Quantum Transformation of School Informatics

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Abstract: The study's objective was to theoretically examine, create, and experimentally test various approaches for instructing lyceum students in the fundamentals of quantum informatics. The following was accomplished as a result of the research assignments: 1) The sources on the issue of teaching quantum informatics in Ukraine and abroad were examined; 2) The structure and content of the competences in the basics of quantum informatics for the lyceum students were theoretically grounded and developed (the results of the expert survey and the European competence framework in the field of quantum technologies were taken into consideration); 3) the structural and functional model for forming the competences in the basics of quantum informatics were developed; 4) in the optional course of the same name, it was proposed a methodological framework for teaching the fundamentals of quantum informatics to lyceum students; and 5) it was also experimentally tested to see how well the developed methodology worked in developing the students' competency in the fundamentals of quantum informatics. Further scientific investigations into the quantum transformation of the school's informatics are also described.

1 INTRODUCTION

The changes that took place in the methodology of teaching informatics in schools were caused by the development of information technology and changes in society as a result of their influence (Semerikov et al., 2021). The latter led to the fact that school informatics together with foreign language became available at all levels of school education – from primary school to vocational training at the lyceum. Informatics tools are an integrator for all school subjects, and its methods are the basis for the integration of natural sciences, mathematics and technology. This creates a deep understanding of the service, subordinate and second-row role of informatics in the system of school education. The fundamentalization of teaching content informatics, in particular – through a quantum transformation of basic knowledge about information processes and systems, hardware and software, networks, algorithms and programs will help to get rid of it.

According to the analytical report of the National Institute for Strategic Studies (NISS, 2020), Ukraine is on the sidelines of the development of breakthrough technologies, in particular quantum technologies, which is due, firstly, due to insufficient state budget financing of scientific research on the whole, and secondly, due to the significant inadequacy of professional and qualification workforce to market demands. At the same time, European job search sites have hundreds of job postings for "quantum software engineer" and "quantum programmer".

The analysis of the experience of teaching informatics in Ukraine and the resources on the problems of research allowed us to identify the contradictions:

- between the importance of quantum informatics for increasing competitiveness and successful self-fulfillment of graduates of lyceums in the labor market (in particular, in the field of informa-

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tion technology) and the lack of adequate training materials in Ukrainian language;

- between the importance of practical experience with quantum computers and the difficulty of direct access to them;
- between the need to form competences in the basis of quantum informatics in the lyceums and undevelopment of the appropriate methods.

The need to solve the above-mentioned contradictions led to the definition of the study's aim and formulation of its hypothesis. The aim of the study was to theoretically analyze, develop and experimentally test the methods of teaching the basics of quantum informatics to lyceums students. It has been suggested that the formation of competencies on the basics of quantum informatics to lyceums students at a high level is possible by changing some components of the methodological system of teaching computer science: content and teaching tools.

2 THEORETICAL FOUNDATIONS OF TEACHING THE BASICS OF QUANTUM INFORMATICS TO LYCEUMS STUDENTS

2.1 Quantum Informatics as a Perspective Field of Information Technology Development

In August 2020, consulting company Gartner published yet version of its Hype Cycle of advanced technologies that will have a significant impact on society and business in the next five to ten years. Based on a review of 1,700 advanced technologies, Panetta (Panetta, 2021) identifies 5 new trends in their development:

- Composite architectures;
- Algorithmic trust;
- Beyond silicon;
- Formative artificial intelligence (AI);
- Digital me.

The Beyond silicon description of the direction says that Moore's Law has run out of steam because it is almost impossible to create transistors smaller than 1 nm. There are technical difficulties in manufacturing, so there is a chance to develop non-silicon technologies – carbon-based transistors and quantum hardware, including quantum computers (Panetta, 2021).

At the time when classical computers continue to develop (processors became multicore, co-processors appeared to solve photo processing tasks, video coding, etc.) the pace of quantum technologies development is gaining momentum and quantum computers are becoming a reality. Appearance and development of quantum equipment, in particular quantum computers, has led to a new field of informatics – quantum informatics (Lehka and Shokaliuk, 2018).

One should understand that quantum computers by no means supersede classical ones, but they are indispensable for certain types of tasks – modeling complex chemical reactions to develop drugs and substances with predetermined properties, modeling of physical quantum systems inaccessible for conventional calculations, quantum calculations of complex mathematical tasks, quantum long-distance communication, etc. The solution of these problems is based on already known quantum algorithms – algorithms for function balancing (Deutsch-Jozsa and Bernstein-Vazirani algorithms), algorithm for determining the totality of functions (Simon's algorithm), harmonic analysis algorithms (the quantum Fourier transform algorithm), cryptoanalysis algorithms (Grover's and Shor's algorithms), quantum teleportation algorithm – and new (still experimental) algorithms.

In many countries of the world the development of quantum technologies is supported by legislation and financed by the government.

Thus, in the U.S., artificial intelligence and quantum technologies have been identified as two strategically important fields for the country's economic growth and national security. In 2018, the U.S. government approved legislation for the National Quantum Initiative, which aims to ensure that the U.S. remains a world leader in quantum informatics and its technological applications. Funding for National Quantum Initiative activities for the first five years is $1.2 billion (NQIA, 2018). Individual commercial research is conducted at the expense of IBM, Microsoft, Google, Intel and others.

In China, in 2016 the government approved the National Science and Technology Innovation Plan until 2030 (NSTI, 2016), and in 2017 the construction of the National Quantum Informatics Laboratory was launched with initial funding of 7 billion yuan (Chen, 2018). The Chinese tech giant Alibaba is making significant investments in its own quantum initiatives, including the launch of a quantum calculator service via a cloud platform (Alibaba, 2018).

Since October 2018, EU countries have launched project program to support fundamental quantum research – "The European Quantum Flagship" (QFlagship), with a minimum duration of 10 years and an expected budget of 1 billion billion euros (EQF, 2021). In addition, to protect against cybersecurity threats, in June 2019, 24 European states participated in the signing of a declaration on the research, development and deployment of quantum communication infrastructures (EDS, 2019).

The demand for specialists in the field of quantum technologies becomes urgent. The lack of quantum-literate specialists hinders the development of the industry. For example, Hilton (Hilton, 2019), vice president of D-Wave, argues that it is necessary to increase the number of quantum-literate workers, invest in the training of teenagers, identify capable young people, develop them in the field of quantum technologies and create a talent pool of promising workers with knowledge in the quantum field.

2.2 Teaching Experience of Quantum Informatics and Popularization of Quantum Technologies in Ukraine and the World

In Ukraine all educational programs on quantum informatics were initiated only in universities within the specialty 104 – Physics and Astronomy (Pinkevych et al., 2018; NUL-bachelor, 2020; NUL-master, 2021), while in the world the training of corresponding specialists is carried out by different specialties (QTEdu, 2022).

The European Competence Framework for Quantum Technologies, launched in 2021, provides for training in quantum informatics, starting from primary school. Such education should be based on conceptual and intuitive understanding of quantum informatics key essences.

Today, both in Ukraine and abroad, mostly programs of non-formal education on individual topics of quantum technologies are offered for students of general secondary education institutions. Its are online schools, master classes, summer camps for children, etc.

Popular science resources about quantum technologies for Ukrainian students are offered by Gnatenko (Gnatenko, 2020a,b). With these electronic materials (after payment) students can get acquainted with fundamental concepts of quantum mechanics – quantum entanglement, quantum beat, quantum parallelism, quantum sensing, quantum entanglement, quantum superposition, tunneling, quantum teleportation, as well as examples of basic tasks of quantum cryptography.

The Richelieu Lyceum, in cooperation with the Odesa I. I. Mechnykov National University, offers a series of lectures "Nanoelectronics: Science and Modernity" (including lectures on quantum effects) (NSM, 2021), and "Quantum Mechanics" (QM, 2021).

Korshunova and Zavadsky (Korshunova and Zavadsky, 2018) in their textbook on informatic for 5th grade (section "Information processes and systems") gives an overview of quantum computers as a technology of the future, pointing out the rapid development of the quantum industry in the next ten years, the use of quantum computers to solve certain types of mathematical problems, emphasizing the use of quantum computers together with conventional computers (Korshunova and Zavadsky, 2018, p. 28-29).

Since August 2020, the White House Office of Science and Technology Policy and the National Science Foundation have launched an innovative project, the Q-12 National Education Partnership, which over the next ten years will bring together industry and science educator leaders for large-scale quantum technology education, ranging from providing classroom tools for hands-on experience, developing educational materials, and supporting students on their way to professional careers in quantum technologies (Q12, 2023). Leading IT companies – IBM, Microsoft, D-Wave, Google and others – offer joint courses with universities, as well as educational resources for informal education, based on the use of a cloud access to quantum simulators and quantum computers, tools for creating and executing quantum circuits and programs, language-independent and language-independent development environments, etc. (QC-IBM, 2021; Google, 2022; QDKit-Microsoft, 2023).

A variety of educational resources on quantum technologies for primary and secondary school students and all those interested are offered on the QT-Edu community portal (QTEduCSA, 2021). The portal is designed to develop an educational ecosystem in support of the QFlagship project aimed at popularizing, informing and educating in the field of quantum technologies. The portal's collection of resources, structured by education level and target audience, includes educational programs, hyperlinks to external resources, quantum games, simulators, video resources, etc., mostly in English, German and Polish (Ukrainian and Russian resources are not available on February, 2023).

Experience of European and world practice of popularization of quantum technologies among high school students is a good evidence of the possibility of mastering the basics of quantum technologies, provided methodical adaptation of educational materials to the specifics of the audience perceiving them.

2.3 The Competencies in the Basics of Quantum Informatics to Lyceums Students

The key idea of the competency-based approach is to provide all interested individuals with a diagnostic tool to measure the level of preparedness of an individual to perform certain activities.

Review of the previous results of the world projects for the selection and determination of the list of competences in quantum technologies – WorldSkills International professional competitions (figure 1 and 2), seminar "Key Concepts for Future Quantum Information Science Learners" (NSF, 2020), Competence Framework for Quantum Technologies (figure 3) – made it possible to identify competencies in the fundamentals of quantum information science of lyceum students as a dynamic combination of knowledge, skills, abilities, ways of thinking, and attitudes, other personal qualities in the field of quantum technologies, which determine the ability of an individual to successfully carry out further professional and/or educational activities using such technologies. Competences in quantum informatics basics of lyceum students include 8 groups of competences:

1) physical basics of quantum technologies (basic concepts of quantum physics, cubic dynamics);
2) mathematical basics of quantum informatics (basics of linear algebra, mathematics of quantum physics basics, basics of quantum measurement statistics);
3) software technology (optical technology, laboratory technology, experimental control);
4) hardware for quantum computers and sensors (spin-based devices, neutral atoms and ions, new types of cubes, equipment for integration, manipulation and counting of cubes, use of hardware platforms for quantum computing);
5) quantum computing and modelling (quantum gates, quantum languages, programming tools and platforms, basic quantum algorithms, quantum error correction, quantum modelling elements);
6) quantum sensors and metrology (atomic gauges, sectors of quantum sensors application);
7) quantum communication (quantum cryptography, quantum networks, quantum communication infrastructure and equipment);
8) practical skills and general competences (basics of classical programming, application of quantum technologies, general skills/competences).

Considering that quantum information technology is an interdisciplinary branch of knowledge, the relevant competencies cannot be defined as part of digital competencies.

3 METHODICAL FOUNDATIONS OF TEACHING THE BASICS OF QUANTUM INFORMATICS TO LYCEUMS STUDENTS

3.1 Special Hardware and Software Tools for Teaching the Basics of Quantum Informatics

For the selection of special hardware and software tools for teaching quantum informatics to lyceums students we analyzed services from Microsoft, QuTech, Amazon and IBM (Lehka and Shokaliuk, 2021; Lehka et al., 2022a,b).

The greatest number of criteria is satisfied with IBM Quantum platform, which was turned into the main instrumental tool for learning the basics of quantum informatics for the course program.

Now IBM provides the greatest opportunities for free use of quantum computers and simulators through two services – IBM Quantum Composer and IBM Quantum Lab.

The first service – IBM Quantum Composer – the simplest tool for working with quantum algorithms in the form of quantum circuits.

The second service – IBM Quantum Lab – provides the possibility to implement quantum algorithms in Python programming language using the Qiskit library.

3.2 Pedagogical Reasonability and Content of Teaching the Basics of Quantum Informatics in Secondary Schools

The model of the educational process (learning) within a single educational unit, which reflects the ordering (elementary in time and space, in accordance with the goals of education and training and taking into account the reverse pedagogy) of the students (those who learn) in terms of the content of training

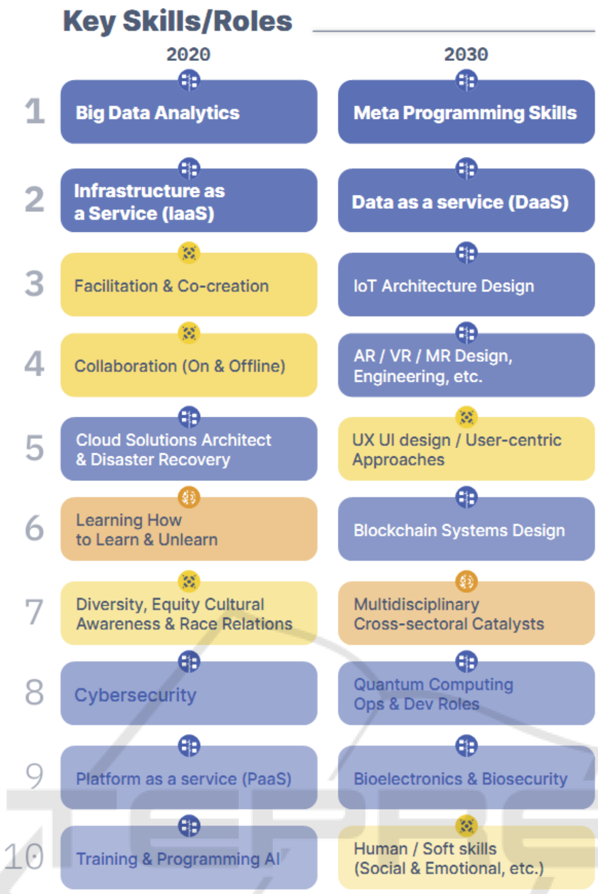

Figure 1: Key skills and roles of the 2020s and 2030s for WorldSkills (WS, 2020, p. 120).

and elements of the learning environment of a particular learning unit, students (those who are taught) regarding the content of the teaching and elements of the learning environment for a particular educational unit is called a normative teaching methods (Bykov, 2008, p. 310).

The real teaching method is based on the normative one and differs from it. The real teaching methods take into account the characteristics of the existing educational environment and mirror the creative aspect of the educational process participants (e.g., specificity of the educational environment of a particular educational institution, mastery of the teacher, additional meaningful elements that he or she uses in the lessons).

The normative teaching method of a certain educational unit (in our case – basics of quantum informatics as a single subject, elective, integrated course, etc.) can be presented in the form of a structural-functional model – a model graphically depicts functional peculiarities of structural elements of a certain process (in our case – formation of competences in quantum informatics basics).

The developed structural-functional model of competence formation in the basics of quantum informatics (Lehka, 2022, p. 82) includes 4 basic (system) blocks – Purpose, Content, Technological and Productive (figure 4) – and 3 additional blocks ensuring the interaction of the model's basic blocks: general didactic principles of teaching quantum informatics, hardware and software tools for teaching quantum informatics and methodological approaches (competence-based, systemic, integrative, personal and activity-based).

Let us consider the aim and content blocks of the model.

The *aim block* of the model includes components (factors) that determine the pedagogical feasibility of the educational unit in the educational process (local or global). Factors of pedagogical feasibility of implementation of quantum informatics basics in the educational process of secondary general education institutions are:

- rapid development of quantum technologies;
- demand of the society for qualified quantum sci-

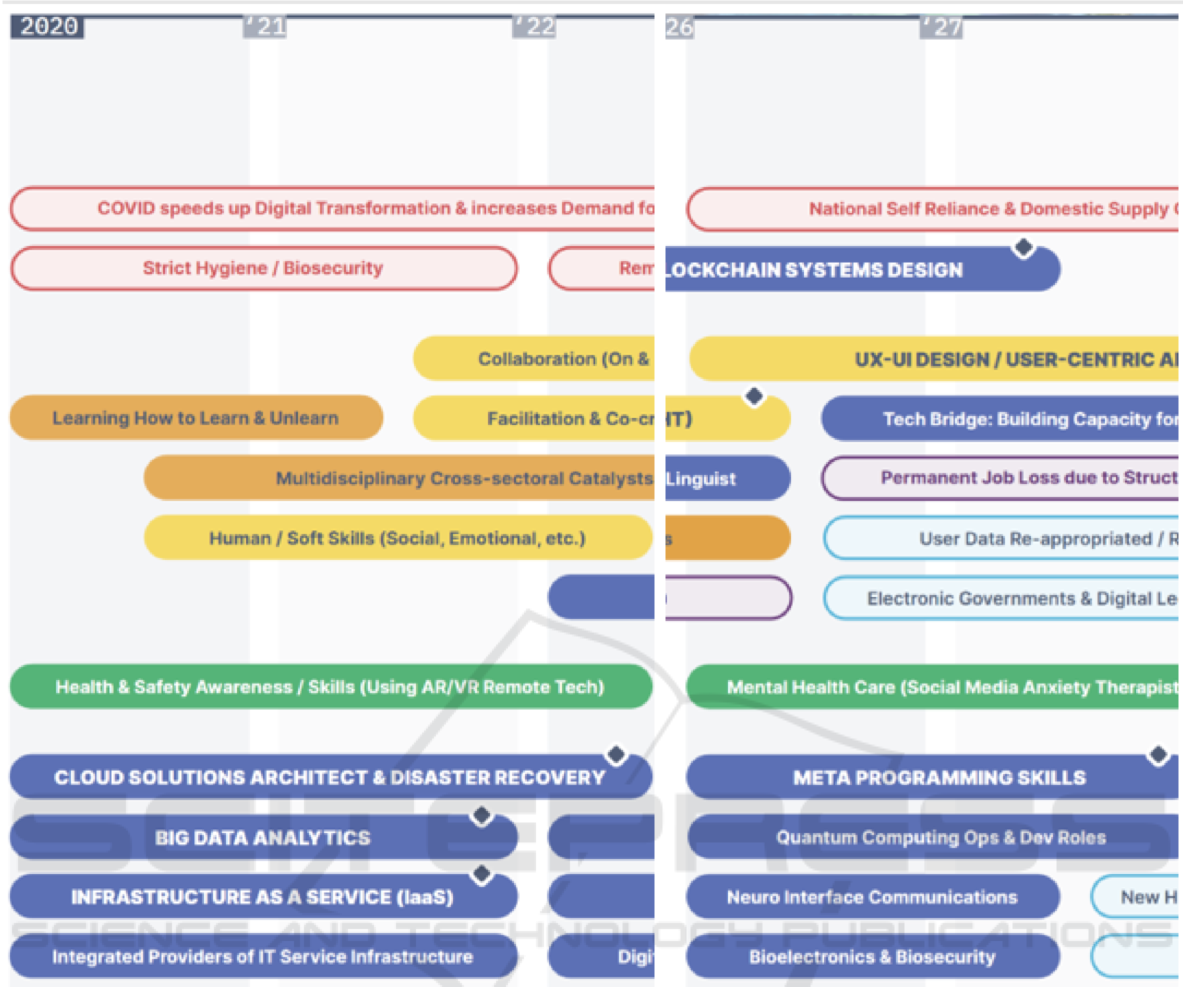

Figure 2: Forecast of the time of mass demand for skills from quantum technologies for WorldSkills (WS, 2020, p. 121).

entists;

- quantum computerization (availability of quantum computers and other quantum equipment);
- free access to quantum computers;
- world experience in “quantum transformation” of the school informatics;
- pre-professional training in quantum informatics.

To substantiate the feasibility of introducing the basics of quantum informatics into educational programs of secondary general education institutions, To find out the state of awareness of teachers in the field of quantum technologies and readiness to teach an elective course (or a course of their choice) to lyceum students we have studied the opinion (conducted an interview) of teachers of informatics in secondary general education institutions. The survey involved 26 IT teachers who teach chemistry, labor and technology, and mathematics at the same time.

100% of respondents supported the opinion that secondary education should provide up-to-date knowledge and take into account the modern achievements of the industry when studying the disciplines. All survey participants indicated that they use moderate technologies when teaching their subject (65.4% – always, 34.6% – only during distance learning).

96.2% of respondents agree that the educational material (in particular, quantum informatics) should be adapted according to the age of the students.

96.2% of the respondents indicated that they would be pleased with the introduction of new sections and topics to the discipline curriculum, especially if sufficient methodological support is available.

The responses of the respondents indicate that 88.5% would like to take the course “Fundamentals of Quantum Informatics”, and 38.5% of them noted that they have encountered a lot of publications on this topic and were interested in it.

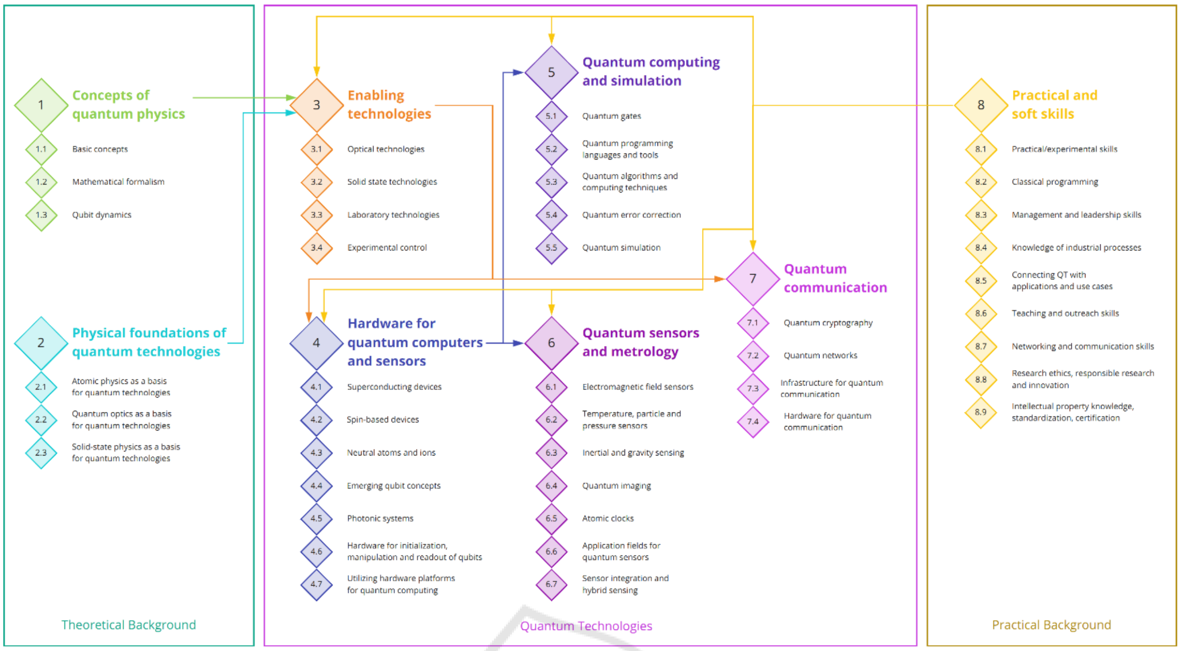

Figure 3: General structure of Competence Framework for Quantum Technologies (Greinert and Müller, 2021).

61.6% of respondents responded positively to the question “Would you offer the course “Fundamentals of Quantum Informatics” for students at your school? 23.1% refused because, in their opinion, this course would not meet the profile of the educational institution where they work. Only 3.8% said no.

The survey indicates that teachers follow new trends in the field and are ready to teach modern and relevant courses in their institutions. As for the implementation of the basics of quantum informatics for lyceum students, the teachers expressed their support for such implementation due to the presence of a corresponding course for teachers and methodological support.

The content block of the model of competence formation in the basics of quantum informatics as a corresponding normative teaching methodology reflects the main content of competence formation in the basics of quantum informatics.

The content block of the model depicts the main content of the competence formation in the fundamentals of quantum informatics:

- European framework of competences for quantum technologies (see section 2.3);
- State educational standards;
- content of informatics curriculum;
- expert selection.

Analysis of the development of methodological systems of teaching informatics (from 1985 and up to now, with the consolidation of four stages) showed that content of teaching school informatics expanded from algorithms and programming through the knowledge of information and information and communication technologies to informatics as a basis for STEM integration.

In order to clarify the content and recommendations for teaching the basics of quantum informatics to lyceums students, to determine the importance of the European framework of competencies for quantum technologies, an interview was conducted among those who are interested in the field of quantum technologies. 36 respondents took part in the survey, some of them combining several positions, such as university teacher and researcher or university teacher and school teacher.

The analysis of the evaluation results (taking into account the competence level of the participant of the expert survey – “have a basic idea” (1), “know with some components” (2), “deeply know with some components” (3), “expert” (4)) has allowed to specify the content of teaching the basics of quantum informatics of the lyceum students and the system of corresponding competences (which included, first of all, those components (knowledge and skills), calculated parameters of which exceeded the specified threshold value).

The first group of competencies “Competencies in the physical foundations of quantum technologies” includes:

- knowledge of the basic understanding of quantum

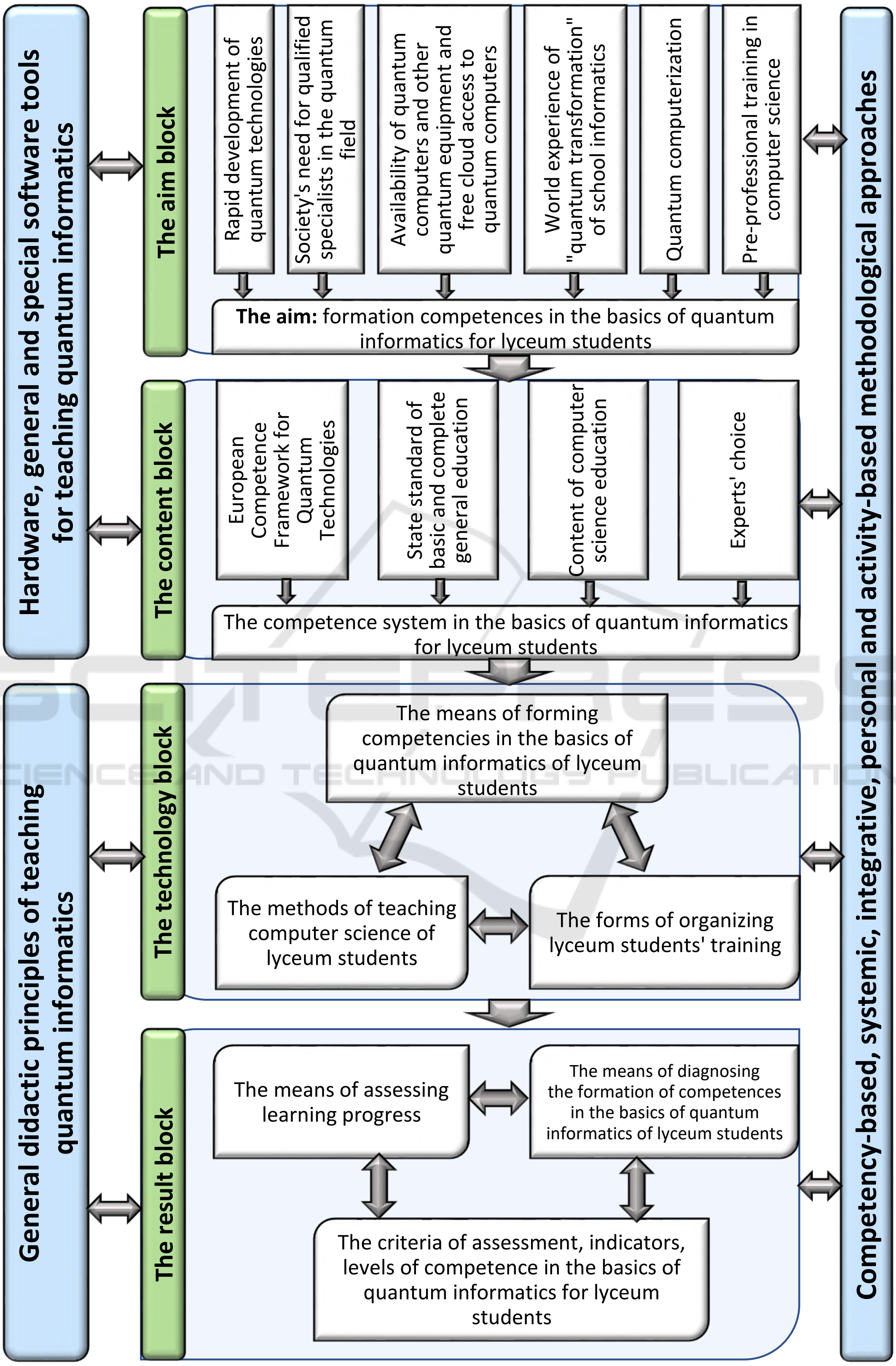

Figure 4: Structural-functional model of competence formation in the basics of quantum informatics.

physics;

- skill to determine whether qubits are in binded states;
- skill to represent qubits on a Bloch sphere.

The second group of competencies "Competencies in mathematical foundations of quantum informatics" includes:

- knowledge of the fundamentals of the theory of complex numbers;
- knowledge of linear algebra fundamentals;
- knowledge of quantum physics mathematical fundamentals;
- knowledge of statistical nature of quantum measurements;
- skill to design vectors (matrix-columns, matrix-rows) of Dirac notation;
- skill to operate with standard bases;
- skill to arrange a vector in a selected basis;
- skill of giving examples of unitary matrices and performing operations with them.

The third group of competencies "Competencies in support technologies" includes:

- knowledge of optical technologies;
- knowledge of laboratory technologies;
- knowledge of experimental control;
- skill to separate photon sources.

The fourth group of competences "Competences in hardware of quantum computers and sensors" includes:

- knowledge of the structure of spin-based devices (in particular, quantum dots);
- knowledge of hardware platforms for quantum computing, methods of their integration with standard equipment;
- skill to describe types of quantum structures of quantum computers and explain their general principles of operation;
- skill to arrange remote access to quantum computers;
- skill to perform quantum programs on quantum computers.

The fifth group of competences "Competences in quantum calculations and modelling" includes:

- knowledge of quantum gates (single-, double- and multi-qubits);
- knowledge of quantum programming languages, tools for development of quantum software and platforms (including graphical ones);
- knowledge of basic quantum algorithms (Shore, Grover, quantum optimization, quantum phase evaluation, quantum linear algebra, etc.);
- skill to record quantum gates by means of unitary matrices;
- skill to separate and use single-cube gates (Pauli transubstantiation, Adamar gate, phase tensions);
- skill to perform operations using multi-qubit gates (CNOT, Toffoli and Fredkin gates);
- skill to use quantum gates for writing quantum algorithms;
- skill to use quantum programming languages and tools;
- skill to implement quantum algorithms (Shore, Grover etc.);
- skill to work with quantum simulators.

The sixth group of competencies "Competencies in quantum sensors and metrology" includes the following:

- knowledge of the quantum sensors applications;
- skill to guide examples of quantum sensors application in various fields.

The seventh group of competencies "Competencies in quantum communication" includes:

- knowledge of quantum cryptography (quantum key distribution, secure authentication, digital signatures, use halls);
- knowledge of quantum networks (quantum internet, sensor and dinode networks);
- knowledge of quantum communications infrastructure and equipment (fiber optic systems, wireless links, satellite systems; quantum random number generators; quantum memory, interfaces, switches; repeaters, terminal nodes);
- skill to describe the operating principles and structure of quantum network equipment;
- skill to give examples of application of quantum cryptography in various fields.

The eighth group of competences "Practical skills and general competences" includes

- knowledge of classical (non-quantum) programming basics: programming languages, algorithms, complexity classes, cryptography;
- knowledge of quantum technologies application;

- skill to implement algorithms of basic complexity classes (in particular, cryptographic algorithms) using programming languages;
- skill to give examples of using quantum algorithms to achieve quantum advantages.

3.3 Teaching Methodology the Basics of Quantum Informatics to Lyceums Students

Experimental realization of the structural-functional model of forming competences on quantum informatics basics is carried out within the optional course "The Basics of Quantum Informatics" for students of 10 (11) grades. The course content is represented by three subject content lines – "Physical and mathematical foundations of quantum informatics", "Quantum computing, algorithms and programming" and "Quantum telecommunication technologies".

Content line "Physical and mathematical foundations of quantum informatics" reveals fundamental physical and mathematical aspects of quantum technique functioning, demonstrates physical realization of microscience phenomena described mathematically.

The conceptual apparatus of the content line "Physical and mathematical foundations of quantum informatics" – quantum physics, quantum, photon, superposition principle, quantum entanglement, tunneling, singularity principle, quantum teleportation, chiral function, interference, diffraction coherence, decoherence, quantum computer, qubit (quantum bit), bracket notation, complex numbers, Bloch sphere.

Here are formulations of concepts, which should be mastered by students in classes on fundamentals of quantum informatics:

- Quantum physics (quantum mechanics) is a science that studies laws of microcosm and describes phenomena at microparticle level (molecules, atoms, electrons, photons, etc.).
- A quantum is an indivisible microparticle, a portion of some quantity (energy, light, etc.).
- Photon (quantum of light) is the elementary particle of which light consists.
- The principle of superposition consists in the ability of a microparticle to be in different states of the same set of characteristics at the same time.
- Quantum entanglement – microcosm phenomenon meaning dependence of microparticles on each other regardless of distance between them.
- Tunneling – ability of microparticles to pass through a barrier. A microparticle can undercut a barrier, "overcome" it or pass through it.
- The singularity principle was formulated by W. Heisenberg and consists in the fact that it is impossible to measure simultaneously coordinates and momentum of a microparticle with a certain accuracy.
- Quantum teleportation is an ultra-fast (on average) transfer of states from one microparticle to another. Quantum teleportation is not transportation or any other physical movement of a microparticle from one place to another.
- Quantum function (state vector) is a quantity, which completely describes a state of a microparticle or quantum system as a whole. Quantum function determines not physical parameters, but approximate law of microparticle state distribution.
- Wave interference is a phenomenon that occurs when two waves arising in the same medium come in contact with each other.
- Diffraction – the ability of waves to ignore imperfections.
- Coherence – coherence of several colival or chiral processes in time, which occurs when they overlap each other.
- Decoherence – incoherence of several colival or chiral processes in time, which is found when they are added to each other.
- Quantum computer – computing device, using quantum superposition and quantum multiplicity phenomena to transmit and process data.
- Qubit (quantum bit) is the most important element for data storage in quantum computers. A qubit is a quantum object with two basic structures, for example: electron spin, photon, neutral atom or ion. Mathematical model of a qubit state is a single two-dimensional vector.

The competence in the basics of linear algebra includes understanding not only the concept of vectors but also matrices, as well as the basic operations over matrices (addition, matrix multiplication by number, usual matrix multiplication, tensor matrix multiplication).

At this stage, students must understand that a vector can be represented algebraically – in the form of a linear (vertical or horizontal) table of numbers or geometrically – in the form of a tensed frame. Vector column, which represents the state of the cube, is a certain table of numbers with one column and two rows. Further, it is worth explaining that there can be several columns and rows of numbers. Such a table of numbers arranged in rows and columns is a matrix. The number of rows and columns determines the matrix size. Vector columns or vector rows are separate (partial) kinds of matrices.

The next step will be to familiarize students with the actions on matrices. We draw students' attention to the fact that matrix multiplication by a number (scalar) is carried out by multiplying each element of the matrix by the required number (scalar). Demonstration of the application of vector multiplication by a number and matrix multiplication by a number.

Explanation of the operation of conventional matrix-to-matrix multiplication begins with matrix-to-vector multiplication, emphasizing that multiplication can be applied only to matrices in which the number of columns of the first matrix and the rows of the second matrix are identical. The result of multiplication is a dimension matrix equal to the number of rows of the first matrix and the number of columns of the second matrix. The elements of the result matrix are the sum of pairwise additions of the elements of the row of the first matrix to the elements of the corresponding column of the second matrix. To multiply a matrix by a vector, each matrix row should be elementally multiplied by the value of the vector.

In the case of a matrix with three (or more) rows and columns, the multiplication technique is analogous.

It is advisable to offer students examples of square matrices and vectors whose elements are exclusively zeros and ones, both for manual (written) execution and using the capabilities of a table processor (and/ or a universal computer mathematics system or programming language) for self-multiplication.

Then students should explain that quantum computing theory uses tensor multiplication of vectors (matrices), which is used to multiply vectors (matrices) of sufficient size. Students must learn that for tensor multiplication two steps are necessary:

1) scalar multiplication of each element of the first matrix by another matrix;
2) to combine the obtained matrices according to the output positions of these elements.

At first, students can find examples of tensor multiplication of vectors. As a practical task, students may be presented with the task of realizing tensor multiplication with the help of a table processor (or/and a universal system of computer mathematics or programming language) for two and three vectors. The following is an application of tensor multiplication of matrices.

Formation of competence in mathematical foundations of quantum informatics is based on knowledge of statistical nature of quantum measurements. Microparticle structures described by the Quantum function have a statistical, i.e., luminescent, nature: the square of the absolute value (module) of the Quantum function indicates the luminescence value of those quantities, on which the Quantum function is dependent.

Before starting to get acquainted with quantum gates (actions that can be performed over cubes), it is necessary to consider the notion of unitary matrix (a special numerical square matrix, elements of which are real or complex numbers, and the result of their multiplication by the Hermite-conjugate matrix is equal to the unity of matrix E), explaining the terms used in the formula. Namely, the square matrix (matrix in which the number of rows is equal to the number of columns), the Hermite-conjugate matrix (the A+ matrix obtained from the A matrix by transposition and replacement of each element with a complex-conjugate one), singular matrix (diagonal matrix, diagonal elements of which are equal to one), diagonal matrix (square matrix, posterior diagonal elements of which are equal to zero). The notion of unitary matrix is suitable to show on two examples – in the first application, we will use matrix with real-integer elements, and in the second – matrix with complex numerical elements.

Methods of teaching the content line "Physical and mathematical foundations of quantum informatics" can be revised, expanded with additional explanations, or shortened, taking into account the training of scientists in mathematics and physics.

Within the framework of the content line "Quantum computing, algorithmization and programming" the competences in hardware of quantum computers and sensors, quantum metrology, competences in quantum computing and modeling are formed and/or developed, first of all, Formation of knowledge and skills to distinguish and use quantum single- and large-cube gates for recording quantum algorithms, use platforms for implementation of quantum algorithms in the form of schemes and programs on quantum simulators and real quantum equipment.

It is advisable to start studying this content line by looking at the structure of a quantum computer and then move to the issue of providing special conditions for their functioning:

- temperature control (close to absolute zero);
- insulation against magnetic, electric and thermal fluctuations, vibrations;
- air dissipation lower than the atmospheric pressure by billions of times.

Further it is advisable to acquaint students with hardware platforms for quantum computing, ways to integrate them with the classical equipment using quantum simulators and computers of IBM, Microsoft, Google, Intel, QuTech and others.

We suggest that competence development in remote access to quantum computers should be based on the IBM Quantum platform, focusing on the specifics of selecting a simulator or quantum computer in graphical (IBM Quantum Composer) and software (IBM Quantum Lab) modes.

The skill to perform quantum programs on quantum computers should be formed starting with simple tasks on using quantum gates to change the state of a quantum system. And then proceed to implementation of quantum algorithms (Bernstein-Vazirani, Deutsch-Jozsa, Grover, Shore).

When introducing the concept of "quantum gates" (basic logical elements/operations for a quantum computer), it is important to pay attention of students, that the understanding of quantum gates is similar to the understanding of gates (logical elements, operations) of a classical computer, and therefore it is necessary to use the previous knowledge about logical operations.

Students must learn that the same logical operations are performed on qubits in order to change their state as on classic bits. It is necessary to consider mathematical representation of each gate (in the form of unitary matrix) and their graphical representation and result of quantum scheme application at the same time.

The interface of the IBM Quantum Composer chromatically oriented service should be considered in a mandatory order, focusing on the instrumental panel of quantum operations, peculiarities of color categorization of gates by type, adding, setting up and disconnecting of quantum gates in the Quantum Scheme Editor area, reviewing changes in the state of qubits.

One should start from one-qubit quantum gates as the simplest, and then go to two- and three-qubit gates. At this stage, students' attention is necessarily focused on the result, which is reflected in the form of the state vector. It is necessary to explain that the received record of the state of qubits in the twofold code is read from right to left. In our application, the result obtained is 01: the zero qubit has a value of 1 and the first one is 0. If there is time, we can ask the students to use a few more cubes on the diagram one after another to observe the display of the results.

After familiarization with basic operations on qubits you can move on to introduction of quantum algorithms, starting with quantum teleportation algorithm. First students are offered a verbal description of the algorithm, then a graphical quantum circuit, and after that a software implementation of the algorithm.

Let us give a verbal description of the quantum teleportation algorithm, which is described graphically using the IBM Quantum Composer service, shown in figure 5:

1) by means of the operation NOT we transfer the zero qubit to state 1, and we leave the first and second qubits in the primary zero state. It should be noted that this operation is mandatory for this example, only to avoid transferring the zero value of the qubit. Indeed, the zero qubit
2) we put the first qubit into superposition by the gate H;
3) we rotate the first and second qubits with the CNOT gates (the first one is control and the second one is purpose. If the control (first) qubit is in state 1, the main (second) qubit is inverted by the CNOT gate);
4) we will similarly loop the zero and first qubits;
5) convert the zero qubit to superposition (using gate H);
6) measurement of the zero and the first qubits (Measurement operation). The measurement results are stored in two classic bits, which are transmitted by the usual (classic, non-quantum) way of communication (channel, protocol);
7) on the side where the zero qubit status is transmitted, there is another qubit to which CX and CZ gates are used (either CX or CZ in turn does not matter which will be the first), as a result we get the value of zero qubit in the other qubit;
8) we measure the value of the other qubit.

After creating the algorithm for quantum teleportation in IBM Quantum Composer, students should be given the task of running this scheme with the help of a simulator or a quantum computer and analyze the results. At this point, it is appropriate to encourage students to focus on automatically generated code in a programming language (e.g., Python). Students should conclude that the resulting code is fully consistent with the structure of the reverse language program. It would be useful to make an analogy between the graphical representation of the gates and their equivalent – the corresponding command (method) in programming language and open this scheme with automatically generated code in IBM Quantum Lab.

After acquiring knowledge about the basic quantum gates, creating a quantum teleportation circuit,

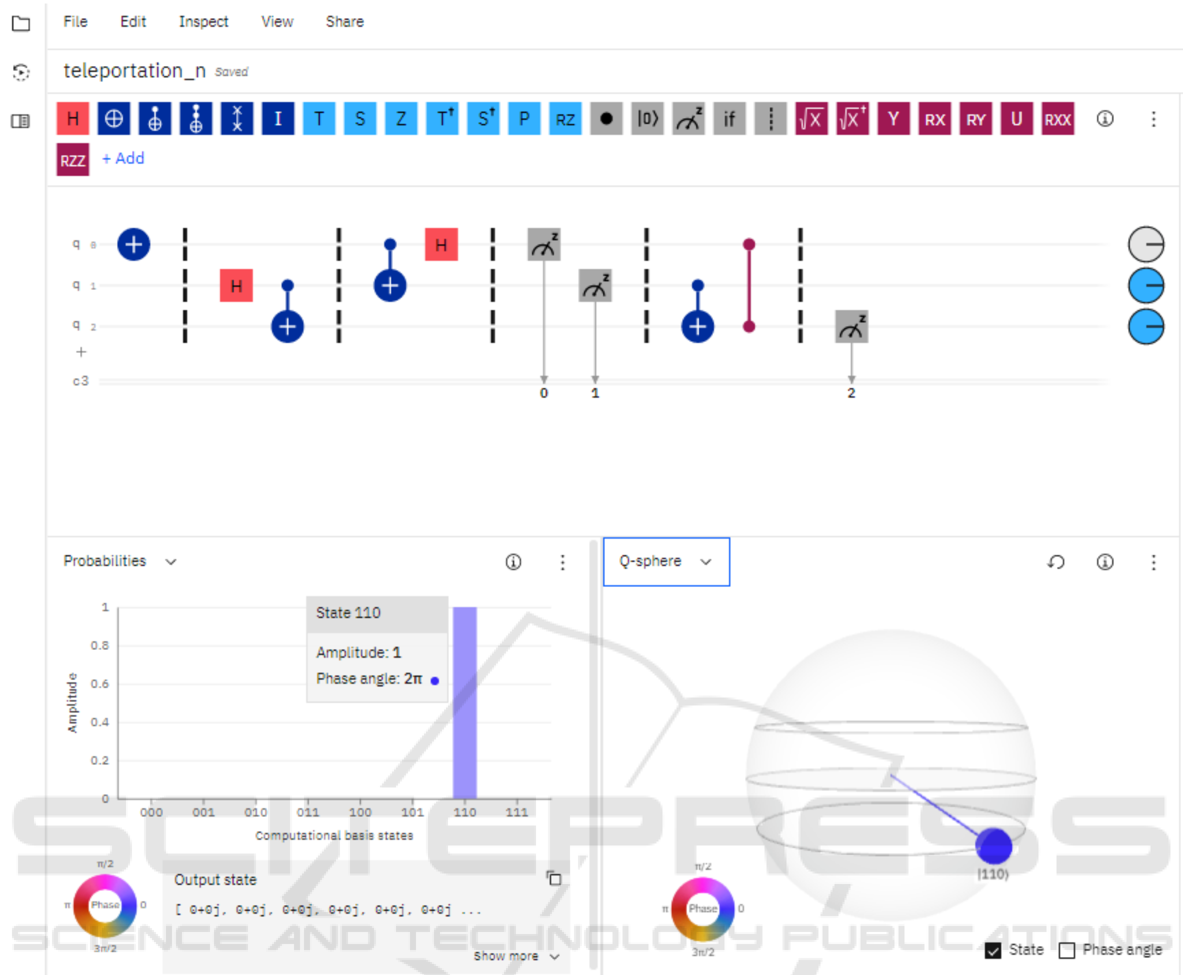

Figure 5: Quantum teleportation algorithm in IBM Quantum Composer

the students are ready to proceed to the next stage of learning the basics of quantum informatics – to implement quantum algorithms in programming language, within the framework of which the formation of knowledge and skills to distinguish and use quantum one-, two- and three-cube gates for the implementation of quantum algorithms in programming language (Python), use online programming services, which support Python work with Qiskit module, for the implementation of quantum algorithms on quantum simulators and real quantum equipment.

The basic foundation for the teaching methodology of this section is the knowledge of the basics of classical (non-quantum) programming and the ability to implement basic classical algorithms in programming language.

This is a dedicated platform for working with quantum algorithms (IBM Quantum) that provides their implementation in Python language. Therefore, it is methodologically appropriate to repeat the basics of structural programming in Python.

Despite the lack of experience of students in the implementation of Python programs with the help of Jupyter Notebook, it is obvious, that before starting to implement quantum algorithms using the IBM Quantum Lab server it is necessary to familiarize students with the peculiarities of their writing and launching, for example, using the online service Google Colab (https://colab.research.google.com/).

After implementing and launching the application programs by means of the online service Google Colab, it is advisable for the students to propose the automatically generated code for the implementation of the quantum teleportation algorithm in IBM Quantum Lab. It is necessary to ask the students: What is similar in the interface of Google Colab and IBM Quantum Lab online services? We make a joint conclusion about the uniqueness of these environments and proceed to consider the features of the connection to the quantum simulators and computers in IBM Quantum

Lab on the requested code fragments.

It should be noted that after completing the content line “Quantum calculations, algorithmization and programming” students will be able not only to learn about the most popular algorithms of quantum programming and try to learn how to implement them on real quantum equipment, but also to improve competence in the basics of programming in Python.

Within the framework of the content line “Quantum telecommunication technologies” the formation of competencies in security technologies (optical technologies, laboratory and experimental control technologies, photon sources) and quantum communication technologies (quantum cryptography, quantum networks, quantum communication infrastructure and equipment).

Formation of competences from the enabling technologies can be carried out in the form of short self-prepared student reports on the topics suggested by the teacher, or in the form of watching short popular science stories that reflect the current state of development of the field.

It is important for students to know about the limitation of quantum communications. The teacher states that the main limitations of quantum cryptography are the speed of key distribution and the distance between the transmitter and the receiver. This problem is trying to be solved by modern physicists who have proposed new protocols, new optical circuits, new methods of quantum-state measurements.

It is also necessary to tell the students that an important task of quantum communication channel quality is to reduce the number of errors (the critical error rate is 11%). Students should know that the greater the distance over which a quantum key is transmitted, the greater the attenuation of the signal in the fiber optic lines, while the noise remains. Because of this, it is not possible to transmit information for hundreds of kilometers in real fiber optic lines.

It will be useful to remember the previously discussed phenomenon of decoherence (disintegration of quantum state due to interaction of quantum system with ambient environment). The teacher can describe that photons after transmission through many kilometers of real fiber optic lines in most cases cease to be quantum entangled (connected) and transform into usual, not interconnected, quanta of light. Therefore, in order to produce efficient fiber optic line it is necessary to ensure preservation of quantum entanglement when the signal is weakened and when it passes through an amplifier. Fibre optic cables laid at the bottom of the oceans contain a number of special amplifiers based on optical warehouse of rare-earth element houses, and these amplifiers make high quality transmission of information possible.

It is worthwhile to find some examples of quantum cryptography application spheres that would motivate further study. It is worthwhile to make an example that today world’s bank data centers have encryptors that use symmetric keys. They are additionally complemented by quantum distribution systems for keys, which are changed not monthly (in the classical approach), but every second. On the one hand, this mechanism is not good for the disposable notebook, but on the other hand, it gives tremendous advantage.

You can ask students to use any search engine to find information about the use of quantum technologies in the field of finance, for example, for the last six months. If a sufficient number of students work, the task can be refined by geographical location (on certain continents, in certain countries, etc.).

It will be interesting for students to learn that quantum cryptography can also be used for distributed data storage. It is possible to distribute information in several data centers and constantly move it by means of quantum-secured channels. Thus, even if someone gains access to some of these data centers, he or she does not receive all of the necessary information. This will also work if some of the data centers are disconnected: a light user will be able, by authenticating to the network of data centers, to restore all relevant information.

We also inform the students that quantum keys will be useful for securing authentication tasks, which, in essence, is a check “friend-or-foe”. In this case, the combination of hash function technologies and a one-time notepad allows you to check if, for example, the data for the online speech system came from the control center or from someone else. This is very important, because in five or seven years the work of quantum computer is a reality. At the same time on the streets will appear a large number of driverless cars, which are not just a few, but will be millions. And all of them will need to receive control signals and update the firmware in a trusted manner, not interacting with people for thousands of years. This means that they will have to receive quantum keys and use them afterwards in the process of flight.

Prospects of quantum cryptography can be described by the application of China, which has already established a national quantum network that connects Beijing, Shanghai, Hefei and Jinan.

The main technological problem nowadays is whether the humanity will be able to produce a high-quality quantum repeater in the nearest ten years? This question can be discussed by the scientists by dividing them into supporters and opponents of this idea.

4 EXPERIMENTAL TESTING OF METHODS FOR TEACHING THE BASICS OF QUANTUM INFORMATICS TO LYCEUMS STUDENTS

Forty-five students from three schools in the city of Kryvyi Rih (Ukraine) took part in the experiment. In order to evaluate the level of competence in the fundamentals of quantum informatics the entrance examination and post-assessment test were conducted.

Positive dynamics of changes in the level of competence was noted in each group of competencies, which confirmed the study hypothesis.

As a result of the experiment the ways of introduction of quantum informatics basics into the educational process of lyceums were determined:

1. choice module "The Basics of Quantum Informatics" (17 hours);
2. cross-curricular study of quantum informatics basics in physics, mathematics and informatics courses (17 hours);
3. integrated course "The Basics of Quantum Informatics" (35 hours).

Regardless of the choice of experimental model of propaedeutic study of quantum informatics, the main goal of its implementation is to develop the components of computer literacy and information culture through the acquisition of basic theoretical knowledge and practical skills to manage quantum computers as a new generation of computers.

5 CONCLUSIONS

Quantum transformation of school informatics course should be carried out due to the perspective of quantum technologies and the demand for quantum-literate specialists.

The competences of quantum informatics basics of lyceums students is a natural integration of some interdisciplinary physical and mathematical competences and new subject-specific informatics competences.

The normative methods of teaching the basics of quantum informatics to lyceum students is the structural-functional model of forming the corresponding competences.

Teaching the basics of quantum informatics to 10 (11) grades on the IBM Quantum platform can be carried out with the author's optional course materials.

This study does not cover all aspects of the problem of quantum transformation of informatics education. Subsequent scientific searches for its solution are appropriate in the following directions: 1) development of partial methods of competence formation in the field of quantum technologies in accordance with the European framework; 2) integrated teaching of quantum physics and informatics to students of scientific lyceums; 3) use of immersive medium for development of virtual manipulatives of quantum technologies; 4) teaching method development of the basics of quantum technologies to professional schools students.

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