adaptive courses, digital portfolios, platforms for feedback, and personalized learning constitutes a qualitative vector in the development of the quality assurance system.

Artificial Intelligence Technologies and Digital Tools in the Quality Assurance System of General Secondary Education Institutions

The Ministry of Education and Science of Ukraine, in cooperation with the Ministry of Digital Transformation, has already developed recommendations on the use of artificial intelligence (AI) in schools, emphasizing its responsible and effective implementation (Alieksieieva, 2025c). These recommendations primarily concern increasing teachers' awareness of potential risks and challenges, fostering their ability to interact critically, effectively, and ethically with AI systems, as well as ensuring respect for human rights and adherence to professional ethical standards. The recommendations apply to any AI systems used by teachers and students, particularly in the following areas: teaching subjects (integrated courses): differentiation, personalization of learning, and adaptation of educational materials to the individual needs of each student; providing socio-emotional support during lessons; extracurricular activities (searching for and creating additional thematic collections for students' independent study; facilitating partnership-based interaction among educational stakeholders; organizing extracurricular activities (developing programs or event scenarios); creating a safe and healthy educational environment (supporting inclusion and addressing individual student needs, especially by designing personalized chatbots to provide counseling for learners with special educational needs; applying art-therapy practices (creating relaxation-oriented therapeutic music compositions, coloring templates, and artistic works); using speech recognition systems to support students with hearing impairments and speech disorders); educational process management (monitoring and analyzing student progress; automated assessment; generating control materials for homework; tracking academic performance through the collection and analysis of student achievement data; timely identification of learning difficulties and provision of necessary pedagogical support); support for administrative decision-making (carrying out administrative tasks; preparing materials for pedagogical meetings; developing programs and content for parent-teacher conferences); professional development (enhancing professional qualifications and lifelong learning (online courses, mentoring, group courses); selecting resources for self-development, structuring information (educational blogs, websites, e-libraries, and similar tools).

A study conducted by Projector Creative & Tech Institute and the Minor Academy of Sciences of Ukraine in September-October 2023 indicated that more than 70% of teachers and 85% of students had already used AI in the learning process (Mala akademiia nauk Ukrainy & Projector Institute, 2024) (see Fig. 2).

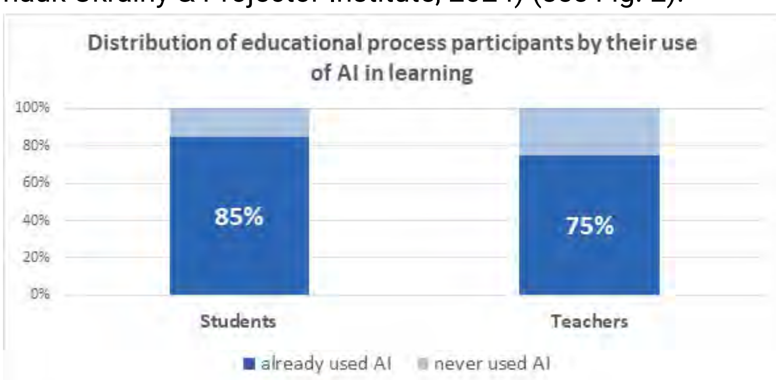

Fig. 2. Distribution of educational process participants by their use of AI in learning

At the same time, the majority of teachers who had experience using AI in their work evaluated this experience as successful, while 14% of surveyed teachers considered their experience unsuccessful. Furthermore, 37% of teachers indicated that they had already engaged students in the use of AI, 50% reported that they had not yet done so but planned to, and only 7% stated that they did not intend to involve students in the use of AI. An additional 7% of teachers remained undecided on this issue (Mala akademiia nauk Ukrainy & Projector Institute, 2024) (see Fig. 3).

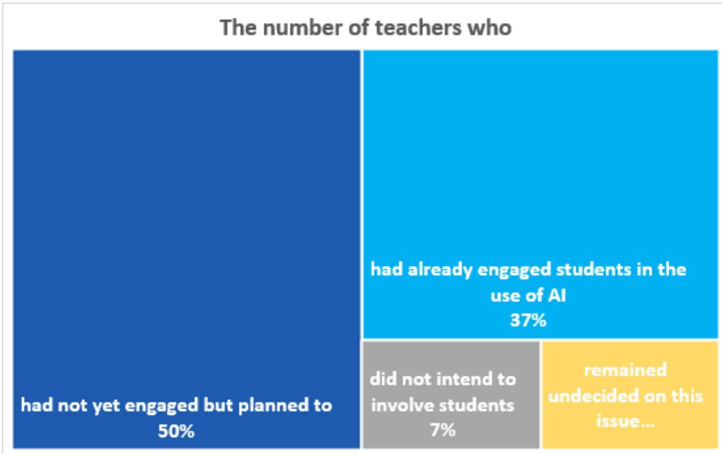

Fig. 3. Teachers' distribution by attitudes toward involving students in the use of artificial intelligence

AI technologies contribute to the individualization of the educational process, create opportunities for the automated assessment of students' learning outcomes, enable the tracking of their cognitive development dynamics, and enhance the effectiveness of managerial decision-making. Let us describe these aspects in the quality assurance system of general secondary education institutions.

For instance, among the key advantages of AI in ensuring personalized learning and monitoring are adaptive AI-driven platforms such as Squirrel AI and Century Tech. These platforms are capable of analyzing students' responses in real time, identifying gaps in their knowledge, and proposing individualized learning pathways. This not only increases the effectiveness of knowledge acquisition but also fosters intrinsic motivation to learn.

Of particular importance are Automated Essay Scoring (AES) systems, which are used to assess written responses on the basis of semantic analysis, cognitive complexity, and the quality of argumentation. Such solutions are widely implemented in international educational practices (for example, ETS e-rater in TOEFL) and could potentially be adapted to the Ukrainian educational context.

Equally significant is the role of AI in the evaluation of learning outcomes. The application of intelligent systems makes possible the automated diagnosis of knowledge while taking into account cognitive styles and the speed of information processing. Predictive analytics applied to learning data enables teachers not only to identify potential learning difficulties but also to design preventive support strategies. One of the key advantages of AI in general secondary education lies in its ability to provide objective, timely, and flexible assessment of educational outcomes. AI technologies enable not only the automation of grading tasks but also the detection of deeper patterns in students' learning behaviors. For example, modern machine learning-based systems can analyze typical student errors in tests (e.g., platforms such as Gradescope or Knewton); track knowledge development over time and forecast risks of academic underachievement; adapt task complexity to students' knowledge level and learning pace; and integrate diverse data sources (tests, portfolios, activity on platforms) into a unified analytical model to generate a comprehensive picture of learning progress.

Moreover, AI opens up opportunities for formative assessment, the primary aim of which is to help students better understand how they learn and to support their progress in real time. This is a key component of contemporary pedagogy, particularly in the context of the New Ukrainian School. Through instant feedback, progress visualization, and personalized prompts, AI fosters student reflection, enhances motivation, and enables teachers to fine-tune the educational interaction. However, the effectiveness of such technologies depends not only on the quality of algorithms but also on pedagogical design, digital ethics, and the teacher's ability to interpret results. Therefore, a crucial task is to integrate AI into assessment not merely as a technical innovation but as a component of a holistic educational ecosystem.

We developed a comparative table of AI-based assessment tools implemented in different countries worldwide.

Table 1

Comparison of AI-based tools for assessing learning outcomes

Platform Name	Core function	Features of use	Potential for Secondary Education Institutions (SEI)
Gradescope (USA)	Automated grading of written and test assignments	Support for open-ended tasks, handwriting recognition, LMS integration	Reduced grading time, support for assessment objectivity
Knewton Alta (USA)	Adaptive learning and real-time assessment	Construction of dynamic learning pathways based on student responses	Opportunities for formative assessment and flexible knowledge diagnostics

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Century Tech (Great Britain)	Personalized learning with AI analytics	Identification of knowledge gaps, recommendations for teachers and students	Support for individual progress, visualization of learning outcomes
ETS e-rater (USA)	Automated essay scoring	Semantic analysis, evaluation of argumentation and text structure	Application in external independent assessment of written tasks
Socrative (USA)	Creation of interactive tests with instant feedback	Usable during lessons or as homework, ease of implementation	Rapid formative assessment, student motivation through gamification

An instructive example is the experience of using AI in assessment in Finland. The introduction of AI into education in Finland is based on the principles of transparency, ethics, and inclusion. For instance, the adaptive platform Eduten is actively used in educational institutions and has been implemented in more than half of the country's schools. The platform personalizes mathematics tasks and provides teachers with real-time analytics on both class-level and individual student progress. The distinctive features of the Eduten adaptive platform include: automated assessment (the platform evaluates task performance, taking into account not only correctness, but also the time spent on problem-solving and typical errors); risk prediction (the platform informs teachers about students who may require additional support); formative assessment (students receive immediate feedback that fosters self-reflection and error correction); and a reduction in teacher workload. Furthermore, national recommendations on the use of AI in education (Finnish National Agency for Education, 2025) require schools to publish annual reports on the assessment algorithms employed and their validity and reliability. An important aspect of the Eduten adaptive platform is the provision of equal access to digital tools for both rural and urban schools.

The use of AI technologies in the assessment of learning outcomes opens new horizons for improving both the quality of the educational process and decision-making in general secondary education institutions. AI-based tools provide more objective, adaptive, and timely diagnostics of knowledge, enabling the construction of personalized educational trajectories. The experience of various countries, particularly Finland, demonstrates the effectiveness of implementing such solutions, especially when technological innovation is combined with pedagogical soundness. Automated assessment systems not only reduce teachers' workload but also foster student reflection, formative feedback, and motivation for self-directed learning. At the same time, it is crucial to ensure adequate teacher preparation for interpreting AI-generated data, adherence to principles of transparency, and protection of personal information. A systemic approach to integrating AI as an element of the digital educational ecosystem will contribute to enhancing the effectiveness of assessment as well as to sustaining and advancing educational quality overall.

AI also has significant potential in the management of educational institutions. Above all, this concerns analytical tools that utilize large volumes of educational data, enabling school administrations to effectively monitor teaching quality, manage workloads, forecast development trends of the educational institution, and make evidence-based decisions. The potential of AI in the management of educational institutions lies in its capacity to transform traditional approaches to strategic planning, quality monitoring, and informed decision-making. By analyzing large datasets (Big Data) and applying machine learning algorithms, school leadership gains the ability to perceive both the overall picture of the educational process and the subtle trends that remain invisible in traditional statistics.

AI-based tools are capable of analyzing learning data, including academic performance, attendance, and grade dynamics. On the basis of such data, it becomes possible to construct predictive risk models, which, in turn, contribute to the optimization of teacher workload distribution and the design of students' individualized educational trajectories. Moreover, the effectiveness of pedagogical methodologies can be assessed through correlation analysis between teaching approaches and students' learning outcomes. Finally, AI facilitates the automation of administrative reporting, including submissions to local authorities as well as internal analytical reports.

A vivid example is the use of analytical dashboards combined with AI algorithms for indicative assessment of teaching quality, which enables school administrations to identify both strengths and problematic areas in educational activities. Some systems, such as Classera (Saudi Arabia), have already successfully integrated educational content, performance monitoring, and administrative functions into a unified digital ecosystem. Furthermore, the use of cognitive analytics to detect micro-behavioral patterns of students (e.g., response time, activity in digital environments) appears highly promising, as it may serve as a basis for early intervention by school psychologists or tutors.

However, the effectiveness of AI in management largely depends on the availability of high-quality digital infrastructure in schools, the level of digital literacy among administrators, and adherence to ethical standards in the collection, storage, and interpretation of data. Thus, AI tools do not replace the head of an educational

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institution but significantly expand their capacity for evidence-based, transparent, and effective management.

AI is already being integrated into the management of educational institutions in Ukraine. An illustrative example is the "Mriia" platform, which serves as a digital management tool for general secondary education institutions. In 2024-2025, the Ministry of Education and Science of Ukraine, together with its partners, is implementing the "Mriia" platform, which combines the functions of an electronic gradebook, an analytical dashboard, and tools for the automation of managerial processes. The platform employs AI elements to analyze educational data, including: monitoring student performance and attendance with automatic identification of students requiring additional support; generating reports for school administrations and educational authorities; providing recommendations for teachers on adapting curricula based on class dynamics; forecasting teacher workload and optimizing schedules. The platform is already being piloted in a number of schools and has demonstrated positive outcomes in reducing administrative workload and increasing the transparency of managerial decision-making (Mala akademiia nauk Ukrainy & Projector Institute, 2024).

There are realistic scenarios for the gradual implementation of AI in school management under conditions of limited financial, technical, and human resources. According to such a scenario, the initial stage is diagnostic, i.e., conducting a self-assessment of the school's digital readiness (available equipment, staff's level of digital literacy, internet access). The second step involves forming an initiative group (principal, IT coordinator, subject teachers) to develop a digital development strategy. Subsequently, a priority area for AI application is selected, for example, performance analytics or the automation of reporting. The next step is the adoption of "free or conditionally free solutions," such as connecting to free analytical platforms (e.g., Google Workspace for Education with built-in Classroom analytics) or introducing AI-based applications for assessment (e.g., using Google Forms with automated grading and feedback). This will facilitate the collection of basic educational data for building local analytics (grades, attendance, participation in competitions, etc.). After data collection, a pilot implementation of a local analytical panel and the creation of a simplified dashboard (e.g., based on Excel + Power BI) for internal administrative use can be undertaken, along with the development of simple risk indicators (e.g., students with three or more grades below six points within a month). The results of the analytics can then be presented at a teachers' council meeting as a basis for collective decision-making. An important step is the expansion of functionality and teacher professional development, for example, conducting a series of internal training sessions for teachers ("What is AI," "How to analyze data"), seeking partnerships with EdTech startups or universities to participate in pilot projects, and gradually implementing the automation of managerial processes (e.g., completion of attendance records or template-based orders). The final stage is institutionalization and scaling, which includes embedding data and AI management principles into the school's Development Strategy, creating a mentoring model to support digital innovation among teachers, and advancing to the regional or municipal level with results (participation in competitions, forums, and presentations).

Thus, the roadmap for implementing AI in school management with minimal resources consists of five steps: 1) assessment of digital readiness (self-assessment; teacher surveys); creation of a resource map: internet, computers, platforms; 2) starting with free tools (Google Workspace, Microsoft Teams for Education, AI applications based on Google Forms, online gradebooks); 3) internal analytics (Excel, Power BI, simple dashboards for administration, visualization: performance, attendance, risks); 4) teacher motivation and mentoring; 5) expansion through partnerships (universities, EdTech startups, participation in grant and pilot programs).

The application of AI technologies in the management of general secondary education institutions is gradually shifting from a theoretical possibility to a practical tool for strategic development. AI systems provide school administrations with means for evidence-based, data-driven decision-making, automation of routine processes, and the identification of hidden patterns in learning dynamics.

The domestic case of the "Mriia" platform demonstrates that even under challenging conditions of digital transformation, Ukraine's educational system is capable of adapting AI tools to national realities. Moreover, the incremental implementation scenario confirms that the key success factor is not the scale of funding but rather strategic vision, readiness for cross-sector partnerships, and the development of digital culture within the teaching staff. Thus, AI not only optimizes management but also contributes to the formation of a new educational culture that is open to innovation, analytics, and sustainable development.

Summarizing the findings of the study, it should be noted that AI and digital tools are gradually becoming not merely auxiliary technologies but full-fledged elements of the modern educational ecosystem. Their application in general secondary education institutions enhances teaching efficiency, ensures flexible and objective assessment of learning outcomes, and optimizes managerial processes.

The potential of AI in the field of educational management is particularly noteworthy. The use of big data analytics, forecasting algorithms, and automated reporting contributes to the formation of a more transparent, accountable, and strategic model of governance. As evidenced by the experience of the "Mriia" platform, innovations can be implemented even in schools with limited resources, provided that a consistent digital strategy, professional staff training, and local leadership are in place. Further steps in this direction should focus on fostering digital culture within the educational environment; adapting ethical standards in data management; and supporting innovation through partnerships among schools, research institutions, and the EdTech community. The integration of AI technologies should not be viewed merely as a technical impulse but as a strategic shift in educational thinking which is oriented toward sustainable development, humanistic values, and social engagement.

Digital tools also play a key role in transforming the education quality assurance system, particularly in the context of contemporary challenges and the needs of the digital generation. Currently, two information and analytical systems are actively used: EvaluEd and Unified School.

EvaluEd is an information and analytical system developed by the State Service for Education Quality of Ukraine in cooperation with the Czech Development Agency and the Czech School Inspectorate (Derzhavna sluzhba yakosti osvity Ukrainy, n.d.). It combines digital technologies with the methodology of educational audit, ensuring transparency, reliability, and systematic approaches in evaluation processes. The system is used for institutional audit and self-assessment of educational institutions, allowing the analysis of strengths and weaknesses in educational activities and enabling prompt responses to challenges. The aim of the system is to create a tool for external evaluation and self-assessment of educational and managerial processes in schools. Its methodological framework is based on four domains of activity: the educational environment, governance, pedagogical practice, and learning outcomes. The main data collection tools include surveys of education process participants, observations, and document analysis.

The capabilities of EvaluEd are presented in Table 2.

Table 2

Capabilities of EvaluEd

Domain	Description
Self-assessment	Educational institutions can conduct annual self-analysis based on institutional audit criteria.

Institutional audit	The State Service for Education Quality conducts audits once every ten years, while EvaluEd enables schools to prepare in advance.
Teacher certification	Applied at the stages of self-assessment and the study of practical teaching experience.
Analytics	Generation of summary reports, identification of problems, and monitoring of change dynamics.
Digitalization	Data storage, integration with other systems, and protection against duplication and falsification..

EvaluEd is a powerful tool for the systematic improvement of education quality, combining digital analytics with an evidence-based approach to management. Its application opens several strategic opportunities. For example, educational institutions can conduct annual self-analysis using clear criteria that align with institutional audit standards. This encourages conscious improvement of educational processes rather than mere preparation for external inspections. The system generates comprehensive reports that include data from surveys, observations, and document analysis. At the same time, school leaders gain the ability to identify weaknesses and develop strategies for growth based on reliable information. EvaluEd minimizes subjectivity in the evaluation process by ensuring unified approaches to quality analysis. This is crucial for fostering partnerships among stakeholders in the educational process, students, parents, and teachers. The system is capable of tracking the progress of an institution over time, responding to new challenges, and adapting to changes. For instance, in the context of martial law or the transition to blended learning, this becomes critically important (Derzhavna sluzhba yakosti osvity Ukrainy, n.d.).

It should also be noted that EvaluEd is used in the stages of teacher self-assessment of professional competence and the study of practical experience. This contributes to the professional development of educators and the enhancement of teaching quality. Its role is particularly significant in the second and third stages of teacher certification, coordinated by the State Service for Education Quality of Ukraine. Certification participants complete a self-assessment questionnaire on their professional competence through EvaluEd. The questionnaire consists of 60 statements, each offering five response options. Teachers select the option that most accurately reflects their practice. Once the questionnaire is submitted, the system generates a visualization of the results, which can then be used to plan professional development. At the third certification stage, EvaluEd facilitates the collection and analysis of data on teachers' actual pedagogical practice. This includes classroom observations, document analysis, and surveys of educational stakeholders, thus

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ensuring a comprehensive approach. The system minimizes subjectivity by applying consistent evaluation criteria. All data are stored in digital format, enabling the tracking of dynamic changes and the formulation of evidence-based conclusions (Nova ukrainska shkola, 2024).

Unified School is an educational information system that provides communication, learning, and assessment within a single digital environment. It was created to support the digitalization of the school process (Yedyna shkola, n.d.-a). The main functions of the Unified School system include: electronic diary and gradebook (recording grades, homework, attendance, and teacher comments); communication, which enables message exchange among students, parents, and teachers; timetable management (automated creation and updating of class and teacher schedules); performance analytics (the system generates reports on academic outcomes, helping teachers and administrators make informed decisions). The integration of Unified School with other platforms is part of the AICOM ecosystem, which enables the aggregation of data from multiple sources for educational management (Podilska ODA, 2024). The platform features an administrative dashboard for school leaders and a user interface for students and parents for daily use. It also supports online learning, which is especially relevant under conditions of distance or blended education. This system enhances transparency, efficiency, and personalization of the educational process, while simultaneously fostering digital culture in Ukrainian schools.

Table 3 presents a comparative analysis of the Unified School system with other educational platforms.

Table 3

Comparative analysis of the Unified School system with other educational platforms

Platform	**Core functions**	**Strengths**	**Limitations**
Unified School	Diary, gradebook, analytics, timetable, communication	Integration into the state ecosystem, localization	Primarily focused on the school segment
Google Classroom	Assignments, assessment, documents, feedback	Flexibility, integration with Google Workspace	Not localized to the requirements of the State Service for Education Quality of Ukraine (SSEQ)
Moodle	Courses, testing, forums, SCORM modules	Powerful learning management system (LMS)	High complexity of administration
OpenEdu	Online courses and tests for professional education	Accessibility for self-learning	Focused mainly on self-education

Unified School is a national educational information system that fully replaces paper-based gradebooks and diaries by integrating digital technologies into the daily operations of general secondary education institutions in Ukraine. The system is officially recommended by the Ministry of Education and Science of Ukraine (letter No. 1/11-9213 of October 18, 2019) and is currently used by more than 3,600 schools across the country (Yedyna shkola, n.d.-b). The key components of the system include: electronic gradebook: recording lesson content, grades, attendance, possibility to attach files (text, photo, video, audio), data export/import in Excel and PDF formats; printing of pages for archival storage; electronic diary (continuous parental access to the learning process, monitoring of attendance and academic progress, push notifications in specific cases, and interactive communication with teachers via internal mail); analytics and reporting (generation of reports on academic performance, creation of report cards, certificates of achievement, scoring final grades, as well as preparation for the new academic year (class transfers, data updates); security and verification (data protection in compliance with national information security standards (CISS), prevention of third-party interference, and authorized access for participants in the educational process). The system is part of the AICOM ecosystem, which enables data integration with EvaluEd and other platforms, thereby strengthening the overall digital infrastructure for educational management.

Key recommendations for the implementation of AI and digital tools in the education quality assurance system of general secondary schools include:

- developing a national framework for the ethical use of AI in education, encompassing principles of transparency, non-discrimination, data protection, and accountability;
- integrating digital and AI literacy into teacher training and professional development, with a focus on interpreting educational analytics and pedagogical reflection on results;
- supporting the gradual implementation of AI solutions through pilot projects in schools of different types and regions, with clear mechanisms for monitoring, guidance, and sharing experience;
- establishing a national ecosystem of digital services for schools, integrating platforms for management, assessment, and learning, including elements of personalization powered by AI;
- ensuring equitable access to digital infrastructure, particularly in rural and schools with small number of students, through state-led or public-private initiatives;

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- encouraging partnerships between schools, universities, and EdTech companies aimed at adapting global AI tools to the Ukrainian educational context;
- promoting student engagement in the development of digital culture through involving learners in evaluating AI systems, fostering critical thinking about algorithms, and encouraging active use of formative assessment outcomes.

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4.2. EUROPEAN EXPERIENCE OF ARTIFICIAL INTELLIGENCE INTEGRATION INTO GENERAL SECONDARY EDUCATION: TRENDS AND STRATEGIES

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The modern world is undergoing a digital transformation, a key driver of which is the rapid development of artificial intelligence (AI). This technology is already having a significant impact on all areas of human life, including economics, medicine, science, and, of course, education. Recognizing the importance of AI for shaping the future requires the immediate integration of relevant knowledge and skills into curricula, especially at the level of general secondary education, which lays the foundation for a person's further development and successful adaptation in modern life.

The integration of artificial intelligence into general secondary education is not just a technological innovation but a necessary step to prepare a new generation for the challenges and opportunities of the 21st century. This will allow students not only to understand the principles of AI but also to critically evaluate its impact, develop skills for collaborating with intelligent systems, and form a responsible attitude toward the ethical and social aspects of this technology.

According to a study by Shivani Zoting, "Artificial Intelligence in Education Market Size, Share, and Trends from 2025 to 2034," the global AI in education market is estimated at $7.05 billion in 2025 and approximately $112.3 billion by 2034. It is projected to grow at a compound annual growth rate (CAGR) of 36.02% from 2025 to 2034. The AI in education market size in the United States was $1.48 billion in 2024 and is projected to grow to $32.64 billion by 2034, with a CAGR of 36.21% (Zoting, 2025).

In the European market, the CAGR for AI in education is expected to be 31.9% from 2025 to 2030 (Horizon Grand View Research, 2025).

According to research from the McKinsey Global Institute (MGI), artificial intelligence could add $575.1 billion to the European economy by 2030. AI technologies can help Europe achieve an annual productivity growth rate of up to 3% by 2030. Although European organizations lag behind their American counterparts by 45–70% in AI adoption, it is in these figures that researchers see the greatest potential. Scaling the introduction of generative artificial intelligence into all spheres of life can lead to breakthrough innovations that will change people's daily lives. Especially in education, personalized learning and game-based learning using AI methods can become the most effective (McKinsey Global Institute, 2024).

The integration of artificial intelligence into general secondary education faces several significant challenges that require careful analysis. First, there is a conflict between the potential of AI and the inertia of the traditional educational system. AI promises revolutionary changes, such as personalized learning, the automation of routine tasks, and the reduction of administrative burdens on teachers. However, traditional teaching methods are often not ready for such changes, remaining tied to outdated curricula and assessment methods. Second, high expectations for AI often clash with limited resources: effective implementation requires significant financial investment in infrastructure and software, as well as qualified personnel and time, which are often in short supply. There is also a need for innovative teaching approaches that contradict traditional methods focused on knowledge transfer rather than the development of critical thinking and creativity. These skills are key to the effective use of artificial intelligence technologies in education.

The changing roles of teachers and students is another important aspect. The intended purpose of artificial intelligence is to serve as a tool for teachers, reducing their workload of monotonous tasks and freeing up more time to focus on individual interaction with students. However, there are fears within the pedagogical community that AI might diminish the teacher's value or even partially replace them, leading to resistance and uncertainty.

For students, AI can facilitate self-directed learning and the development of self-regulation skills. At the same time, it carries the risk of encouraging passive information consumption and an over-reliance on cheating, which undermines the principles of academic integrity. Additionally, despite the personalization opportunities offered by AI, over-dependence on it can limit the crucial face-to-face interaction between students and teachers that is key for developing social skills, collaboration, and emotional intelligence.

Ethical and social aspects also demand attention. Despite AI's potential to make education more accessible, there is a risk of deepening the digital divide due to unequal access to technology. A serious challenge is data protection and privacy: for AI to work effectively, it requires the collection and analysis of large volumes of students' personal data, raising concerns about their security, especially for minors.

Moreover, it's important to remember that AI's objectivity is an illusion; algorithms trained on existing data can inherit hidden biases, potentially leading to unfair evaluations or even discrimination, which contradicts the fundamental principles of equality and fairness in education. The opacity of some AI algorithms creates additional difficulties in determining ethical responsibility for potential errors or negative outcomes generated by artificial intelligence. Thus, for the successful integration of AI into education, it is necessary to develop adaptive curricula that account for the dynamics of technological progress and foster the development of critical thinking, creativity, and social skills. Society must actively work to overcome existing barriers to fully realize the potential of artificial intelligence in the educational process.

The relevance of this study is deeply rooted in several interrelated factors that define the contemporary educational landscape. First and foremost, we are witnessing a global digital transformation, where artificial intelligence (AI) has become an integral part of both daily life and professional activities. AI in education is no longer a futuristic concept or a science fiction plot, but an inevitable reality that requires practical implementation and deep reflection. Young people who do not understand the essence and possibilities of AI will inevitably face limitations in their competitiveness in the labor market and their ability to adapt to new conditions.

This is directly related to the need to prepare the "human of the future." Modern education must meet the demands of our time, providing students not only with the knowledge to use AI, but also with the skills to develop it and solve complex problems that arise from its application. This includes the development of critical thinking, creativity, problem-solving skills, digital literacy, and ethical awareness. For the Ukrainian education system, this research presents both significant opportunities and certain challenges. Ukraine is seeking to integrate into the European space, and therefore it is extremely important to take into account the best practices of our European partners. European countries are actively investing in the development of AI in education, creating innovative approaches to teaching, assessment, and administration. Studying this experience will allow Ukraine to avoid common mistakes, adapt successful strategies, and significantly accelerate the process of AI implementation in the national educational process.

Analysis of European experience in integrating AI into general secondary education. The European Union is actively developing common strategies and policies for the integration of artificial intelligence into the education system, recognizing its potential to fundamentally transform the learning process and prepare citizens for the challenges and opportunities of the digital age.

These efforts are focused on several key areas:

- developing a regulatory framework for AI;
- creating ethical guidelines for its application;
- supporting research and innovation projects;
- fostering cooperation and the exchange of best practices.

The European Commission report, "The Impact of Artificial Intelligence on Learning, Teaching, and Education" (2018), prepared by researchers under the leadership of Ilkka Tuomi, emphasizes that the implementation of AI in the educational sphere will lead to systemic transformations. The authors stress the urgent need to rethink the role of education in modern society, its organization, goals, and objectives, in order to ensure the relevance of the learning process in the context of a new technological paradigm (Tuomi et al., 2018, p. 2). Artificial intelligence (AI) in education is the use of computer systems to simulate human learning and decision-making with the aim of improving teaching and learning (Tuomi et al., 2018).

The report defines the concept of "artificial intelligence" as "a computer system capable of performing tasks that are typically associated with intelligent beings" (Tuomi et al., 2018, p. 10). This definition emphasizes the machine's ability to imitate human cognitive functions. Historically, the first clear definition of artificial intelligence was proposed in a financial proposal to the Rockefeller Foundation back in 1955. It

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was based on the assumption that "every aspect of learning or any other feature of intelligence can be so precisely described that a machine can be made to simulate it" (ibid). This vision laid the groundwork for the further development of AI technology.

In the EU document "Artificial Intelligence for Europe" (2018), the concept of "artificial intelligence (AI)" was defined as systems that "display intelligent behavior by analyzing their environment and taking actions – with some degree of autonomy – to achieve specific goals" (European Commission, 2018). Thus, compared to the previous definition, this new interpretation emphasized the ability of AI to analyze the environment and act with a certain degree of autonomy to achieve specific goals.

The modern understanding of AI expands upon this initial definition, adding adaptability, the ability to learn, and predictable actions to its key characteristics. These features allow AI systems not just to imitate but to evolve in their interaction with the environment and accumulated data. Therefore, artificial intelligence is not merely a technology but a powerful catalyst that demands a rethinking of educational paradigms to prepare future generations for life and work in the context of digital transformation and global challenges of the modern world. This is a process of modeling and reproducing human thinking, demonstrating autonomy and effectiveness in decision-making. A comprehensive analysis of these definitions leads to the conclusion that artificial intelligence is not just a technology but a dynamic field that develops systems capable of analyzing information, learning, adapting, and acting autonomously to achieve set goals.

In the context of education, this means not only automating routine tasks but also creating new opportunities for personalized learning, data analysis, early identification of educational needs, and the development of future skills. Understanding AI as a tool that can function with a certain degree of autonomy and intellectually and dynamically respond to its environment is critically important for shaping effective educational policies and practices in the digital age.

The main element of the regulatory framework is the AI Act. Although this law does not focus exclusively on education, it is a foundational document that regulates the use of AI in all sectors, including education. It establishes general principles and requirements that will affect the development, implementation, and use of AI systems in educational institutions.

In parallel, the European Commission and expert groups are developing detailed ethical guidelines designed to ensure the responsible implementation of AI solutions in the educational environment. These guidelines cover several key aspects. First, they

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require adherence to the principles of fairness and non-discrimination to prevent AI systems from reinforcing existing biases that could unfairly affect students. Second, transparency and human oversight are crucial: it is necessary to clearly explain how AI works and always maintain the possibility for a human to intervene or verify its decisions. Significant attention is paid to data privacy and security, ensuring robust protection of the personal information of students and teachers processed by AI. The guidelines also define accountability, clearly distinguishing who is responsible for decisions made or supported by artificial intelligence systems. Among other things, they emphasize the well-being of students and teachers, ensuring that AI is used to benefit the learning process and does not harm the mental or physical health of participants in the educational process.

It is worth noting that the EU actively supports numerous research and innovation projects aimed at developing and implementing AI in education through programs such as Horizon Europe and Erasmus+. These projects explore personalized learning, intelligent assessment systems, teacher support, and the creation of virtual learning environments. Currently, the EU actively promotes cooperation and the exchange of best practices among member states and with international partners, which helps countries learn from each other and avoid duplicating efforts in developing national strategies and implementing AI in education. All these joint strategies and policies reflect a comprehensive EU approach that combines legal regulation, the development of digital skills, ethical considerations, unique ways of using digital technologies in the educational process, innovation support, and international cooperation (Dzhurylo & Shparyk, 2019; Shparyk, 2021; Sharlovych et al., 2023).

EU Regulatory Framework for AI. Today, few countries have comprehensive legislation on artificial intelligence. Only two countries stand out for their early and significant steps in this area: China and Singapore. In 2021, China adopted the Law on Promoting the Development of the Internet of Things and Artificial Intelligence. This law lays down the principles of responsible AI development, with a focus on data security and risk management. In the same year, 2021, Singapore introduced its Directive on AI Governance. The document establishes key principles for the use of AI, such as transparency, accountability, and non-discrimination (Hrytsenchuk, 2024).

In May 2025, Japan approved the “Act on the Promotion of Research and Development and the Utilization of AI-Related Technologies.” This law aims to balance innovation with risk management, recognizing potential threats such as crime, personal data leaks, and copyright infringement. It grants the government the

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authority to investigate serious incidents. Other major players, such as the United States, the United Kingdom, Canada, and India, are also actively working on their own regulatory frameworks for AI, although their initiatives may currently be less comprehensive or still in the development stage.

That is why the Artificial Intelligence Act, proposed by the European Commission in 2021, is extremely important. The working group of developers, relying on the achievements of the international community of specialists from various fields, presented this draft for a wide discussion (Hrytsenchuk, 2024). In March 2024, the European Parliament adopted the Artificial Intelligence Act (AI Act) (European Parliament, 2024).

Its main provisions and objectives can be summarized as follows:

1. Risk Classification. The Act introduces a risk-based approach, classifying AI systems into four risk levels: unacceptable, high, limited, and minimal. This allows for the regulation to be adapted to the potential harm an AI system could cause.

– Unacceptable Risk. AI systems with unacceptable risk, which threaten people's safety, livelihoods, and rights, are prohibited. Examples include social scoring, manipulating human behavior, and the unrestricted use of real-time biometric identification.

– High Risk. High-risk AI systems, such as those used in critical infrastructure, education, employment, healthcare, and law enforcement, are subject to strict requirements, including conformity assessments, data quality controls, transparency, and human oversight.

2. Support for Innovation. Despite strict regulations, the Act aims to stimulate innovation in the field of AI. It provides for the creation of regulatory sandboxes and support mechanisms for small and medium-sized enterprises (SMEs) to develop and test innovative AI systems in controlled environments.

3. Transparency and Obligations. The legislation sets high transparency requirements for AI systems, especially for general-purpose AI (GPAI) models and generative AI systems. Developers must provide detailed information about their systems, including the data used for training and evaluation metrics. For generative AI, it is also mandatory to label content as being AI-generated.

4. Protection of Human Rights. The Act focuses on protecting fundamental human rights. It establishes clear obligations for AI developers and providers to avoid discrimination, ensure privacy, and adhere to ethical standards. Mechanisms are provided for citizens to file complaints regarding AI systems.

5. Governance and Oversight. To ensure the Act's enforcement, a new European AI Office is being established. It will be responsible for overseeing the implementation

and application of the rules and for fostering cooperation among national authorities (European Parliament, 2024).

Overall, the AI Act strikes a balance between promoting innovation and ensuring safety, transparency, and ethical principles in artificial intelligence. This makes it a key document for the future development and implementation of AI in Europe and beyond.

The AI Act is part of a broader package of policy measures aimed at fostering trustworthy artificial intelligence, which also includes the AI Innovation Package, targets for launching AI factories, and a coordinated plan on AI. Together, these measures guarantee safety, respect for fundamental rights, and a human-centric approach to AI, while also increasing the pace of AI adoption, investment, and innovation across the EU (CEE Digital, 2024).

EU Strategies on AI in Education. The European Union has consistently built a strategic framework for the development and regulation of artificial intelligence (AI). This began in April 2018 with the publication of the European Commission's agenda for promoting AI in Europe (European Commission, 2018).

In the spring of 2020, the "White Paper on Artificial Intelligence" was published (European Commission, 2020b), which proposed a framework for trustworthy AI based on the principles of excellence and trust. The document aimed to stimulate the development and adoption of AI while minimizing risks such as decision opacity and discrimination. The strategy envisaged creating an "ecosystem of excellence" by mobilizing resources for AI research, innovation, and implementation, including support for small and medium-sized enterprises. Simultaneously, it aimed to create a regulatory framework that would ensure AI systems comply with European values and fundamental rights, especially for high-risk systems. The document emphasized the need to increase investment, advance research, address skills gaps, and ensure access to data and computing infrastructure to strengthen Europe's global leadership in trustworthy AI.

A further step towards the EU's global leadership in this area was the "Coordinated Plan on Artificial Intelligence," published in April 2021 (European Commission, 2021a). The main goal of the document is to strengthen the EU's global leadership in the development of human-centric, trustworthy, and sustainable artificial intelligence (AI) by accelerating investments, taking active steps on AI strategies, and aligning AI policies to overcome fragmentation and address global challenges. The document is based on the eponymous plan from 2018, which laid the foundation for cooperation

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and encouraged member states to develop national AI strategies. As a result, most member states have adopted national AI strategies, investments in the sector have increased, and the EU has mobilized significant resources to support these processes.

At the same time, the European Commission presented "Proposal for a Regulation laying down harmonised rules on artificial intelligence" (European Commission, 2021b), which marked the first step toward creating the European AI Act. These efforts culminated in the final version of the AI Act being adopted in December 2023, following successful trilateral negotiations among EU institutions, which ensured its status as law.

The key EU initiative that determines how technology can support education and training is the strategic document titled "Digital Education Action Plan – DEAP" (2020) (European Commission, 2020). In particular, it includes goals and actions related to AI. The DEAP plays a crucial role in integrating artificial intelligence into the EU's educational system. Specifically, it aims to build digital skills, enhance digital literacy, and develop the ability to work with AI among pupils, students, and teachers. This involves not only a technical understanding of AI fundamentals but also an awareness of its ethical aspects and practical applications. Furthermore, the DEAP actively supports digital transformation, encouraging the use of AI and other digital technologies to improve teaching and learning methods, which in turn fosters the personalization of the educational process and the creation of adaptive learning environments. The plan also actively supports the development of new, innovative AI solutions for the education sector and promotes the exchange of best practices among EU member states, helping to spread successful experiences and move forward together.

It should be noted that the sixth action of the DEAP was focused on developing ethical guidelines for teachers and educators on the use of AI and data in teaching and learning. These guidelines addressed several key aspects. Primarily, they were intended to raise awareness of how artificial intelligence and data can be used in education, as well as to draw attention to all related risks, particularly ethical ones. In addition, an important task was to provide practical support to primary and secondary school teachers, especially those with limited experience working with AI. The guidelines also aimed to support the development of appropriate systems and administrative processes that would facilitate the implementation of AI in the educational environment. They provide advice on the effective use of AI and its adaptation to achieve various educational goals.

In 2022, the European Commission published the "Ethical guidelines on the use of artificial intelligence (AI) and data in teaching and learning for educators" (European Commission, Directorate-General for Education, Youth, Sport and Culture, 2022). This document is a crucial component of the EU's overall strategy, which aims to ensure the ethical and responsible use of AI, particularly in a key sector like education.

A key aspect of these guidelines is the ethical integration of AI into education. This field is of critical importance for societal development and the training of future specialists, which underscores the European Union's commitment to the responsible and human-centered development of AI.

The document is also aimed at raising awareness and fostering critical thinking among teachers and educators. It helps them understand the potential benefits and risks of using AI in education, thereby promoting a positive, critical, and ethical interaction with AI systems. This fully aligns with the broader EU strategies that ensure the development and implementation of AI is human-centric, reliable, and responsible.

By providing practical recommendations for teachers and educators, the document actively promotes the development of AI literacy and ethical awareness from the very beginning of the educational process. This is an extremely important step for the successful and responsible integration of AI into various sectors of society and the economy.

Finally, the unified European approach to this issue is underscored by the fact that the document is available in many official EU languages. This demonstrates a commitment to its widespread dissemination and the adoption of ethical principles across all member states, strengthening the common European strategy for AI governance.

Thus, the European Union is demonstrating a comprehensive and proactive approach to integrating artificial intelligence into the education system, seeking to maximize its transformative potential and prepare citizens for the challenges of the digital age. This work includes the formation of a regulatory framework, notably the AI Act, which governs the use of AI in all sectors, including education. The EU is also developing ethical guidelines for teachers and educators that focus on fairness, transparency, and data protection, while supporting innovative projects and fostering the exchange of best practices. This balanced approach allows for the responsible and effective use of AI's potential, distinguishing the EU's strategy from many other countries. All of this ensures a human-centric development of AI in the educational sphere for the benefit of future generations and the creation of a more inclusive, effective, and individualized educational system in Europe.

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In 2023, the European Commission published a report on artificial intelligence titled “AI report: by the European Digital Education Hub’s Squad on artificial intelligence in education” (European Commission, European Education and Culture Executive Agency, 2023). This report is a key document highlighting the current state and future directions of artificial intelligence integration into school education in the European Union countries. It covers a wide range of issues, from the necessary competencies for teachers to the ethical and legal aspects of using AI.

Specifically, the document presents general trends and approaches to integrating artificial intelligence (AI) into the European educational system, and also analyzes the associated potential risks and methodological challenges.

In the context of the European Union’s educational system, general trends and approaches to artificial intelligence (AI) integration are observed, which include the application of a three-dimensional approach to implementing AI in the learning process:

Teaching for AI. This approach is fundamental for building “AI literacy,” particularly among teachers and students. It focuses on developing competencies for confident, critical, and safe interaction with AI systems in everyday life. Key aspects include understanding the daily impact of AI, critical thinking and bias detection, safe and responsible interaction, as well as ethical and legal considerations. This approach lays the groundwork for all students, regardless of their future career paths.

Teaching with AI. This direction is focused on the practical application of AI tools to enhance the teaching and learning process and involves using AI as an auxiliary tool to achieve educational goals. Applications include personalized learning, automated assessment and feedback, content generation, collaborative support, and optimization of administrative tasks. Specifically:

- Personalized learning pathways. Adapting courses to students’ individual needs, learning styles, and pace.
- Intelligent tutoring systems. Providing virtual mentors that offer one-on-one guidance, diagnose knowledge gaps, and provide feedback.
- Automated assessment and feedback. Streamlining the evaluation of both objective and subjective work, which reduces teacher workload and provides prompt feedback for students.
- AI-driven content creation. Generating diverse learning materials such as textbooks, presentations, and quizzes, allowing for quick content updates and varied learning formats.

- Virtual and augmented reality (VR/AR) in learning: creating immersive, interactive learning environments that offer realistic simulations without physical constraints (e.g., medical training, historical reconstructions).
- Gamification with AI. Integrating game elements into learning, creating adaptive and engaging experiences that motivate students through personalized challenges and rewards.

It is crucial for teachers to be able to critically select AI tools that align with the curriculum and pedagogical goals (EIMT, 2025).

Teaching about AI. This is the more technical part, aimed at teaching students the fundamentals of AI from a developer's perspective, including principles of perception, representation and reasoning, learning (machine learning), and natural interaction. This requires basic knowledge of mathematics, programming, and computer science.

Among other significant trends, a human-centric approach, the development of teacher competencies, personalized learning, the reduction of administrative burden, and the promotion of inclusion and equity should be highlighted.

The report highlights several significant risks associated with the use of AI in education:

- Risk of bias and discrimination. AI systems trained on biased data can reinforce existing stereotypes and lead to discrimination.
- Privacy and data protection. The collection and analysis of large volumes of students' personal data raise serious privacy concerns, highlighting the importance of adhering to GDPR.
- Lack of transparency (Black Box Problem). AI algorithms often operate as "black boxes," making it impossible to understand their decisions.
- Dependency and loss of human control. Excessive reliance on AI can lead to a loss of human judgment, especially in cases that affect students' future opportunities.
- Academic integrity. Generative AI poses a threat to traditional assessment formats and raises concerns about plagiarism.
- Risk of exclusion (Digital Matthew Effect). Unequal access to AI technologies can exacerbate existing inequalities.
- Ethical implications. Broad ethical questions concerning the impact of AI on human rights, democracy, and the rule of law.

Moreover, AI-related risks are classified by their level of danger, which requires an appropriate management approach:

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- Unacceptable risk. AI systems that pose a clear threat to people's safety, life, and rights will be banned (e.g., emotion recognition in educational institutions).
- High risk. AI systems used in critical infrastructures, as well as those that can affect a person's access to education or career path, require strict risk assessment, high data quality, transparency, and human oversight.
- Limited risk. AI systems with specific transparency obligations (e.g., chatbots, where users must know they are interacting with a machine).
- Minimal or no risk. Free use of AI with minimal risk, such as AI games or spam filters.

Thus, according to the document, the use of artificial intelligence in education is of great importance, as it offers significant benefits. AI can improve the learning process by providing formative feedback, assisting teachers with lesson planning and administrative tasks, and adapting learning strategies through learning analytics.

Overall, the EU's strategic vision for AI in education is a balanced approach that maximizes benefits while minimizing risks. The European Union emphasizes the importance of human oversight, especially in cases where AI begins to influence key aspects of the educational process. The document warns against over-reliance on AI for decision-making and underscores the need to support human values in educational applications. Special attention is paid to the implementation of Explainable AI, which allows for understanding the logic behind decisions made by AI systems. The risk level of AI use is determined by the context of its application, not the tool itself, which requires a thorough analysis before implementation. The document also recommends starting with minimal-risk applications, such as providing feedback and assisting with administrative matters, and warns against the use of AI for decisions that could affect students' future opportunities.

Several other common European initiatives in the field of AI implementation, which directly or indirectly relate to the field of education, should also be mentioned. In February 2025, at the AI Summit in Paris, European Commission President Ursula von der Leyen officially announced the launch of the InvestAI initiative. This initiative is aimed at mobilizing 200 billion euros in investments to accelerate the development of artificial intelligence (AI) in the European Union. A key element of InvestAI is the creation of a new European fund of 20 billion euros, designated for building "AI gigafactories." These advanced computing centers are designed to ensure the open and collaborative development of state-of-the-art AI models, which should strengthen Europe's position as a leading global player in this field (CEE Digital, 2024).

The creation of four AI gigafactories is planned, which will be located in different EU countries. Their main task will be to train complex and the newest AI models, which requires significant computing power. Each of these factories will be equipped with approximately 100,000 state-of-the-art AI chips, which is four times the power of existing computing centers. They will become the world's largest public-private partnership aimed at developing trustworthy artificial intelligence, and their activities will support open innovation as well as industrial and strategic applications. Access to such powerful computing resources will help increase the competitiveness of smaller companies and startups on the global market. The European Commission has already announced the creation of seven AI factories and plans to announce five more. The 10 billion euros in investments, co-financed by the EU and its member states, represent the largest public support for an AI project in the world, and they are expected to attract ten times more private investment (CEE Digital, 2024).

In addition to the InvestAI fund, the European Commission is implementing a number of accompanying measures to stimulate innovation in the field of AI in Europe. These include financial support through the "Horizon Europe" and "Digital Europe" programs dedicated to generative AI. An important direction is the strengthening of the EU's human potential in the field of generative AI through education, training, and reskilling. The Commission also continues to encourage public and private investment in startups and the scaling of AI companies, particularly through venture capital. The development and implementation of common European data spaces, which are critically important for training and improving AI models, are being accelerated. The "GenAI4EU" initiative has been launched, aimed at supporting the development of new applications of generative AI in 14 European industrial ecosystems (including robotics, healthcare, manufacturing, etc.) and in the public sector. Additionally, the Commission is creating a European Artificial Intelligence Research Council to pool resources and explore the potential of data to support AI. By the end of 2025, the "Applying AI" initiative is planned to be launched to stimulate the industrial implementation of AI in key sectors (CEE Digital, 2024).

Although the InvestAI initiative and the creation of AI gigafactories are aimed at the overall development of AI infrastructure and innovation in Europe, their impact on education is critically important. Providing access to vast computing power to smaller companies and startups means that educational technology developers will also get the opportunity to create and test more complex and effective AI solutions. And the support for the EU's human potential in generative AI through education, training, and reskilling indicates direct investment in the educational sphere to prepare specialists who will work with new AI technologies. While the "GenAI4EU" initiative covers 14 industrial ecosystems, it will also create new use cases that can be integrated into curricula and methodologies. Thus, these initiatives are part of a broader EU strategy aimed at creating an ecosystem that supports the development, implementation, and ethical use of AI in all sectors, including education, which ensures the preparation of future generations for the digital economy and society.

So, the European Commission is actively working on a common European strategy for artificial intelligence (AI) that aims to drive scientific breakthroughs and tech leadership, while making sure new tech works for all Europeans and respects their rights. This joint approach to strengthening Europe's innovation potential focuses on several interrelated key areas (see Table 1 and Table 2).

Table 1

Key directions for strengthening European innovation potential

Political goals and investments	The EU's main political goal is to achieve global leadership in trustworthy AI. This involves a significant expansion of investment and development of AI infrastructure. The vision is to establish a clear AI policy and attract large-scale investments. The total annual investment in artificial intelligence is planned to be €20 billion, including both public and private funds. To achieve this goal, the development of an "AI-on-demand" platform is envisioned to provide access to AI resources, as well as targeted funding for companies and startups through the European Fund for Strategic Investments (EFSI) and the InvestEU program. Special attention is paid to the application of AI in the public sector through the "AI uptake" program.
Education, research, and skills	A key element of the strategy is to promote education and research in the field of AI. This includes developing skills related to artificial intelligence in order to retain and attract the best scientists. The EU aims to bring together centres of excellence and support changes in the labour market through special training programs funded by the European Social Fund. The goal is not only to provide technical training for specialists, but also to foster broad AI literacy and ethical awareness.
Infrastructure	Significant investments are being made in the development of AI infrastructure. This includes investments in high-performance computers, quantum computers, and AI and data infrastructure itself. The EU is also committed to further developing the European Cloud for Open Science and developing a common European high-performance computing infrastructure, which is a fundamental basis for innovation in AI.

Ethical and legal framework	To ensure the reliable and responsible development of AI, the EU is actively creating an ethical and legal framework. The main document is the EU Artificial Intelligence Act (AI Act), which is a legally binding regulation. In addition, standards are being developed to clarify the content of this Act for practical application (through CEN and CENELEC), as well as concepts for monitoring and certifying risky AI systems. The ethical principles for AI development are based on the EU Charter of Fundamental Rights and are being developed in close cooperation within the European Alliance on Artificial Intelligence, with a focus on existing European directives on data protection and product liability.
Market transition and cooperation	The EU strategy also provides for active market transition and promotion of practical AI implementation. This is being implemented through the creation of a network of European centers of excellence in AI, test centers (e.g., for autonomous driving), and the development of platforms and large-scale pilot projects with AI elements in key sectors such as energy, healthcare, manufacturing, mobility, geoinformation, and agriculture. The aim is to promote the integration of AI and data analytics into cutting-edge initiatives and to move from isolated test projects to concrete, far-reaching value creation measures. This is accompanied by the further development of Member States' national strategies on artificial intelligence, as well as the development of joint measures for specific sectors and active coordination within the framework of strategic measures and coordination.

Source: compiled by the authors

Table 2

AI in school education

Pilot projects and exchange of experience	The EU actively supports pilot projects in member states that demonstrate the effective implementation of AI tools at the school level. Examples from Italy and Germany show how AI can be used for personalized learning and improving intelligent assessment systems. These national initiatives are harmoniously integrated with common European strategies. Another important aspect is the exchange of knowledge between member states; the EU actively promotes the dissemination of best practices, successful implementation models, and effective solutions to overcome challenges using platforms such as the Digital Education Hub and other cooperation networks.

Training and retraining of teachers	The successful implementation of AI in education is impossible without proper training and retraining of teachers. The EU funds programs for the development of teachers' digital competencies through initiatives such as Erasmus+ and Horizon Europe. These programs include courses, training, and the development of methodological guides aimed at improving digital literacy and developing practical skills for working with AI. In addition to technical aspects, great attention is paid to the ethical training of teachers, teaching them to recognize and resolve ethical dilemmas related to the use of AI, such as algorithm bias, student data privacy, and the potential impact of technology on psychological well-being.
Development and availability of AI tools for schools	The EU is investing in the development and accessibility of AI tools for educational institutions. Initiatives such as InvestAI and the creation of AI "gigafactories" provide EdTech solution developers with access to significant computing power. This contributes to the creation of more sophisticated, effective, and accessible AI tools for schools. In addition, the formation of European data spaces plays a key role in the development of educational AI solutions that meet European values and standards. To ensure quality and safety, developers have the opportunity to test their AI solutions in "regulatory sandboxes" before their widespread implementation in educational institutions.
Challenges and overcoming barriers	Despite significant efforts, there are certain challenges and barriers to the full implementation of AI in school education. The EU is actively working to overcome digital inequality by ensuring equal access to technology and AI resources for all regions and schools. Another important aspect is overcoming resistance to change on the part of teachers, students, and parents, which requires effective communication and outreach. At the same time, ensuring the quality and safety of AI systems used in education is a priority. This is achieved through the development and implementation of certification and monitoring mechanisms that comply with the requirements of the AI Act.

Source: compiled by the authors

Overall, the EU demonstrates a comprehensive and proactive approach to integrating artificial intelligence into its educational system. This strategy combines legal and regulatory frameworks, the development of ethical guidelines, significant investments in infrastructure (InvestAI), and support for research and the development of digital skills. The goal is to create a more inclusive, effective, and individualized educational system that maximizes the benefits of AI while ensuring its responsible, human-centered, and ethical use to prepare future generations for the digital economy and society.

National strategies and policies on AI in education in key European countries. As of 2025, most EU countries are actively integrating aspects of artificial intelligence (AI) into their education systems, although the level of detail and specificity of approaches vary. Some countries have clearly defined strategies specifically for AI in education, while others include educational aspects in broader national AI strategies:

Germany is investing heavily in AI education. In October 2024, the Conference of Ministers of Education of the Federal States (Bildungsministerkonferenz) adopted "Recommendations for action for education administrations on the use of artificial intelligence in educational processes in schools" (Eurydice Unit Germany (Länder), 2025). Germany's national AI strategy, updated in 2020, also focuses on developing AI skills and competencies (German Federal Government, 2020). There is also a digital learning platform called AI Campus, funded by the Federal Ministry of Education and Research (BMFTR).

Italy is actively introducing artificial intelligence into its schools. The Italian government is experimenting with AI-supported software in classrooms (The Role of AI in Modern Education, 2024). Italy's national AI strategy, published in June 2022 (Minister for Technological Innovation and Digitalization of Italy, 2022), prioritizes the education system, which includes the development of skills and talents, as well as the integration of AI at all levels of education.

France has a national AI strategy called "France 2030" (updated in 2021, covering the period 2022-2025), which continues the work of the previous phase, "AI for humanity" (European Commission / Digital Skills & Jobs Platform, n.d.). This strategy aims to increase the number of AI-trained specialists and accelerate France's research potential. It includes the development of digital skills in education. There is also an initiative "AI4T - Artificial Intelligence for and by teachers", that explores and supports the use of AI in secondary education.

Spain's National Artificial Intelligence Strategy (ENIA) (Ministry of Economic Affairs and Digital Transformation of Spain, 2020) provides for a wide range of policies in the field of education and training to develop digital skills and the ability to understand and develop AI technologies. It includes the expansion of postgraduate programs and master's and doctoral programs offering training in AI.

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Poland has a strategic document on AI development titled "AI Development Policy in Poland since 2020" (Ministerstwo Cyfryzacji, 2021). This document serves as a framework for the country's approach to AI, setting out directions for action in six key areas, including education. The policy's provisions are aimed at making Poland a significant player in the AI field by developing education, supporting businesses, and promoting scientific research. The document places significant emphasis on integrating AI into the educational system at all levels, from primary to higher education. The implementation of AI in school education is focused on several key areas: teaching digital competencies, adapting curricula, introducing various programs for schools and teachers, and establishing national AI laboratories in schools.

As we can see, Poland is actively integrating artificial intelligence into education, starting from primary school, in line with its "AI Development Policy in Poland since 2020" strategy. Key positions include teaching digital competencies and understanding how AI works, not just how to use it. This is achieved through curriculum adaptation, integrating AI-related topics, and implementing special programs for schools and teachers, such as "AI Schools & Academy". These programs, which have different levels (from kindergarten to secondary school), teach children programming, algorithms, logical thinking, and the use of AI tools like Scratch and IBM Watson. Additionally, National AI Laboratories are being launched in schools, providing teachers with training, equipment, and educational materials. All this is aimed at preparing students for the future job market and creating a digitally literate society.

Overall, in the field of education, the strategy envisions creating AI training units for professionals, introducing AI-related courses/modules in schools and universities, and establishing a committee to monitor changes caused by AI in academic and professional circles. Significant funds have also been allocated for digital education reforms, infrastructure, and teacher training (Ministerstwo Cyfryzacji, 2021, p. 42–45).

In addition, we would like to note that on December 16, the document "Artificial Intelligence Development Policy in Poland 2025–2030" (Polityka Rozwoju Sztucznej Inteligencji w Polsce 2025–2030), developed by the Artificial Intelligence Working Group (GRAI), was published on the website of the Ministry of Digital Affairs. It presents a vision for the development of artificial intelligence in Poland, based on four pillars: human capital, innovation, investments, and implementation. This document was released as a draft and is currently undergoing public consultations (Ministerstwo Cyfryzacji, 2024).

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The Netherlands has a Strategic Action Plan for AI (Ministry of Economic Affairs and Climate Policy of Netherlands, 2019), which includes building a foundation for education and skills development, as well as promoting research and innovation in this field.

Sweden has a national approach to AI (Government Offices of Sweden, 2018), which is aimed at leveraging the opportunities of digital transformation. Although specific details regarding education may vary, skills development is a key component of most national AI strategies.

Most European countries are actively integrating aspects of artificial intelligence (AI) into their educational systems, recognizing its key role in digital transformation and future economic development. Approaches vary in level of detail, but common features include:

Integration of AI into Educational Systems. Countries either have separate strategies for AI in education (e.g., Germany) or include educational aspects as a priority in broader national AI strategies (e.g., Italy, France, Spain, Poland, the Netherlands, Sweden).

Development of Skills and Competencies. A central element is the development of digital and AI-related skills at all levels of education, from schools to postgraduate programs. This includes training AI specialists and ensuring that teachers and students understand and can use AI.

Investment and Funding. Significant investments and budget allocations are directed toward supporting AI research, expanding curricula, implementing AI solutions in classrooms, and training educators.

Research and Innovation. Countries actively promote research potential and innovation in AI, often through national strategies and specialized initiatives designed to connect laboratories with the market.

Collaboration and Initiatives. Initiatives exist to support teachers in using AI ("AI4T" in France) and to create digital learning platforms (AI Campus in Germany), demonstrating a systemic approach to AI integration.

In general, European countries demonstrate a clear understanding of the need to adapt their education systems to the challenges and opportunities presented by artificial intelligence, with an emphasis on developing human capital and ensuring leadership in this field.

There are several key European platforms and initiatives where information on common European policy and national strategies in the field of artificial intelligence can be found (see Table 3).

Table 3

European resources with information on common European policies and national strategies in the field of artificial intelligence

Resource name	Description
European Commission – Digital Strategy / Artificial Intelligence	This is the main official resource that provides information about the EU's overall AI strategy. Here you will find official documents such as the AI Act, which is the world's first comprehensive AI regulation, as well as other policies and initiatives. In particular, their "Shaping Europe's digital future" website has a dedicated section on artificial intelligence: https://surl.lu/afovtj. Here you can also find information about initiatives like the «AI Continent Action Plan» and plans for developing AI infrastructure.
AI Watch (European Commission, Joint Research Centre - JRC):	«AI Watch» is an initiative of the European Commission that monitors the development, implementation, and impact of artificial intelligence in Europe. They publish reports, analytics, and data on the national AI strategies of EU member states, providing a detailed overview of each country's approach.
The European AI Alliance	This European Commission initiative was created to facilitate open dialogue on artificial intelligence policy. It brings together thousands of stakeholders through events, public consultations, and online forums. Although it is primarily a platform for discussion, it also provides information on current policy directions and the positions of various stakeholders.
European Parliament	The European Parliament website provides information on legislative processes related to AI, including the adoption of the AI Act and other regulatory initiatives.
Digital Skills and Jobs Platform	This platform is the official website of the European Union. It gives an overview of national strategies, policies, and nationwide initiatives related to developing digital skills. The main goal of the platform is to promote and support the development of digital competencies for ICT professionals, workers, citizens in general, and education systems in EU member states. The platform also contains information on various topics, such as artificial intelligence, cybersecurity, 5G, and digital transformation, and allows you to filter strategies by topic, geographical context, and level of digital skills.

Organization for Economic Co-operation and Development – OECD	Although the OECD is not strictly a European organization, it plays an important role in shaping global recommendations on AI, which often influence European policies. They publish reviews of national AI strategies from various countries, including European ones, and provide recommendations on responsible AI. OECD.AI The OECD AI Policy Observatory is a specialized platform that provides policy, data, and analysis for trustworthy AI. This integrated initiative was created in July 2024 by combining the efforts of the Global Partnership on AI (GPAI) initiative and the work of OECD member countries in the field of AI under a single GPAI brand. The platform offers a variety of resources, including the "AI Wonk" blog, up-to-date data, country-specific information, and details on priority issues such as risks and accountability, AI, data, and privacy, generative AI, the future of work, and AI in healthcare. It also includes tools like the AI Incidents and Hazards Monitor (AIM) and the Catalogue of Tools & Metrics for Trustworthy AI. OECD DPP (The Digital Economy Policy Programme (DEPP) directly covers AI policies and strategies, and provides internationally comparable information on the national digital strategies and key digital policies of OECD member and partner countries. One of the key aspects of these strategies is artificial intelligence. The OECD DEPP complements the information available on OECD.AI.
Centre for European Policy Studies – CEPS, and Bruegel	Many European think tanks are actively engaged in research and publish reports on European AI policy. They often provide in-depth analysis and recommendations that complement official sources.

Source: compiled by the authors

Therefore, when analysing the common European strategic vision for the development of AI and its implementation in school education in EU countries, several key aspects can be identified. The European Union recognizes the transformative potential of AI and strives to create an ecosystem that is human-centred, reliable, and ethical. This is reflected in the AI Act, which classifies AI systems by risk level, imposing strict requirements on high-risk systems used, in particular, in education. This approach ensures not only technological development but also the protection of fundamental rights and values. In addition, the European Commission is actively developing ethical guidelines for educators, emphasizing the importance of responsible use of AI in the learning process. In general, the EU's strategy is not only to introduce AI as a tool, but also to develop "AI literacy" among citizens, the ability to think critically and interact ethically with intelligent systems.

In the context of implementing AI in school education, Europe is adopting a multifaceted approach that includes developing competencies for interacting with AI, using AI as a tool to enhance the learning process, and a deeper, technical study of AI fundamentals. This reflects the understanding that AI is not just changing teaching methods but also transforming the very essence of the skills needed for the future. Initiatives like the Digital Education Action Plan aim to improve digital skills and media literacy among students and teachers, and support innovative projects through programs like Horizon Europe and Erasmus+. At the same time, challenges such as algorithmic bias, data protection, the transparency of AI "black boxes," and the risk of digital exclusion are being actively discussed and addressed.

In Ukraine, despite the lack of a single, comprehensive national strategy for the targeted implementation of artificial intelligence (AI) specifically in general secondary education (unlike, for example, Poland's "AI Development Policy"), there is active work in this area. A significant regulatory framework exists, and an intensive process of developing relevant documents is ongoing, which forms the basis for integrating digital technologies, including AI, into the educational process. Among the key documents and initiatives related to the implementation of AI in school education are: the Law of Ukraine "On Education" (2017), the "New Ukrainian School" Concept (2016), the Concept for the Development of the Digital Economy and Society of Ukraine for 2018–2020 and Beyond (2018), the Concept for the Development of Artificial Intelligence in Ukraine (2020), the National Strategy for the Development of Artificial Intelligence in Ukraine until 2030 (2021), the Roadmap for the State's European Integration in Education and Science until 2027 (2023), and the Recommendations of the Ministry of Education and Science of Ukraine jointly with the Ministry of Digital Transformation on the Responsible Use of Artificial Intelligence in General Secondary Education Institutions (2024).

According to the Concept for Artificial Intelligence Development in Ukraine (2020), the main directions for applying artificial intelligence (AI) in general secondary education are focused on improving the educational and methodological base, enhancing the qualifications of teaching staff in the field of AI and data, and promoting digital literacy among students, including the use of AI tools and media literacy (Kabinet Ministriv Ukrainy, 2020).

In the Concept, artificial intelligence (AI) is defined as "an organized set of information technologies, with the application of which it is possible to perform complex tasks by using a system of scientific research methods and algorithms for processing information, which is either obtained or independently created during work, as well as to create and use one's own knowledge bases, decision-making models, algorithms for working with information, and to determine ways to achieve set goals" (Kabinet Ministriv Ukrainy, 2020).

Both in Ukrainian legislative documents and in acts of the European Union, the concept of AI is characterized as a technology or a set of systems designed to solve complex tasks that traditionally require human intelligence, as well as the ability to process information and make decisions. However, the key difference in the initial definitions lay in the emphasis: the Ukrainian interpretation (Kabinet Ministriv Ukrainy, 2020) viewed AI primarily as a set of tools that function through organized processes to achieve specific goals. In contrast, in the European Union's definitions from the same period (Tuomi et al., 2018; European Commission, 2018), the focus was shifted to the dynamic nature of AI and its ability to learn, adapt, and operate with a certain degree of autonomy.

It should be noted that contemporary Ukrainian analytical documents and recommendations (specifically, the Methodological Guidelines for the Implementation and Use of Artificial Intelligence Technologies in General Secondary Education Institutions, 2024; the Recommendations on the Responsible Implementation and Use of Artificial Intelligence Technologies in Higher Education Institutions, 2025), which are currently under public discussion, already take into account such characteristics of AI as autonomy in decision-making, adaptability, and flexibility. This indicates an evolution in the understanding and harmonization of approaches to defining artificial intelligence in Ukrainian educational policy and practice.

An example of the effective use of digital technologies to ensure broad access to educational content is the "All-Ukrainian Online School" project, developed by the Ministry of Education and Science of Ukraine. This platform has the potential for further integration of advanced technologies, including artificial intelligence (AI), which will allow for the development of adaptive learning. The Deputy Minister of Education and Science of Ukraine for Digitalization, Dmytro Zavhorodnii, notes that this project demonstrates a wide reach of the target audience while maintaining a relatively low cost of operation. Statistical data indicate a high demand for the resource: the monthly number of video lesson views on the "All-Ukrainian Online School" platform exceeds 2 million (Boiko, 2025).

The implementation of artificial intelligence (AI) related subjects in general education schools is one of the key elements of the National AI Development Strategy

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in Ukraine. This direction aims to prepare students for life and work in conditions of rapid digital transformation and active use of AI. The plan is not simply to add a separate subject, but to integrate basic knowledge about AI into existing school curricula, particularly in the subjects of computer science, mathematics, technology, and possibly other fields through interdisciplinary projects. (Ministerstvo osvity i nauky Ukrainy, Natsionalna akademiia nauk Ukrainy, Instytut problem shtuchnoho intelektu, 2021).

Currently, the Ministry of Digital Transformation of Ukraine, together with partners and experts, is actively working on the Artificial Intelligence Development Strategy until 2030. This document will become a roadmap for the integration of AI into key areas: healthcare, economy, education, security, public administration, etc. In 2025, the Ministry of Digital Transformation of Ukraine, in cooperation with the Ministry of Education and Science of Ukraine, developed recommendations for the responsible implementation and use of artificial intelligence technologies in higher education institutions (Ministerstvo tsyfrovoi transformatsii Ukrainy, Ministerstvo osvity i nauky Ukrainy, 2025).

Thus, the implementation of AI in education is potentially disruptive technology that will fundamentally change our approach to learning by providing a personalized learning experience, automating administrative tasks, and improving educational outcomes. For Ukraine, the European experience of integrating artificial intelligence technologies into education is of great importance. In its pursuit of integration into the European space, Ukraine can draw several key lessons from it.

First, there is a need to develop a clear national strategy for AI integration into education that will comply with European standards of safety, ethics, and transparency. This includes the development of an appropriate legislative and regulatory framework to govern the use of AI systems in schools.

Second, Ukraine should actively work on increasing “AI literacy” among teachers and students, as quality AI integration is impossible without an understanding of its principles and potential consequences. This requires the development of new curricula, the retraining of teaching staff, and the provision of access to modern technologies.

Finally, it is important to focus on developing critical thinking and an ethical attitude toward AI in schoolchildren, as well as on finding solutions to overcome the digital divide and ensure equal access to AI technologies for all students, regardless of their socioeconomic status or place of residence.

Overall, adapting European best practices will allow Ukraine not only to modernize its educational system but also to prepare a competitive generation for life and work in the digital age while minimizing possible risks. However, it should be emphasized that the analysis of innovative European practices for using artificial intelligence in education must be applied considering the strategic development priorities and specific features of Ukraine's national education system.

Therefore, the integration of AI into Ukrainian education is not just a step forward in technology but a strategic investment in national security, economic development, and the formation of a strong, modern Ukraine.

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4.3. APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN EDUCATION: PROSPECTS FOR REFORMING THE EDUCATION SYSTEM

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At the present stage of development of society and education, the use of artificial intelligence (AI) technologies is gaining special importance. Due to the increasing digital transformation of all spheres of life, the education system is facing the need to adapt to new challenges that require a fundamentally new approach to the processes of teaching, assessment, management and formation of key competencies of students. In this context, the concept of Education 4.0, proposed by the World Economic Forum, is becoming increasingly important as a strategy for preparing students for the future, aimed at developing global citizenship, creativity, technological and social competence.

Artificial intelligence technologies, in particular generative models such as LLM (Large Language Models), have a powerful potential to transform the educational environment. However, their implementation is associated not only with opportunities,

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but also with numerous challenges that require system analysis, research and strategic planning. The main challenge is how to effectively integrate AI into educational practice in a way that not only improves the quality of learning but also preserves the human factor, ethical standards, equality of access, and pedagogical integrity.

The purpose of this section is to provide a scientific analysis of the opportunities and limitations of using AI technologies in education, taking into account relevant examples, theoretical recommendations, and practical cases.

Overview of current research. In recent years, leading international scientific journals have been actively researching the use of AI technologies in education. While at the initial stage, researchers focused mainly on the automation of routine tasks and the use of chatbots, in recent years, there has been a growing interest in more complex systems that can adapt learning content to the needs of a particular student (Zawacki-Richter et al., 2023). Scopus and Web of Science publications for 2022-2025 show a trend towards the integration of AI not only in teaching, but also in the administration of the educational process, management of educational systems, and knowledge quality assurance (Siemens & Baker, 2022).

Studies by international organisations are of particular importance. For example, UNESCO (2023) emphasises that the effectiveness of AI in education depends on national digitalisation strategies and the development of ethical standards. The OECD (2024) emphasises that AI can support teachers but cannot replace them, and therefore the key task is to train teachers to work with intelligent systems. The World Bank (2023) draws attention to the potential of AI in the field of education management, in particular in crisis situations, which is especially relevant for countries experiencing military conflicts.

An important area of current research is the analysis of inclusiveness. AI can provide personalised support for students with special needs, as evidenced by publications in Computers & Education (Smith & Lee, 2023) and Educational Technology Research and Development (Chen et al., 2024). Thus, the review of scientific papers shows the multidimensionality of the problem, which covers pedagogical, managerial, social and ethical aspects.

Global challenges of modern education. Education systems face numerous challenges that hinder their ability to respond to the demands of the times. First and foremost, there is a global shortage of teaching staff, which is worsening in many regions, especially in sub-Saharan Africa. According to UNESCO's forecasts, more than 44 million more teachers will be needed by 2030 to ensure that the Sustainable

Development Goals are met, in particular Goal 4 - access to quality education for all. This issue is acute not only in developed economies, but also in countries where education remains inaccessible to a large number of children.

Along with the shortage of teachers, inefficient administrative processes and flawed assessment systems are also important challenges. Many countries face the fact that a significant portion of a teacher's time is spent on nonpedagogical tasks such as paperwork, attendance, grading, etc. In the United States, for example, the average weekly workweek for a teacher lasts 54 hours, of which only 46% is spent directly on teaching. In OECD countries, on average, only 44% of the time is spent in direct contact with students, which leads to a loss of teacher motivation, high levels of fatigue and professional burnout.

Another significant problem is the digital divide, which is increasingly separating certain groups of people from the opportunities of modern education. Even the most advanced technologies will only be effective if they are accessible to all. Currently, more than 2.6 billion people do not have basic access to the Internet, which automatically excludes them from the process of receiving education through digital tools. It's also worth considering that only 30% of AI specialists are women, which indicates a gender inequality in the technology sector that can affect the educational space as well.

Ukraine, like many other countries, also faces similar challenges. The shortage of teachers, low salaries, limited access to digital resources, and low digital literacy among teaching staff all require urgent action. That is why the introduction of artificial intelligence technologies should not be just a technical solution, but part of a broader educational policy focused on real transformation.

The methodology for analysing the use of AI in education is based on a combination of several approaches. The theoretical and analytical method was used to study modern publications, educational standards, and regulations. This made it possible to identify the main trends in the introduction of technologies and assess their compliance with the requirements of educational systems in different countries.

Empirical methods include surveys of teachers and students to assess the level of readiness of educational communities to use AI (Ivanova, 2022). Observations of AI implementation practices in universities and schools show that success depends not only on the availability of technological solutions but also on organisational culture and teacher training (Peterson & Wong, 2023).

The comparative method allows comparing international and national experience, identifying common patterns and differences. In particular, adaptive platforms are widely used in the EU, while similar initiatives are at the stage of pilot projects in Ukraine (Kovalchuk, 2024). A predictive approach is used to model possible scenarios of education development under the influence of AI, which allows us to assess the potential implications for educational policy and practice.

International experience shows that countries with developed strategies for the digitalisation of education achieve significant results in the use of AI. For example, in Finland, the course «Elements of AI» has become mandatory in many universities and has contributed to the formation of digital literacy among the general population (Salmi, 2023). Estonia has integrated AI into educational information systems, which has made it possible to predict staffing needs and track student performance (Laar et al., 2022). In Singapore, adaptive educational platforms are actively used to individualise learning, and in the US, AI is becoming widespread in inclusive education, providing support for students with special needs (Brown & Davis, 2023).

For Ukraine, the experience of these countries is extremely valuable. In the context of martial law and the restoration of the educational system, AI can become a tool to ensure access to education for internally displaced persons, support distance and blended learning. Pilot projects of Ukrainian universities show that AI helps to adapt educational programmes to the needs of students and improve the efficiency of educational process management (Shevchenko, 2023). At the same time, the integration of AI in Ukraine requires solving the problems of financing, training, and creating a regulatory framework.

AI as a tool for education reform

New technologies, such as large-scale language models (LLMs), have the potential to automate a number of administrative tasks that traditionally take up a significant portion of a teacher's time. According to a study conducted by Accenture, approximately 20% of the time spent on clerical and organisational tasks can be automated using AI. This makes it possible to free up time for tasks that require human interaction, such as psychological support for students, individualised learning, motivation, and the development of social intelligence.

In addition, AI can enhance the role of the teacher instead of replacing it. For example, intelligent systems can analyse test results, provide instant feedback, offer differentiated tasks, and assist teachers in lesson planning. Studies have shown that in November 2023, 42% of teachers in the UK used generative AI models to prepare materials for classes, compared to 17% in April of the same year, which indicates a rapid growth in interest in these tools.

However, despite the potential benefits, it should be borne in mind that humans remain the central element of the educational process. Only a teacher can establish emotional contact with a student, understand their inner state, and create an atmosphere of trust and motivation. Therefore, AI integration should be aimed at supporting rather than replacing teachers. It is necessary to develop clear mechanisms that will ensure effective cooperation between humans and algorithms.

The use of AI in education opens up prospects for individualising the learning process, automating assessment, improving management efficiency, and supporting inclusiveness. For Ukraine, the use of AI in the post-war reconstruction of the educational system is a promising area. This applies to both the development of new educational programmes and the creation of intelligent management systems capable of ensuring transparency and accountability.

Integrating AI into the teacher training system is also of practical importance. Developing teachers' digital competencies is a key to the effective use of technology in the classroom. Moreover, research on the impact of AI on student motivation and results is promising, which will allow to justify educational policy and investments in this area.

Personalisation of learning

One of the most important advantages of using AI in education is the ability to personalise the learning process. Research, including that conducted by the World Economic Forum, shows that personalised learning supported by intelligent systems can significantly improve student outcomes. An example of this is the Letrus project in Brazil, where the introduction of an AI-based system to analyse students' texts and provide instant feedback led to a significant improvement in the results of the programme participants. In schools in the state of Espirito Santo, students achieved second place in national exams in literary analysis within five months of the project, while the control group was only eighth. This example shows that AI can not only analyse academic achievements but also identify problem areas, offer remedial tasks, and track the progress of each student. Algorithms can change the complexity of the material, taking into account the learning style, the pace of learning, and the individual's strengths and weaknesses. Thus, technology allows us to implement one of the key principles of Education 4.0 - personalised and independent learning that meets the needs of modern society. This creates the basis for flexible, adaptive learning environments where each student receives an individual development trajectory, which contributes not only to improving academic results but also to developing motivation, self-regulation and critical thinking.

Improving the education assessment and analytics system

Another important area of AI implementation in education is the improvement of the assessment system. Traditional assessment methods are often ineffective due to their standardisation, lack of prompt feedback, and limited consideration of individual student characteristics. As noted in the World Economic Forum's report (2024), many education systems conduct comprehensive assessments only once a year, which does not allow for timely identification and response to knowledge gaps. Generative models and machine learning can change this by enabling continuous assessment, real-time data analysis, and prediction of learning outcomes. This approach allows us to move from occasional testing to continuous monitoring of each student's progress, which is a key element of the Education 4.0 concept. Of particular importance is the use of AI to analyse non-standard forms of assessment, such as essays, projects, and research tasks. For example, in one case study, teachers worked with algorithms to create sample comments that AI subsequently used to analyse students' work. This ensured not only an objective assessment but also an individual approach, which helped to increase student motivation. For example, an AI-based system can detect that a student consistently makes mistakes in argumentation and offer targeted exercises to eliminate them. In addition, the use of AI allows education systems to obtain real-time analytical data, which can serve as a basis for making management decisions. School leaders, ministries of education, researchers - all these entities can receive detailed reports on student performance, identify trends, and plan investments in educational programmes. This approach ensures systemic accountability, transparency, and efficient use of resources. In a pilot project in the UAE, where an AI tutor was used, the time for checking assignments was reduced from several days to several minutes, which significantly increased the efficiency of feedback. Thus, AI is transforming assessment from a formal procedure into a dynamic, information-rich process aimed at supporting learning, not just assigning grades.

Building digital and AI literacy

One of the main areas of education reform in the context of technological development is the inclusion of AI in the curriculum. The issue is not that all students should become specialists in artificial intelligence, but rather that they should consciously use technology, understand its nature, be able to think critically about the use of artificial intelligence, recognise false information and analyse ethical implications. It is important to develop students' ability to distinguish between tools that truly enhance learning from those that can cause manipulation or spread misinformation

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(UNESCO, 2024). Thus, the integration of AI into curricula is not limited to technical aspects, but also involves the development of media literacy, information culture, and social responsibility. In this section, we will give an example of the Pensamiento Computacionale IA programme in Uruguay, where teachers are taught to integrate elements of computational thinking into different subjects - mathematics, language, and science. The programme also aims to combat gender inequality in technological education, which is one of the most pressing challenges in the modern educational environment (OECD, 2023). Particular attention is paid to the development of teaching materials that take into account the diversity of social groups and the creation of an educational space where every student can realise their potential regardless of gender or social background. As part of this programme, students learn how machine learning models work, how data is analysed, and how bias can occur in algorithms. They learn to critically analyse the decision-making process of algorithms, recognise the risks of discrimination, and understand why transparency and explanation of AI results are necessary. This fosters responsibility in the use of AI, which is a key stage in preparing young people for the digital economy. In addition, students acquire practical skills in working with data sets, developing simple models, and conducting experiments, which helps develop their scientific thinking and prepares them for future professional activities in a world where artificial intelligence is becoming an integral part of most industries (World Bank, 2023).

Integrating AI into educational materials

Another important aspect is the creation of accessible, personalised learning materials. A report at the World Economic Forum cited the example of the UNICEF initiative aimed at creating accessible digital textbooks (ADT). These textbooks are based on the principles of universal design for learning (UDL) and allow for the adaptation of educational material to the needs of different categories of students, including children with disabilities. As part of the ADT project, more than 500,000 digital textbooks have been introduced to schools in sub-Saharan Africa and Latin America, which can be used offline, especially in regions with limited Internet access.

These textbooks include:

- audio and video materials;
- sign language translation
- text synthesis;
- interactive tasks;
- adaptation of content to different formats.

Research conducted by UNICEF partners has shown that the use of such textbooks significantly increases student motivation, integration into the learning process and learning outcomes. This is a strong argument in favour of scaling up such technologies worldwide.

Developing digital skills and cybersecurity

In the context of the growing use of AI in education, it is important to pay attention to preparing for the safe use of technology. Grok Academy's research in

Australia and New Zealand has shown that digital literacy is not only the ability to use tools, but also the ability to understand the risks associated with the use of algorithms, processing of personal data, and the spread of misinformation.

Grok Academy's cybersecurity education programme has reached more than 91,000 students, including a significant number of girls, helping to close the gender gap in this area. The programme includes:

Cryptography courses;

- digital threat analysis;
- studying the impact of AI on society;
- developing critical thinking about the use of technology.

The results of the study showed that the students who participated in the programme had a much better understanding of the risks associated with the use of AI and actively used the knowledge gained in their further studies and professional activities. This once again confirms the importance of including an ethical aspect in educational programmes aimed at developing digital skills.

Practical examples of AI implementation in education (Table 1.1)

AI tutors and virtual assistants

The Kabakoo Academies programme in West Africa is an example of how AI-powered virtual tutors can significantly support students in their learning process. This initiative offers personalised learning based on interaction with a virtual tutor who can

- provide instant feedback
- analyse students' work
- provide recommendations;
- engage in dialogue in the learner's native language (including minority languages).

In Mali, for example, a model is being developed that provides learning in Bambara, the most widely spoken language in the country. This approach ensures inclusivity, personalisation and social justice, which are key features of the education of the future.

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STEM education and creativity development

Another example of AI implementation is the 3D Africa for Girls project implemented by the Youth for Technology Foundation in Nigeria. This initiative offers girls aged 10 to 18 years old the opportunity to learn basic STEM skills (science, technology, engineering, mathematics) using 3D printing, programming, design, and entrepreneurship.

The project has demonstrated high efficiency:

- over 90% of participants continued their studies at higher education institutions;
- over 85% chose a career in the technology sector;
- over 90% of participants achieved a level of proficiency of 95% or more in basic and advanced digital skills.

This experience shows that technology has not only educational, but also emancipatory potential, especially in conditions where traditional avenues of social growth are limited.

AI in the fight against inequality in education

The JA Europe programme is implementing a curriculum that combines entrepreneurship and AI to teach young people how to solve the world's most pressing problems. The programme covers 10 countries and aims to train 30,000 young people over two years.

A special feature of this initiative is the integration of AI into rural and remote regions where access to technology is limited. The programme uses an interactive platform that allows students to:

- develop business plans
- learn to analyse data
- work in teams;
- apply AI in real-life situations.

In addition, the focus on supporting disadvantaged schools and refugees from Ukraine demonstrates that technology can be a tool to reduce social inequality rather than exacerbate it.

Innovative approaches in the face of limited resources

One of the most interesting examples of innovative educational practices in countries with relatively limited resources is the Ceibal initiative in Uruguay. It is known as a comprehensive programme for the digitalisation of education that combines technical infrastructure, pedagogical support, and the development of digital competencies. An important component of the programme was to train teachers not only in the technical aspects of working with artificial intelligence, but also in the ethical use of algorithms, data analysis methods, and the recognition of bias in information flows (OECD, 2023).

The key goals of implementation can be summarised as follows:

- to ensure equal access to education with AI elements, regardless of the social or economic status of students;
- to develop data analysis competences that become the basis for participation in the digital economy;
- teach students to use technology ethically, which is especially important in the context of the spread of disinformation and automated decisionmaking systems (UNESCO, 2024).

The results of the programme confirm its effectiveness. In particular, the participation of students who studied under the initiative in the international Bebras competition showed a significant increase in their results compared to control groups. This indicates not only an increase in technical skills, but also the development of critical thinking and the ability to apply the acquired knowledge in practice (World Bank, 2023). Thus, Uruguay's experience demonstrates that even in countries with limited resources, it is possible to create effective innovative models for preparing students for life in a world where artificial intelligence technologies play a key role.

AI texts and digital textbooks

As part of the educational reform strategy, South Korea is planning to introduce AI textbooks starting from the 2025-2026 academic year. These textbooks should be adapted to different levels of knowledge, learning pace, and perception peculiarities. They will be used in mathematics, English, computer science, and later other subjects, except for practical disciplines such as music, physical education, and fine arts.

The systematic implementation includes:

- pilot testing among 400 teachers;
- analysis of effectiveness;
- scaling up based on the experience gained.

One of the goals is to reduce the workload of teachers, increase access to education, and create a culture of lifelong learning. A special place is given to the cooperation between a teacher and an AI assistant, which ensures a balance between technological capabilities and the human factor.

AI tutors and individualised learning

The United Arab Emirates has launched a pilot version of an AI tutor that offers

individualised tasks;
- instant feedback
- analysis of students' progress;
- multilingual support;
- detailed reports for parents and teachers.

The pilot showed a 10% improvement in academic performance, which is a significant achievement for the testing period. This tool is expected to help not only improve the quality of education, but also reduce dependence on private tutors, who are unaffordable for most families.

Table 1.1.

Examples of AI implementation in education

Country	Project	Objective
Brazil	Letrus	Personalised reading and writing
Uruguay	Ceibal	Computational thinking and AI education
Ukraine	Pilot projects in KPI	Student evaluation
United Arab Emirates	AI Tutor Project	Implementation of an intelligent tutor
Korea	AI-powered digital textbooks	Personalisation of learning
Australia	Grok Academy	Cybersecurity and digital literacy

Risks, limitations, and ethical issues

Despite the obvious benefits, the introduction of AI in education is accompanied by numerous risks that need to be considered. Among them:

- Privacy violations: collecting large amounts of data about students can raise concerns about the use of personal information;
- Changing the role of the teacher: there is a growing risk that teachers will lose their central role in the learning process;
- Increased inequality: lack of access to technology may further widen the educational gap;
- use of AI for cheating: there is a growing number of cases when students use AI to write homework, which violates the principles of academic integrity;
- ethical dilemmas: algorithms may have biases that affect equality of opportunities.

The integration of AI into education is accompanied by some other important risks. Firstly, there is a threat to academic integrity, as AI tools can be used to automatically complete assignments for students (Johnson, 2023). Second, there is a risk of increasing digital inequality between countries and institutions with different levels of resources (UNESCO, 2024). Third, the issue of personal data protection is relevant, as AI-based educational platforms collect large amounts of information about users (OECD, 2024).

It should be noted that 61% of respondents believe that they are not ready to trust AI, and 71% are worried about the risks associated with the use of these technologies. This indicates the need to create an ethical code of conduct for the use of AI in education, introduce standards of algorithm transparency, data protection, and guarantee equal access.

Ethical aspects also include the transparency of algorithms and the prevention of discriminatory practices. In Canada, special working groups have been established to develop recommendations for the responsible use of AI in education (Taylor, 2022). These examples demonstrate the importance of developing national policies that take into account the ethical dimension of technological innovation.

Necessary conditions for successful integration of AI in education

Based on the analysis of the experience of the countries presented in this section, we can identify five key conditions that must be met for the effective integration of AI in educational practice:

- Collaboration with teachers: any technology should be developed together with teachers so that it can meet the real needs of the educational process rather than formal standards.
- Data protection and transparency of algorithms: it is necessary to ensure transparency in the work of AI, use only the necessary data, anonymisation of personal information, and mandatory consent to data processing.
- Financial support and independent expertise: to scale technologies, it is necessary to create funding models, independently test AI products, and implement them only after confirming their effectiveness.
- Teacher training: teachers should be trained to work with intelligent systems, taught to be critical of algorithms, and to use AI as a tool, not a replacement.
- Focus on equity and inclusion: it is necessary to ensure access to AI education for all, taking into account the specifics of regions, the capabilities of children with disabilities, cultural and linguistic features.

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Artificial intelligence technologies open up new horizons for the development of education, enabling personalised learning, automated assessment, digital literacy, and increased accessibility of education. At the same time, their implementation is accompanied by numerous challenges that require a systematic approach.

- AI has a powerful potential to transform education through personalisation, automation, and analytics.
- The introduction of AI technologies into educational practice should be regulated, taking into account ethical, legal and social aspects.
- Ethical and legal standards for the use of AI in education should be developed.
- Educational institutions should actively prepare teaching staff to work with intelligent systems.
- It is promising to develop a hybrid learning model where AI complements rather than replaces the human factor.

Thus, artificial intelligence technologies are a powerful catalyst for change in education. However, the successful implementation of these tools requires a clear strategy, interaction of all parties to the educational process, social justice and ethical use of technology.

Further research could be aimed at:

- developing methodological recommendations for the use of AI in specific subject areas;
- long-term analysis of the effectiveness of AI implementation in education;
- studying the impact of AI on the formation of critical thinking;
- studying the effectiveness of hybrid learning models using AI;
- development of international standards for the use of AI in education.

It is especially important to study the impact of AI on pedagogical ethics, the formation of academic culture, and the development of digital literacy among teachers and students. Only through comprehensive scientific research can a balance between innovation and educational goals be achieved.

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4.4. INTEGRATION OF ARTIFICIAL INTELLIGENCE INTO ENGLISH LANGUAGE INSTRUCTION IN UKRAINIAN GENERAL SECONDARY EDUCATION INSTITUTIONS: OPPORTUNITIES, BARRIERS, AND PROSPECTS

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In the 21st century, global digitalization has transformed the educational paradigm, particularly in the field of foreign language acquisition. One of the key driving forces behind this transformation is artificial intelligence (AI), which is rapidly permeating the educational process, reshaping both the content and the methods of instruction. The use of AI in English language teaching is especially relevant, as English is not only a compulsory academic subject but also a tool for integration into the global information space.

The integration of AI into English language instruction has become a focal point for international educational organizations and the academic community, serving as a subject of active research and professional discourse. The growing scholarly interest in this topic is reflected in bibliographic data from the Web of Science database: between 2024 and 2025, 44,500 publications were indexed under the keywords "AI or Artificial Intelligence" within the topic "AI in English Learning." In comparison, during the 2020-2021 period, a total of 23,296 results were recorded under the same parameters, indicating nearly a twofold increase in the volume of academic work in this area.

A global survey conducted by the British Council among 1,348 English language teachers from 118 countries revealed that 76% of teachers already incorporate AI tools in their teaching practices. The most commonly used tools include language learning applications (48%), generative AI (37%), and chatbots (31%). Among the specific tasks delegated to AI, teachers most frequently mentioned the creation of teaching materials (57%), support in language practice (53%), and lesson planning

(43%). However, 24% of respondents reported not using any of the mentioned AI tools, highlighting disparities in the global adoption of these technologies (Edmett et al., 2024, pp. 30-31).

Despite the relatively high rate of AI usage, only 20% of teachers considered themselves adequately prepared to use it effectively in the classroom, while 54% acknowledged insufficient preparation (Edmett et al., 2024, p. 36). This underscores the urgent need for systematic professional support for educators amid the digital transformation of education.

In Ukraine, the Minor Academy of Sciences of Ukraine and Projector Institute conducted a study analyzing the prospects of AI in school education (Projector Creative & Tech Institute & MAN, 2023). The survey involved over 3,000 respondents, including 1,747 teachers (10% of whom were English teachers) and 1,443 students from grades 8 to 11. According to the survey, 87% of teachers were aware of AI technologies, 69% had used at least one AI tool, and 37% had already engaged students in working with such services (see Chart 1). Among teachers who had experience using AI in their professional activities, 65% rated the experience as successful.

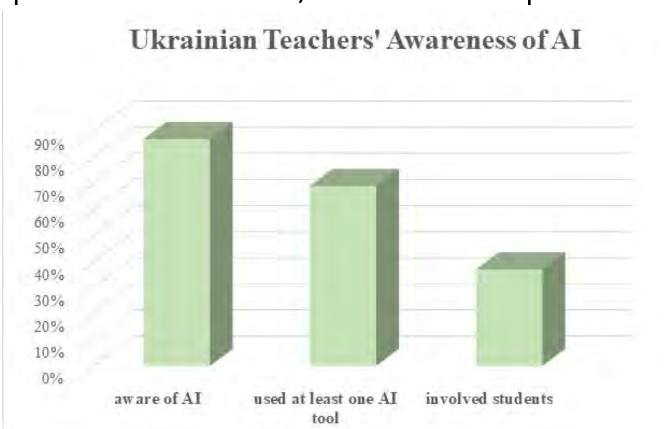

Figure 1. Ukrainian Teachers' Awareness of AI According to the National Survey on the Use of AI in School Education (Projector Creative & Tech Institute & MAN, 2023)

Ukrainian teachers use AI for lesson preparation (44%), creating homework tests (30%), conducting lessons (28%), assessing students' knowledge (22%), and even in extracurricular activities (20%). These data are visually presented in Figure 2 below.

It is worth noting that students appeared to be even more active AI users than teachers: 85% of students reported having experience with AI, and nearly 60% had already used AI services to complete homework assignments. Additionally, around 40% stated they had used AI during lessons (particularly for independent tasks).

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Beyond academic activities, students also reported using AI in extracurricular contexts (43%) and for personal development purposes (38%). A graphical representation of these results is provided in Figure 3.

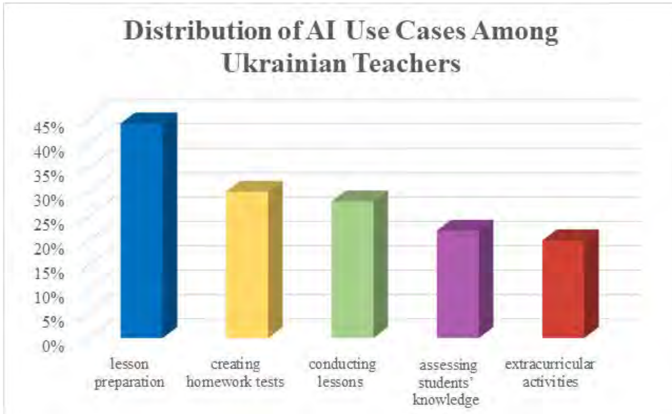

Figure 2. Most Common AI Use Cases Among Ukrainian Teachers According to the National Survey on the Use of AI in School Education (Projector Creative & Tech Institute & MAN, 2023)

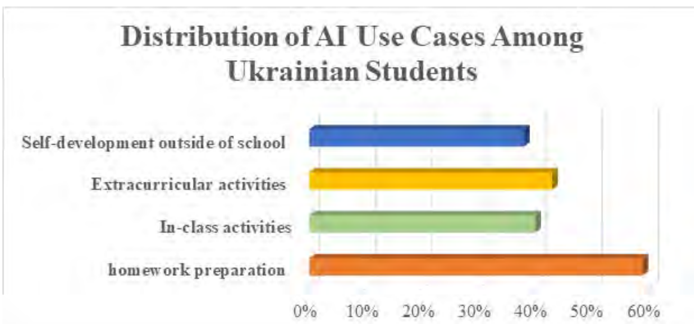

Figure 3. Most Common AI Use Cases Among Ukrainian Students According to the National Survey on the Use of AI in School Education (Projector Creative & Tech Institute & MAN, 2023)

The results of an online survey conducted in April 2024 by O. Chukhno among 683 respondents (English language teachers, high school students, and university students from several regions of Ukraine) revealed a predominantly positive attitude toward the use of AI from both teachers and students. Specifically, 69.1% of teachers expressed a positive attitude toward AI, compared to 85.2% of students. In contrast, 18.2% of teachers and 6.4% of students demonstrated a negative attitude, largely due to concerns about the lack of development of critical thinking skills, the unreliability of generated content, and the potential risks to academic integrity. At the same time, both groups highlighted several advantages of using AI in education, such as the speed of generating learning materials, the ability to provide instant answers

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to questions, and the capacity to generate new ideas (Chukhno, 2023, pp. 57-58). The author of the study rightly emphasizes the specificity of AI perception within the educational context of Ukraine. Ukrainian students, who live and study amid an accelerated digital transformation driven not only by the global COVID-19 pandemic but also by the ongoing full-scale war, both of which have caused a dramatic shift toward online education, demonstrate a high degree of adaptability and an almost unanimous positive evaluation of AI's potential in learning. This level of acceptance is significantly higher than in many other countries where the implementation of digital tools has been less intensive. In contrast, Ukrainian teachers exhibit a more cautious attitude, which is attributable not only to insufficient digital preparedness but also to experiences with breaches of academic integrity resulting from students' unethical use of AI tools. It is also worth noting that Ukrainian schoolchildren view AI not merely as a means of learning but as a tool for expanding their capabilities, such as creating music and images, studying topics beyond the school curriculum, and completing homework assignments. This multifunctionality indicates an adaptive strategy in the use of AI in response to the challenges of the current socio-political situation. In this regard, the author reasonably recommends the development of a professional training system for teachers on the integration of AI into foreign language instruction, the establishment of clear ethical standards for its use at all levels of education, as well as regular monitoring of feedback from participants in the educational process to identify real needs and challenges (Chukhno, 2023, p. 58).

In response to the growing need for the development of teachers' digital competencies in the context of integrating AI into the educational process, both state and private sectors in Ukraine are actively offering professional development and self-guided learning courses. Among the most notable initiatives is the free online course "Generative AI for Teachers", developed by Google in collaboration with MIT RAISE. This course, available in Ukrainian, focuses on time-saving strategies, instructional material creation, and lesson personalization. The course familiarizes teachers with generative AI tools for: (1) writing communication texts for parents and students (messages, emails, newsletters); (2) creating tests and providing feedback; (3) individualizing instruction to meet the diverse needs of learners; (4) designing teaching strategies that make lessons more engaging for students (Google, n.d.). Since April 2025, the Ministry of Education and Science of Ukraine, in collaboration with Google, has also been implementing a three-tiered course for educators. This program covers the safe use of AI, pedagogical practices, and sharing experience

(Google, n.d.). In addition, domestic platforms such as Prometheus ("Introduction to ChatGPT") (Prometheus, n.d.), Naurok ("AI – A Teacher's Personal Assistant") (Na Urok, n.d.), Galaxy ("School Artificial Intelligence for Teachers") and Mathema ("Canva + AI" (Ministerstvo osvity i nauky Ukrainy, 2025), offer both free and paid educational products that introduce teachers to the fundamentals of ChatGPT, ethical aspects of AI use, and practical cases of AI integration into teaching. Of particular note is the webinar series "The Grand Course on AI in Education", conducted in May-June 2025 by Kyiv National Linguistic University, which focused on the impact of AI on academic integrity and legislative issues (Kafedra metodyky ta menedzhmentu inozemnykh mov KNLU, 2025). These programs contribute to the development of teachers' practical AI skills and enhance their readiness to work within the framework of education's ongoing digital transformation.

Thus, the analysis of the educational landscape in Ukraine, as well as globally, reveals a growing interest among the state, teachers, and students in implementing AI tools into the educational process, particularly in English language instruction.

In the context of AI integration into English language learning, it is essential to establish an effective balance between the potential of AI tools and traditional language teaching methods. This approach entails not only the efficient use of AI capabilities, such as personalized learning, material adaptation, and immediate feedback, but also the preservation of the pedagogical value of live communication, the development of critical thinking, and the cultivation of intercultural competence.

To fully comprehend the specifics of AI application in English language education, it is first necessary to clarify the concept of "artificial intelligence" itself and to analyze its interpretation within the context of educational practice.

In academic discourse, the term artificial intelligence (AI) has become widely used, though it remains polysemous and context-dependent, varying across fields of application. In general, AI refers to the ability of computer systems to perform tasks that typically require human intelligence, such as speech recognition, translation, decision-making, text analysis, and data-driven learning. According to the definition proposed by the European Commission in its White Paper on Artificial Intelligence (2020), "Artificial intelligence refers to systems that display intelligent behaviour by analyzing their environment and taking actions – with some degree of autonomy – to achieve specific goals" (European Commission, 2020).

The Oxford Dictionary offers the following definition: artificial intelligence is the capability of computer systems or other technological devices to replicate or simu-

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late intelligent behaviour, as well as the corresponding scientific field dedicated to studying such processes. In its contemporary understanding, AI is also viewed as software capable of performing tasks or generating outputs that were previously thought to require exclusively human intelligence. In this context, machine learning plays a particularly important role, as it enables algorithms to identify patterns and make generalizations based on the analysis of large datasets (Oxford English Dictionary, n.d.).

It is important to emphasize that AI does not refer to a single technology; rather, it serves as an umbrella term encompassing a wide range of digital technologies from simple algorithms or mobile applications to complex systems based on machine learning and artificial neural networks. In the field of education, AI is understood as a set of digital tools that support the adaptation of the learning process to students' individual needs, assist teachers in preparation and assessment, and open up new possibilities for autonomous learning. AI in education refers to the application of AI technologies for analyzing educational data, shaping personalized learning pathways, providing feedback, expanding access to quality education, and fostering inclusive learning environments. In Luckin, R. et al. (2016), the concept of artificial intelligence in education (AIEd) is introduced, describing the integration of AI methods with advances in educational science to create adaptive learning environments and digital tools that enable personalized, effective, inclusive, and flexible learning. «It can provide teachers and learners with the tools that allow us to respond not only to what is being learnt, but also to how it is being learnt, and how the student feels. It can help learners develop the knowledge and skills that employers are seeking, and it can help teachers create more sophisticated learning environments than would otherwise be possible. For example, AIEd that can enable collaborative learning, a difficult task for one teacher to do alone, by making sure that the right group is formed for the task-at-hand, or by providing targeted support at just the right time» (Luckin et al., 2016, p. 11).

AI tools used in education are commonly classified into three functional categories, based on their primary interaction focus: (1) learner-facing, (2) teacher-facing, and (3) system-facing (Baker et al., 2019). The first category, learner-facing AI tools, includes adaptive educational technologies that interact directly with students, tailoring content and instruction to their individual needs. This category encompasses intelligent tutoring systems, as well as personalized and differentiated learning platforms.

Key functions include:

- developing personalized learning pathways based on student knowledge and progress data;
- identifying knowledge gaps;
- providing automated feedback;
- facilitating collaboration among learners (Baker et al., 2019, p. 11).

The second category, teacher-facing AI tools, is aimed at supporting educators in their professional activities, both in planning and analytics. Its key functions include:

- automating routine tasks (such as creating instructional materials, assessment, and providing feedback to students);
- analyzing individual and class-wide progress (learning analytics);
- supporting innovation and experimentation in teaching (e.g., adapting pedagogical methods, grouping students based on specific characteristics for targeted instructional purposes) (Baker et al., 2019, p. 12).

The use of this category of AI tools enables teachers to save time and redirect their efforts toward other aspects of their professional roles that require creativity and personal engagement. While AI tools can take over certain teaching tasks before, during, and after lessons, the teacher's role is by no means diminished, it is transformed. The teacher becomes an active user, coordinator, and moderator of students' interaction with AI tools. As Rose Luckin et al. emphasize: "It is teachers who will be the orchestrators of when and how to use AIEd tools" (Luckin et al., 2016, p. 31). This position is shared by researcher Nermin Özçelik, who notes: "The role of teachers in language education is mostly facilitator, and this role remains irreplaceable, guiding students in using AI tools effectively and fostering critical thinking" (Özçelik, 2025, p. 621). Furthermore, as researchers note, the teacher's role may expand to include that of an analyst and innovator in the educational process. Teachers should become active participants in the development of AI tools and the methods of their implementation. This approach allows for a more accurate consideration of the realities and complexities of the educational environment, as well as the actual interests and needs of today's teachers and learners.

The third category of AI tools in education is system-facing. Tools in this group are designed to support decision-making processes at the level of individual schools, educational institutions, or entire educational systems. Examples of their application include:

- automated scheduling;
- forecasting inspections or audits;

- resource allocation optimization;
- inter-institutional data analysis (typically requiring data exchange across institutions) (Baker et al., 2019, p. 14).

The process of learning a foreign language, particularly English, entails the development of four fundamental language skills: receptive (listening and reading) and productive (speaking and writing). At the current stage of digital technology development, AI tools demonstrate considerable potential in supporting and optimizing this process. The results of several empirical studies (Çakmak, 2022; Chen et al., 2022; Hew at al., 2023; Jeon, 2021; Kazu et al., 2023; Nazari et al., 2021; Zou et al., 2020) indicate increased effectiveness in English language learning when pedagogical methods are combined with the functional capabilities of AI-powered services.

Listening Comprehension. The development of listening skills, which traditionally poses challenges for learners, has been significantly facilitated through the use of interactive AI technologies. Voice assistants (such as Amazon Alexa and Google Assistant), personalized platforms, and mobile applications provide learners with access to authentic language content, offering features such as adjustable speech tempo, audio repetition, vocabulary clarification, and interactive engagement. These tools not only activate auditory memory but also enhance learners' understanding of context, intonational patterns, and grammatical structures in speech.

Recent studies indicate the growing role of AI in listening comprehension instruction. For instance, Annamalai et al. (2023) demonstrated that the integration of chatbots into the learning process enabled students to practice listening in a safe environment, where they could repeat utterances, listen at varying speeds, and thereby improve their auditory competence (Annamalai et al., 2023). Respondents reported improvements not only in listening skills but also in speaking, writing, and reading, suggesting a comprehensive impact of such technologies.

Similar findings were confirmed in a study by Hew et al. (2023), which introduced a chatbot "companion" based on the principle of social presence. This chatbot supported learners during listening tasks by providing immediate feedback and employing communicative strategies to sustain a sense of co-presence and interaction in an online environment. The author notes that students perceived this "language companion" as a helpful and user-friendly tool for extracurricular learning, contributing to a positive emotional experience and increased motivation (Hew et al., 2023).

Reading. The development of reading skills in the process of learning English as a foreign language requires effective engagement with both authentic and adapted texts. It is essential that such texts not only contain the vocabulary, grammatical structures, and other elements required by the curriculum, but also be contemporary and engaging for students. AI tools, particularly generative language models and AI-based content creation platforms, open up new opportunities for a personalized approach to reading, for adapting text complexity, and for increasing learners' emotional engagement. Depending on the level of foreign language proficiency, AI tools can be used by the teacher to prepare lesson materials and gradually introduced to students for independent work. Tools such as ChatPDF, DeepL, QuillBot, and LingQ not only facilitate comprehension but also stimulate analytical thinking through question generation, summarization, or fill-in-the-gap tasks. One promising approach involves the use of AI generators to create individualized stories based on keywords provided by the learner, making reading not only informative but also captivating. An empirical study by Lee et al. (2023), conducted among primary school learners, demonstrated a significant positive effect of using an AI content generator on students' enjoyment of reading in English. The study involved 121 students, divided into control and experimental groups. The students in the experimental group used a text-generation tool that produced stories based on their interests and topics suggested via keywords. As a result, participants in this group not only showed greater interest in reading but also expressed a willingness to read more frequently outside of class.

An interesting case is presented in the study by Zheng et al. (2015), which examined how vocabulary acquisition and reading comprehension develop during the completion of in-game tasks in the English-language version of World of Warcraft (WoW). The authors concluded that in the process of completing "quests," which are accompanied by a substantial amount of English-language textual information, players are able not only to actively interact with linguistic content but also to contextualize lexical items that in a traditional textbook or classroom environment are often presented in isolation from real-life situations. Through the inclusion of AI-powered characters (neural agents functioning on algorithmic bases), the game creates a dynamic linguistic environment that requires the player to comprehend instructions, dialogues, and descriptions of objects and situations. Such interaction activates not only passive text perception but also the "read-understand-act" connection, which is a key component of functional reading. An additional factor is the presence of navigational algorithms that drive the development of in-game events, forcing the player to adapt to new situations. This helps to create a motivational impulse to read for the sake of action rather than merely for the formal completion of tasks.

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Speaking. Interactive chatbots and virtual language partners have become valuable tools in developing productive oral communication skills. Applications such as ELSA Speak, Speak, and HelloTalk, along with generative language models (e.g., ChatGPT, Bing AI), provide conditions for simulating dialogues and practicing pronunciation, intonation, and real-time speech response. A notable advantage is the psychologically safe environment they offer, enabling learners to practice speaking without the fear of being judged. Particular attention should be paid to pronunciation work, which traditionally poses considerable challenges for learners. As noted by Kazu and Kuvvetli (2023), learners often rely on online dictionaries for pronunciation models, yet they are not always able to reproduce them accurately. In this case, AI-driven speech recognition systems, implemented through platforms such as Google Speech or other voice assistants, prove to be particularly useful. Studies by Liakin et al. (2017) and McCrocklin (2019) demonstrate that the use of speech recognition systems in the classroom supports not only the provision of individualized feedback but also leads to significant improvements in pronunciation compared to traditional teacher comments or corrections. Kazu and Kuvvetli (2023) experimentally confirmed that the use of AI-powered speech recognition during pronunciation practice has a positive impact not only on phonetic accuracy but also on the retention of vocabulary, since articulatory rehearsal activates deeper language-memory mechanisms. Their study examined the use of the Web 2.0 platform «Games to Learn English», specifically its «Talk Easy» component. During the experimental training, learners could select from 28 lexical categories and practice pronouncing words, which were automatically evaluated via Google Speech Recognition. In cases of errors, learners could repeat the word, listen to a model pronunciation, or adjust the difficulty level. Pronunciation scores were not subject to formal assessment but were used for feedback provision. Post-test results showed that participants acquired new vocabulary significantly more effectively due to the combination of game-based dynamics and voice-based feedback.

At the same time, a number of researchers, including Zou et al. (2020), Crompton (2023), and Kim & Sim (2024), emphasize the limited adaptability of AI to diverse accents. This issue is particularly relevant in the Ukrainian context, where learners study English as a foreign language while exhibiting phonetic features characteristic of Slavic language speakers. Speech recognition-enabled language applications are typically configured to process standard American pronunciation; consequently, learners whose articulation reflects national phonetic traits (e.g., consonant hardness, reduced vowel reduction, or distinctive intonation patterns) often receive inaccurate or biased feedback. This can lead to decreased self-confidence, avoidance of speaking practice, and, in some cases, the internalization of a perception of one's pronunciation as "incorrect" or unacceptable.

For example, participants in the experimental study by Kim and Sim (2024) reported experiencing psychological discomfort when using AI tools, particularly due to the system's failure to recognize their non-American accent. Feedback was highly sensitive to deviations in pronunciation, and correct responses were accepted only when learners precisely reproduced predefined speech patterns, thus depriving them of opportunities for communicative flexibility. Such interaction mechanisms not only complicated the learning process but also hindered the development of learner autonomy, as students felt compelled to adjust to the system rather than act freely.

The researchers emphasize that the use of rigidly standardized AI models in English language instruction risks disregarding linguistic diversity and learners' individual language experience. They underscore the need for the development of more flexible language models capable of recognizing a wider range of accents and pronunciation variants, thereby creating a more inclusive, pedagogically sound, and ethically sensitive environment for speaking skills development. In this regard, there is an urgent need for adaptive AI platforms capable of accurately processing English speech with various non-native accents, which, in turn, would contribute to more inclusive and effective oral language learning oral language learning.

Writing. Writing is one of the most extensively researched areas of using AI in English language learning. At the same time, similar to speaking, this skill remains challenging for many learners as it requires the simultaneous engagement of lexical, grammatical, logical, and cognitive resources. Writing tasks often cause elevated levels of stress, lack of confidence, and even boredom among students, due to the formulaic nature of exercises or the fear of making mistakes during assessment. In this context, AI tools can significantly optimize the writing process, making it less formalized, more adaptive, and psychologically safer for learners. First, automated AI-based evaluation reduces psychological pressure by eliminating the factor of subjective teacher assessment. Second, AI platforms can provide instant feedback, which fosters learner autonomy and an analytical approach to text composition. Third, such tools actively support vocabulary enrichment, improvement of grammatical structures, development of logical text organization, and critical thinking in students. Automated writing feedback systems such as Grammarly, Write & Improve

(Cambridge), and ChatGPT function as virtual tutors, guiding the learner through the writing process from idea generation to final editing. These tools enable self-checking, error correction, text structuring, and the reception of recommendations on style, vocabulary, and grammar.

Studies by Dizon & Gayed (2021), Nazari et al. (2021), and others confirm that students who consistently used Grammarly demonstrated substantial improvements in writing accuracy, complexity, and coherence, as well as more positive attitudes toward the writing process. In the study by Chon et al. (2021), conducted among college students in South Korea, the use of Google Translate as a writing tool was examined. Findings revealed that less proficient students who used the translator achieved writing performance comparable to that of their more advanced peers. Furthermore, these students employed more sophisticated vocabulary and produced syntactically more elaborate texts.

One of the most notable effects of introducing AI tools into English language learning is the enhancement of learners' motivation and the positive influence on their emotional well-being. This is largely due to the ability to receive immediate feedback, work at a comfortable pace, avoid evaluation by a human, and interact with learning materials in formats aligned with the digital habits of contemporary youth.

Recent studies confirm that the use of AI tools in English language instruction positively affects not only academic outcomes but also learners' motivation, emotional engagement, and overall psychological comfort. For example, research by Hew et al. (2023), Chen et al. (2022), Çakmak (2022), and Jeon (2022) has demonstrated that AI-supported learning can reduce anxiety, which often arises from fear of public speaking, making mistakes, or experiencing communication difficulties. At the same time, AI-assisted learning is perceived as engaging, enjoyable, and emotionally appealing due to its interactive format, rich visualization, and gamification features. Such elements help create a positive emotional atmosphere during lessons, thereby increasing learning motivation.

In summary, current research suggests that the integration of AI tools into English language learning fosters the development of language skills, enhances students' motivation, and promotes a positive attitude toward the learning process itself. The use of adaptive, interactive, and visually engaging AI resources allows educators to create a more flexible, individualized, and psychologically safe learning environment.

However, it is equally important to critically assess the barriers, potential risks, and negative aspects associated with implementing AI in English language teaching. One significant limiting factor is the insufficient preparation of teachers for such integration. Despite positive findings from a survey conducted by the Minor Academy of Sciences of Ukraine and the Projector Institute, which revealed that most teachers and students are familiar with and use AI tools, their level of mastery cannot be confidently described as high. A considerable proportion of educators report lacking the knowledge and skills required for effective AI integration. This is supported by the findings of a survey by the Talan Financial Knowledge Center, in which 93.6% of teachers expressed a desire and need for additional training, while only 0.4% stated they were ready to share their own experience in applying AI in the educational process (Bank Talan, 2024). Without proper methodological support, there is a risk that teachers may either avoid using AI or rely on it excessively, without fully understanding its limitations.

Another significant barrier to the systemic implementation of AI in school education is the unequal accessibility of technological resources and infrastructural limitations. Under the conditions of martial law, particularly in regions that are constantly under attack by Russia, many educational institutions face unstable internet connectivity, limited access to modern equipment, and, in some cases, a complete inability to ensure a safe digital learning environment. This significantly restricts the potential of AI to guarantee equal access to quality language education for all categories of students. Moreover, learners from certain socio-economic backgrounds, such as children from low-income families or those residing in rural areas, may also experience limited access to AI resources or insufficient digital literacy, thereby deepening educational inequality. Addressing these issues requires state-level initiatives to strengthen the infrastructure of educational institutions (including hardware and software), implement targeted supportive measures for vulnerable groups, and develop strategies for using AI to engage students with diverse learning backgrounds, life experiences, and abilities.

The other pressing challenge relates to the risk of academic dishonesty among students. Both in the results of surveys among Ukrainian teachers (Projector Creative & Tech Institute & MAN, 2023) and in international research (Edmett et al. (2024), Özçelik (2025), Alqaed (2024); Kohnke et al. (2023), significant concerns have been expressed by the academic community and teachers regarding plagiarism and cheating when students use AI to complete assignments, particularly writing tasks. Students may rely on AI tools to produce essays, reviews, letters, or feedback, tasks that typically require not only linguistic knowledge and skills but also logical, critical, and creative thinking, as well as more time for completion compared to other language activities. This raises concerns about excessive dependence on AI (Huertas-Abril & Palacios-Hidalgo, 2023), which may hinder the development of critical thinking, argumentation, and reflective skills. In the long term, such reliance could reduce the quality of learning outcomes and foster a consumerist attitude toward the educational process. This issue has also been emphasized in the UNESCO policy document on the integration of AI into education: “The resultant concentration on aggregated second-hand information may also reduce learners’ opportunities for constructing knowledge through proven methods such as directly perceiving and experiencing the real world, learning from trial and error, performing empirical experiments, and developing common sense. It may also threaten the social construction of knowledge and the fostering of social values through collaborative classroom practices” (Miao et al., 2023, p.37). In this regard, recommendations aimed at preventing academic dishonesty and maintaining academic integrity in the context of AI use in the educational process may prove valuable (University of Kansas, Center for Teaching Excellence. (n.d.); Centre for Teaching and Learning. (n.d.); McMaster University, Office of the Provost. (n.d.)):

- clear rules for students specifying in which cases they may use AI and when it is strictly prohibited;
- rethinking the structure of assignments: introducing creative, reflective, and process-oriented tasks that are difficult to complete with AI without the student’s own input (e.g., analysis of personal experience, comparative reviews, oral explanations);
- introducing elements of oral assessment: presentations, discussions, and the defense of written work make it possible to identify the actual level of mastery of the material;
- digital ethics education: conducting mini-trainings or awareness sessions on academic integrity, plagiarism, and responsible AI use among students;
- integration of formative assessment methods: working with drafts, providing comments on the stages of writing, and peer review by students contribute to process transparency;
- combining automatic and manual verification methods: using such tools as Turnitin, Grammarly, and Copyleaks in combination with high-quality expert analysis by the teacher.

Thus, the issue of cheating cannot be resolved solely through technical means; it requires comprehensive pedagogical support, updated evaluation methodology, and the cultivation of students' academic culture, where AI is regarded not as a "shortcut" but as an additional tool for developing language competence.

One of the significant challenges in introducing AI into English language teaching is the potential reduction of live interpersonal communication in favor of digital interaction. This problem is particularly relevant in the context of language competence formation, which requires continuous verbal, non-verbal, and emotional interaction between students and the teacher. As noted by Kushmar et al., "Learning and teaching a foreign language in an artificial learning environment often arises. But there are real emotions of people. With AI, the need for real people will not disappear; it will only exacerbate the feeling of fear about unreal life" (Kushmar et al., 2022, p. 271). Therefore, it is important to maintain a balance between digital tools and traditional interaction, as language learning is not only a cognitive but also a socio-emotional process. Excessive automation may lead to isolation and distortion of interpersonal skills.

In this context, teachers also express legitimate concerns about the potential reduction of their role in the educational process. As noted above, it is essential to recognize that the role of the teacher is not diminished but rather transformed under new conditions. At the same time, UNESCO emphasizes the need to develop an appropriate educational policy that strategically rethinks how AI may alter the functions of teachers and how educators can be prepared to work effectively in an AI-rich educational environment (Miao et al., 2021, p. 27).

Another important factor influencing the effectiveness of AI in the educational process is the issue of trust in AI technologies, which is shaped by two key aspects: errors in AI systems and risks of personal data breaches. For example, in a survey of Ukrainian teachers on the reasons for not recommending AI to colleagues and students, one of the main concerns was AI's limitations and errors in its functioning (Projector Creative & Tech Institute, & MAN, 2023). Despite the rapid development and improvement of AI tools, the likelihood of technical inaccuracies and incorrect outputs still persists. In the study by Ericsson et al. (2023), it was found that virtual conversational agents (virtual humans) often failed to understand students' responses or only accepted pre-scripted options. This matter forced students to repeat themselves, lose interest and motivation, and thereafter reduced the spontaneity and creativity of their speech production (Ericsson et al., 2023; Kushmar et al., 2022).

Unlike a real teacher, who can take into account the context, the student's emotional state, and the multidimensional nature of a language situation, AI often operates based on statistical models without a deep understanding of meaning, communicative intent, or cultural nuances. This is also illustrated by the studies mentioned above (Zou et al., 2020; Crompton, 2023; Kim & Sim, 2024), which demonstrated that students experienced discomfort when interacting with AI due to its limited ability to recognize non-native accents; this hindered effective language interaction and lowered motivation to learn. These examples highlight the risk of excessive algorithmization of the communicative process in the context of unbalanced AI use in education, which leads to an artificial narrowing of linguistic variability. Such an approach is opposite to the nature of a living language, which entails richness of forms, intonational flexibility, contextual dependence, and the potential for multiple interpretations. As Kushmar et al. (2022) note, AI systems foster the standardization of language, where creativity and authenticity are relegated to the background, contradicting the aims of the communicative approach to language teaching.

Continuing the discussion on the limitations of AI in education, UNESCO emphasizes the shortcomings of deep learning technologies applied in educational systems. In particular, it is noted that "Current AI technologies can also be very brittle. If the data is subtly altered, for example, if some random noise is superimposed on an image, the AI tool can fail badly" (Marcus & Davis, 2019, cited in Miao et al., 2021, p. 7). In language learning practice, this may manifest in incorrect assessment of students' responses, inaccurate error correction, or misleading feedback, which can lead to frustration or a loss of trust in the system.

Moreover, the issue of AI's limitations is closely linked to the problem of embedded algorithmic bias, which directly affects the objectivity and quality of the learning process. Douglas (2017) notes, as quoted in the UNESCO report: "In particular, if the algorithms are trained on data which contains human bias then of course the algorithms will learn it, but furthermore they are likely to amplify it. This is a huge problem, especially if people assume that algorithms are impartial" (Miao, Holmes, Huang, & Zhang, 2021, p. 25). This means that the algorithms used in AI systems for analyzing, evaluating, or adapting educational content are not inherently objective. They reflect and even amplify the biases already present in the learning data on which they have been developed. This is particularly critical for language education, where sociocultural aspects, such as gender, accent, racial identity, or culturally specific speech patterns, play an important role in shaping the learner's linguistic identity. Thus, in situations where, for instance, the system fails to recognize non-native accents or penalizes the use of non-standard vocabulary, this may not simply be a technical error but a manifestation of systemic discrimination. Even more concerning is the fact that users often tend to trust algorithms as objective and impartial judges, while in reality, they may reproduce social stereotypes that discriminate against certain groups of learners. In the context of English language teaching, this can have negative consequences for students from diverse cultural, linguistic, and social backgrounds, as the AI system may not only fail to recognize their uniqueness but also potentially boost learners to use "normative" speech patterns. This not only undermines students' motivation and self-confidence but also contradicts the principles of inclusive education.

The issue of data leakage has become particularly acute, representing a matter of concern not only for the global community and scholars but also for teachers, students, and their parents. This issue has been the subject of numerous studies, including those by Akgun & Greenhow (2022), Kostka & Toncelli (2023), Jobin et al. (2019), , and Manire et al. (2023), and is consistently raised in reports by international organizations, notably UNESCO. For example, the report "AI and Education: Guidance for Policy-makers" emphasizes that education may become a testing ground for untested or unverified technologies, particularly in the absence of adequate governmental policy for monitoring the use of AI in the learning process (Miao et al., 2021, p. 20).

The study by Kushmar et al. (2022) also reported a high level of anxiety among students regarding the security of personal information. In particular, the majority of surveyed respondents expressed concerns about potential cyberattacks, unauthorized access to accounts, and the leakage of confidential data stored in AI systems.

Privacy concerns are of exceptional importance in the field of foreign language learning, as AI-based interactive platforms require the continuous collection, processing, and storage of large volumes of sensitive learner information. This encompasses not only typical educational indicators, such as knowledge level, language production, or progress, but also personal data, including interests, preferences, and individual cultural and emotional experiences. In certain cases, AI systems may even collect biometric data, such as intonation, speech rate, or distinctive linguistic patterns, which potentially increases the risk of personal identification or the commercial use of such data without user consent.

In response to the issue of privacy and the security of teachers' and learners' data, UNESCO proposes a systematic approach to the ethical regulation of AI use in education. This primarily involves the comprehensive testing of new AI technologies prior to their large-scale deployment in order to identify potential vulnerabilities related to personal data protection. In addition to technical improvements, an important direction is the development of a legal framework that regulates the collection, storage, access, reuse, and deletion of personal educational data. In this context, UNESCO recommends the need to "develop comprehensive data protection laws and regulatory frameworks to guarantee the ethical, non-discriminatory, equitable, transparent and auditable use and reuse of learners' data" (Miao et al., 2021, p. 20).

Thus, it can be concluded that the integration of AI into English language teaching in general secondary education institutions is a phenomenon that is already actively transforming traditional approaches to language education. Contemporary AI technologies demonstrate significant potential in supporting English language learning by: (a) fostering autonomous learning; (b) increasing learner motivation; (c) enabling the personalization of learning content; (d) intensifying practice across the four core language skills; and (e) reducing teacher workload by optimizing lesson preparation, assignment grading, and the maintenance of reporting documentation. However, alongside these expanded learning opportunities, these tools also reveal a number of ethical, technical, social, and pedagogical challenges.

One of the key challenges identified through the analysis is the reduction in live interpersonal interaction during the learning process, which is particularly critical for language education. The development of communicative competence requires emotional engagement, flexibility in communication, opportunities for non-verbal feedback, intonational variation, and cultural context – all of which AI is currently unable to fully provide.

The barrier also lies in the limitations of AI itself. Although many AI systems demonstrate high efficiency in tasks such as text analysis and response generation, significant technical constraints persist, including difficulties in recognizing non-native accents, inability to grasp speech context or communicative intent, repetition of formulaic responses, and instances where AI generates inaccurate or illogical information. Such errors raise concerns regarding the objectivity of feedback and the fairness of assessment.

Another substantial issue is AI's tendency towards response standardization. Most systems operate within a limited range of "correct" answers embedded in their scenarios, which can diminish learners' creativity, hinder the development of an individual speaking style, and promote formulaic thinking. Attention should also be given to the problem of bias in AI algorithms, as it may contribute to reduced learner self-confidence, decreased motivation, and other negative educational outcomes. Among the most critical challenges is the risk of leakage of confidential information belonging to participants in the educational process.

Despite widespread concerns about the potential replacement of teachers, the findings indicate that AI cannot fully substitute the pedagogical function. Rather, the nature of teaching is transforming: from a content transmitter, the teacher becomes a facilitator, mentor, critical interpreter of results, and moderator of an ethical learning environment.

Given the scale and depth of the challenges outlined, the need to reconsider the role of AI in the educational process becomes evident. This involves not only its technological integration but also the development of a comprehensive, ethically grounded, and human-centered strategy aimed at preventing undesirable consequences.

In our view, the following steps are essential:

- continuing interdisciplinary research at the intersection of pedagogy, IT, ethics, psychology, and law;
- accumulating empirical research within general secondary education institutions in Ukraine on the effectiveness of AI use in the educational process, followed by analytical processing of the results and the development of practical recommendations;
- defining the boundaries of AI application in language education, with a clear understanding of which functions should remain within the human domain and which can and should be delegated to AI;
- developing a regulatory framework and codes of ethical AI use;
- intensifying and scaling up teacher training, subject-specific in particular, for work in AI-enhanced environments, including digital literacy and critical thinking skills;
- providing teachers with methodological support in the form of manuals, guidelines, practical handbooks, and other resources for the effective and safe use of AI in the educational process.

Thus, the use of AI in English language teaching should be viewed as a complex yet powerful tool that requires responsible, ethically balanced, and pedagogically sound implementation. The goal is not to set AI tools in opposition to traditional teaching methods, but rather to seek a productive balance between them, harnessing the advantages of each approach. Only under these conditions will it be possible to create a truly effective, inclusive, and safe educational environment that meets the challenges and opportunities of the XXI century.

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DIGITAL TRANSFORMATION OF EDUCATION: CHALLENGES AND PROSPECTS

Monograph

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Serhii Kryzhanovskyi, Viktor Matsyuk, Serhii Yashanov, Hlib Lazarenko, Iryna Holiiad, Vasyl Tutashynskyi, Anatolii Tarara, Dmytro Puzikov,
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Valentyn Rogoza, Fessalonika Levchenko, Mariia Tyshkovets, Vladyslav Pelekh,
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Oksana Strutynska, Mariia Umryk, Oleh Topuzov,
Svitlana Alieksieieva, Kateryna Ladonia, Oksana Shparyk, Oksana Hlushko,
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