Prospects of Quantum Informatics and the Study of Its Basics in the School Course

Liudmyla V. Lehka[1][a], Andrii O. Bielinskyi[1][b], Svitlana V. Shokaliuk[1][c], Vladimir N. Soloviev[1][d], Pavlo V. Merzlykin[1][e] and Yelyzaveta Yu. Bohunenko[1]

[1]*Kryvyi Rih State Pedagogical University, 54 Gagarin Ave., Kryvyi Rih, 50086, Ukraine*

Keywords: Quantum Calculations, Quantum Computer, Quantum Circuit, Quantum Algorithm, IBM Quantum Experience, Python, Jupyter Notebook.

Abstract: The purpose of this study is to review the main points of the experimental content of the basics of quantum computer science adapted for lyceum students, based on the prospects of the quantum approach to information processing for ultra-fast calculations in modeling objects of complex dynamical systems. In addition, software tools and Internet services are offered to organize effective training.

1 INTRODUCTION

According to experts, the modern IT market is in the initial state of another technological breakthrough due to integration (interpenetration, convergence) of 1) nanotechnologies (the ability to control matter at the atomic level), 2) biotechnologies (the ability to manipulate genes and genetic information), 3) information technologies (the use of communication and communication tools) and 4) cognitive technologies (the study of the fundamental essence of thought processes and their mechanisms) (Sigov et al., 2019).

The capabilities of modern supercomputers ("computers of classical architecture", "classical computer") are no longer enough for efficient processing of large amounts of data during modeling of nanoobjects, biogenetic systems, cognitive processes, and other phenomena. It is felt that the development of transistor computers has almost reached its limit and that Moore's Law, which consists in doubling the computer power every one and a half to two years, will soon cease to hold since the size of transistors will stop decreasing every 18 months (Rotman, 2020; Fog, 2015; Al-Kilani and Umkeeva, 2016). A quantum approach has a significant potential for data processing (information), for increasing the productivity of cumbersome and secure calculations, for reliable storage of their results in scientific fields, in logistics, safe trade, and finance, i.e. new computer science – quantum information science, or quantum informatics.

Quantum informatics (as a new branch of science, the subject of which is the theory and practice of using quantum objects for transmission and procession of quantum information), in addition to quantum information theory and quantum algorithms, includes physics and mathematics of quantum computers, problems of decoherence description, measurement problems, issues of quantum cryptography, simulation modeling of quantum systems, quantum intelligence, etc.

Leading IT companies, in particular, IBM (since 2016), Intel (since 2017), and Microsoft offer free access to experimental models of next-generation computers as an Internet service (IBM, 2021; Microsoft, 2021; Amazon, 2021) to all interested parties. However, school computer science course, which is updated every 3–5 years, does not address at all either the general principles of functioning of quantum computers and the peculiarities of their management or the fundamental principles of quantum computer science.

Taking into account the prospects of quantum modeling of complex systems of various nature, particularly cryptographic, chemical, and economic (Ackerman, 2021; YouTube, 2020, 2019), we con-

[a] https://orcid.org/0000-0001-5768-5475
[b] https://orcid.org/0000-0002-2821-2895
[c] https://orcid.org/0000-0003-3774-1729
[d] https://orcid.org/0000-0002-4945-202X
[e] https://orcid.org/0000-0002-0752-411X

Lehka, L., Bielinskyi, A., Shokaliuk, S., Soloviev, V., Merzlykin, P. and Bohunenko, Y.
Prospects of Quantum Informatics and the Study of Its Basics in the School Course.
DOI: 10.5220/0010922900003364
In *Proceedings of the 1st Symposium on Advances in Educational Technology (AET 2020) - Volume 1*, pages 233-240
ISBN: 978-989-758-558-6

sider it appropriate and possible to generalize, systematize, and adapt the basics of quantum informatics for mastering it by lyceum students.

2 RESULTS AND DISCUSSION

The study of the basics of quantum informatics and programming is proposed to be organized either within the framework of a new (experimental) sample module of the same name – "Fundamentals of Quantum Informatics and Programming" – a standard-level program for pupils of 10-11th grades, or, in an extended version, within the framework of the same elective course, the amount of study hours is 17 and 35, respectively.

The purpose of teaching the sample module (elective course) "Fundamentals of Quantum Informatics and Programming" (table 1) there should be the development of the components of computer literacy and information culture of lyceum students through the acquisition of basic theoretical knowledge and practical skills to manage quantum computers as new generation computers.

To achieve this goal (according to the content presented in table 1), it is planned to solve the following tasks:

- to form the concepts of "quantum computer", "qubit", "quantum superposition", "quantum logic gate", "quantum algorithm", "quantum circuit", "quantum entanglement", "quantum programming language", etc.;
- to acquaint with the history of formation, the current state, and development prospects of quantum informatics;
- to introduce physical and mathematical foundations of quantum computing;
- to study the potential and determine the advantages of quantum computers for solving individual applied problems, modeling problems of complex systems of various nature, etc.;
- teach the pupils to implement basic quantum algorithms in special and universal environments with remote and local access.

The expected results of mastering the educational material of the first three lessons – "Digital technologies: history of formation, current state, development prospects", "Basics of classical computer arithmetic", and "Basics of classical computer logic" are as follows:

- student explains the concepts of digital technologies, classical computers, processor and memory of a classic computer; number system, number system alphabet, basis of the positional number system; binary message code, length of binary message code, units of measurement for the length of binary message code;
- student knows the quantum computer definition, general principles of its structure and functioning, and the peculiarities of its using;
- student understands the typical architecture of a classic computer and the general principles of its operation;
- student names the units of measurement of the length of the binary message code (bits, bytes, kilobytes, megabytes, gigabytes, terabytes);
- student describes the general principles of operation of the processor and internal storage devices;
- student is able to convert natural numbers from decimal to binary and vice versa; determine the length of the binary message code; arithmetic addition and multiplication of binary numbers; logical operations not, and, or, xor over binary numbers;
- student is aware of the role of existing (classical) digital technologies and the significance of their development prospects.

In particular, a quantum computer should be understood as a computing device which CPU is based on the logic of quantum mechanics. Such a computer is fundamentally different from a classical computer (a computer of the von Neumann architecture) and uses for calculations not classical algorithms of the macrocosm, but algorithms of phenomena of the microcosm of quantum nature, based on quantum parallelism and quantum entanglement (connectivity) (Bernhardt, 2019).

The expected results of mastering the learning material of the next three lessons of the module – "Complex numbers fundamentals", "Working with objects of linear algebra: vectors", and "Working with objects of linear algebra: matrices" should be as follows: student

- student explains the concept of a complex number; vector, row vector (bra vector), column vector (ket vector), orthonormal basis, standard basis, linear combination (superposition) of vectors; matrix, square matrix, unit matrix, orthogonal matrix, unitary matrix;
- student knows about the Euclidean and Hilbert spaces;
- student is able to determine the real and imaginary part of a complex number written in alge-

Table 1: "Fundamentals of Quantum Informatics and Programming": draft content of the sample module (17 hours).

No	Topics
1	Digital technologies: history of formation, current state, prospects of development
2	Basics of classical computer arithmetic
3	Basics of classical computer logic
4	Complex numbers fundamentals
5	Working with linear algebra objects: vectors
6	Working with linear algebra objects: matrices
7	Key concepts of quantum computing
8	Quantum circuits and their design environments
9	Quantum NOT gate
10	Hadamard quantum gate
11	Quantum CNOT gate
12	Quantum Toffoli and Fredkin gates
13	Basic quantum algorithms and peculiarities of their implementation using a programming language
14	Quantum teleportation algorithm
15	Deutsch–Jozsa algorithm
16	Shor's algorithm
17	Grover's algorithm

braic form; perform operations on vectors (addition, scalar, and tensor multiplication, determination of coordinates in a new basis) and matrices (transposition, multiplication by a number, matrix multiplication, inversion);

- student understands the role of vector-matrix apparatus in quantum informatics.

After propaedeutics of the basics of quantum programming, it is the turn of the first main section – "Fundamentals of quantum computing using algorithms implemented in circuits". For 6 lessons students should get the following abilities:

- explain the concept of a qubit, spin, qubit state, quantum superposition, qubit measurement, qubit entanglement, quantum algorithm, quantum circuit quantum gate, purpose and content of basic quantum gates (NOT, Hadamard, CNOT, Toffoli, Fredkin);
- distinguish between reversible and irreversible operations;
- establish a correspondence between the matrix operator and the quantum gate designation in quantum circuits;
- be able to build basic quantum circuits in a special environment, use the necessary quantum gates and interpret the obtained results.

In the first lesson of the section, students should learn that the basis of quantum computing is a qubit (quantum bit). To explain the concept of "qubit", it is necessary to use the method of analogy (with the classical bit) and the ideas of quantum mechanics.

The teacher states that quantum particles have certain characteristics that can be used to describe their behavior and that can be determined in practice (and therefore implemented in quantum computers). In particular, photons have a polarization, which is determined by the behavior of the vector of their electric field; some microparticles have their own magnetic moment (spin), the projections of which on the direction of the outer magnetic layer are found experimentally (Bernhardt, 2019). The teacher recalls that the concept of bit is used in traditional calculations. It is based on the fact that technically only two states can be realized: 0 and 1 – for example, the current flows or does not flow (that is, there is a charge or there is no charge) (figure 1).

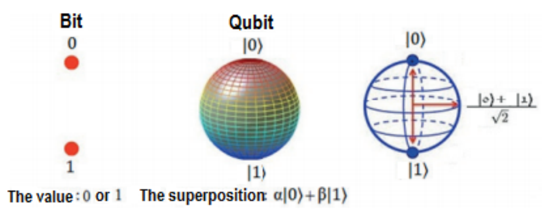

Figure 1: Qubit representation.

Talking about qubits, the teacher focuses students' attention on the fact that a qubit may have not only two states (for example, the spin of a quantum particle is located in the direction of the external field – 0 or against – 1), but also their superposition, due to the quantum nature of the phenomena of a microcosm. The superposition of the qubit states is represented graphically as a coordinate grid on a sphere, where each node corresponds to a certain state (see the central part of figure 1).

If the base states of the qubit are denoted as $|0\rangle$ (ket vector with coordinates $(1,0)$, which describes the spin direction of the quantum particle against the external field) and $|1\rangle$ (ket vector with coordinates $(0,1)$, which describes the spin direction of a quantum particle along an external field), then any other state from the set of possible states will be determined by the relation (linear combination, superposition):

$$\alpha|0\rangle + \beta|1\rangle,$$

where α and β are complex numbers that satisfy the relation $|\alpha|^2 + |\beta|^2 = 1$; $|\alpha|^2$ and $|\beta|^2$ represent probability amplitudes of transition to the states $|0\rangle$ and $|1\rangle$.

Qubits can be connected (entangled) with each other. This means that a connection can be established between them, as a result of which each time changing the state of one of several qubits, the rest change in accordance with it, and the set of entangled qubits is interpreted as a filled quantum register. Like a single qubit, the quantum register is much more complex than the classical bit register. It is able not only to be in all possible combinations of its constituent bits but also to implement subtle relationships between them, which significantly increases the computational power of systems based on qubits.

In the state of entanglement and superposition, qubits represent a quantum register. During calculations in the quantum register, the amplitudes of qubits ($|\alpha|^2$ and $|\beta|^2$) are arranged in such a way that positive values of the amplitude of one qubit neutralize the negative amplitudes of another qubit, and computational errors are canceled (positive amplitudes of qubits, on the contrary, amplify each other). This is how the scenario of getting the correct answer is formed.

Explaining the differences in the principles of classical and quantum computers, teachers turn to the problem of finding a way out of the maze, using the example of which they illustrate and convince that the classical computer consistently goes through all ways, hitting a dead end once at once, but the quantum computer can check all possible variants at once (Sigov et al., 2019). Next, teachers focus attention and interest, especially of bright and inquisitive students, on the fact that the main engineering complexity of the implementation of quantum processor registers is to maintain the state of superposition and entanglement of qubits during calculations (measurements) – coherence time.

The calculations in a quantum computer are performed using quantum algorithms. It is proposed to be understood as an algorithm containing a finite sequence of unitary (reversible) operations/gates with an indication of the qubits on which they need to be performed. The correctness of the calculation result using the corresponding quantum algorithm is determined with a certain probability. To increase the probability of getting a correct outcome in quantum algorithms, the multiplicity of operations is especially increased, which are selected in such a way that incorrect results are mutually destroyed with a high probability, and the probability of a correct result increases.

The last section – “Basic quantum algorithms and their implementation on circuits and using a programming language” – is the second main section of the sample module, because the expected results of mastering it that the student:

- knows the particularities of the implementation of quantum algorithms in an environment with remote access and a local one; the basics of the syntax of quantum algorithm implementation by a general-purpose programming language;
- understands the basic concepts of quantum algorithms;
- explains the step-by-step structure of basic quantum algorithms;
- uses the capabilities of remote and/or local access environment to implement quantum algorithms in the form of circuits and programs;
- implements and executes basic quantum algorithms in a special environment using a general-purpose programming language and the graphical editor;
- is aware of the effectiveness of quantum computing in comparison with classical ones;
- evaluates the compliance of the results of the program with the task at hand;
- follows the rules for writing readable code and comments to it, explains the code to others;
- checks, hypothesizes, critically evaluates, identifies the shortcomings of the implemented algorithms.

Problems that can be solved with the help of quantum computers can also be solved on the computational basis of classical computers. However, the advantage of quantum computers, or more precisely, quantum algorithms (Zahorodko et al., 2021), is to reduce the time spent on solving the problem by parallelizing operations through the generation of entangled quantum states and their further use. Such cases are called quantum acceleration. The application of quantum acceleration is the most advantageous when solving problems of modeling complex dynamical systems, mathematical search problems, in a particular search.

The main advantages of quantum computers and algorithms in comparison with classical ones are the effective solution of *quantum cryptography problems* and *problems of simulation modeling of quantum systems*.

To master the training material of the module/course, in particular, to acquire practical skills in the field of quantum computing, students are offered to work with universal and special software and Internet services:

1) for building the quantum circuit using drag-and-drop technology in remote mode – Circuit Composer from IBM Quantum Experience Lab (figure 2, (IBM, 2021));
2) to master the mathematical foundations of quantum calculations and the implementation of basic quantum algorithms in the local mode of Anaconda Navigator environment – the manager of packages and programming environments (figure 3);
3) for studying the mathematical foundations of quantum calculations and the implementation of basic quantum algorithms remotely using Collaborative Calculation and Data Science cloud-based educational and scientific natural information environment (CoCalc).

CoCalc (figure 4, (CoCalc, 2021)) is an entire computer lab in the cloud where:

- each student works 100% online – in their own, isolated workspace;
- you can follow the progress of each student in real-time;
- at any time you can jump into a file of a student, right where they are working;
- you can use TimeTravel to see each step a student took to get a solution;
- integrated chat rooms allow you to guide students directly where they work or discuss collected files with your teaching assistants;
- the project's activity log records exactly when and by whom a file was accessed.

The author's team is developing a set of educational and methodical materials, which includes:

- educational and methodical manual;
- collection of educational presentations;
- collection of educational video podcasts;
- electronic workbook;
- bank of test tasks.

After finishing the development of a set of educational materials adapted for students, it will be possible to move on to a large-scale experiment on studying the basics of quantum informatics and programming by the lyceum students.

A survey was conducted among computer science teachers of general secondary education institutions to study the expediency and readiness of teachers to teach the course "Fundamentals of Quantum Informatics and Programming" for lyceum students. 26 teachers of Computer Science, Chemistry, Technology, and Mathematics took part in the survey, the vast majority of them live in a city of regional subordination. The age of teachers who answered the questions was as follows: 7.7% – 25–35 years; 30.8% – 25–35 years, 42.3% – 35–45 years, 15% – 45–55 years; 3.8% – over 55 years.

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

Only one survey participant disagreed with the fact that the training material can and should be adapted according to age.

96.2% of teachers indicated that they are happy to accept the introduction of new sections and topics in the curriculum of the discipline, especially if there is sufficient and high-quality methodological support.

Responses from respondent teachers indicate that 88.5% of those who took part in the survey expressed the opinion that they would like to personally take the course "Fundamentals of Quantum Informatics and Programming", and 38.5% of them said that they had met many publications on this topic and were interested. 61.6% of teachers said that you would offer a course "Fundamentals of Quantum Informatics and Programming" for applicants for education in your institution. 23.1% refused because, in their opinion, this course would not correspond to the profile of the educational institution where they work. Only 3.8% answered "no". The survey shows that teachers follow new trends in the development of the industry and are ready to teach students in their institution modern and relevant courses. Regarding the study of "Fundamentals of Quantum Informatics and Programming" in lyceums, the interviewed teachers expressed their support for the implementation of this course if there is an appropriate course for teachers and methodological support.

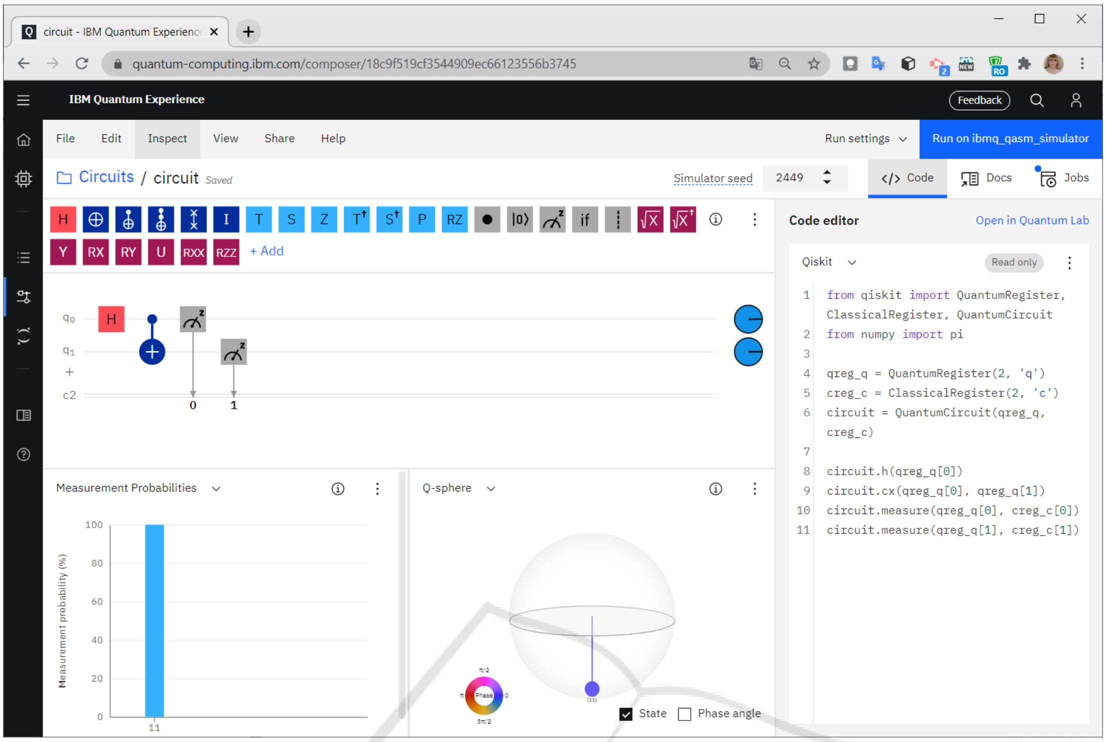

Figure 2: Page with quantum circuit composer from IBM Quantum Experience.

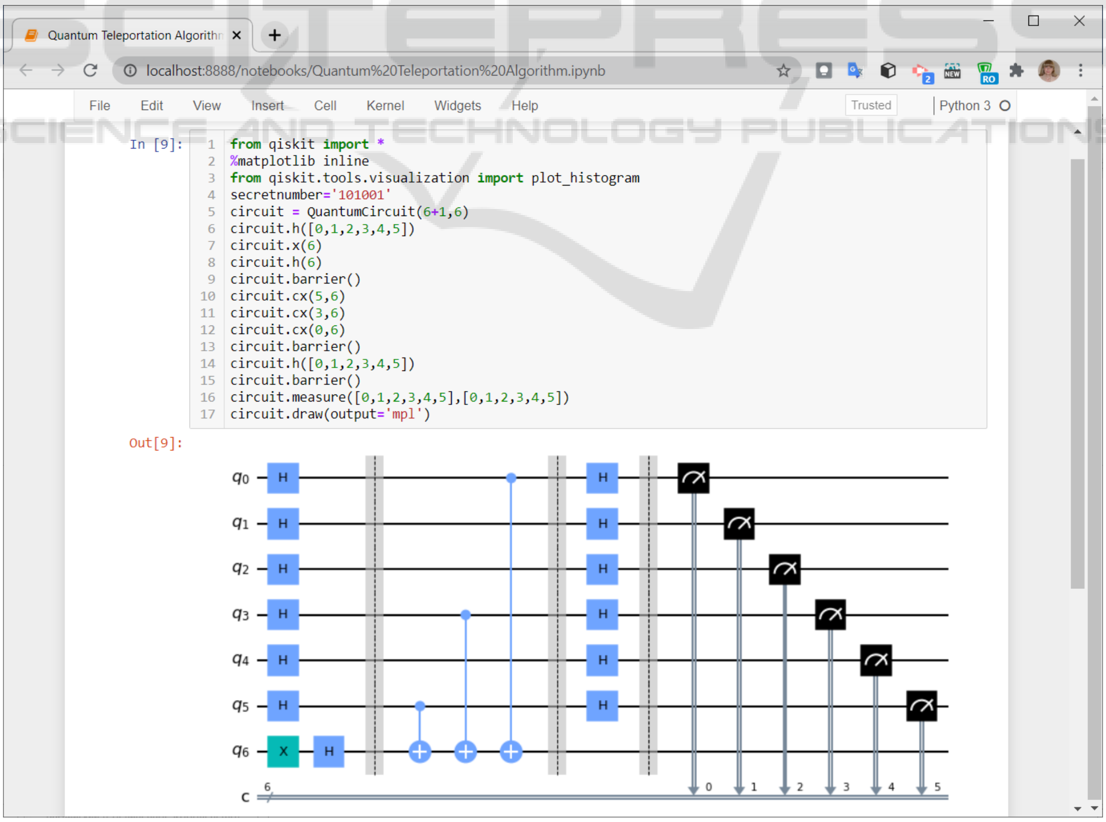

Figure 3: Jupyter notebook page in local access.

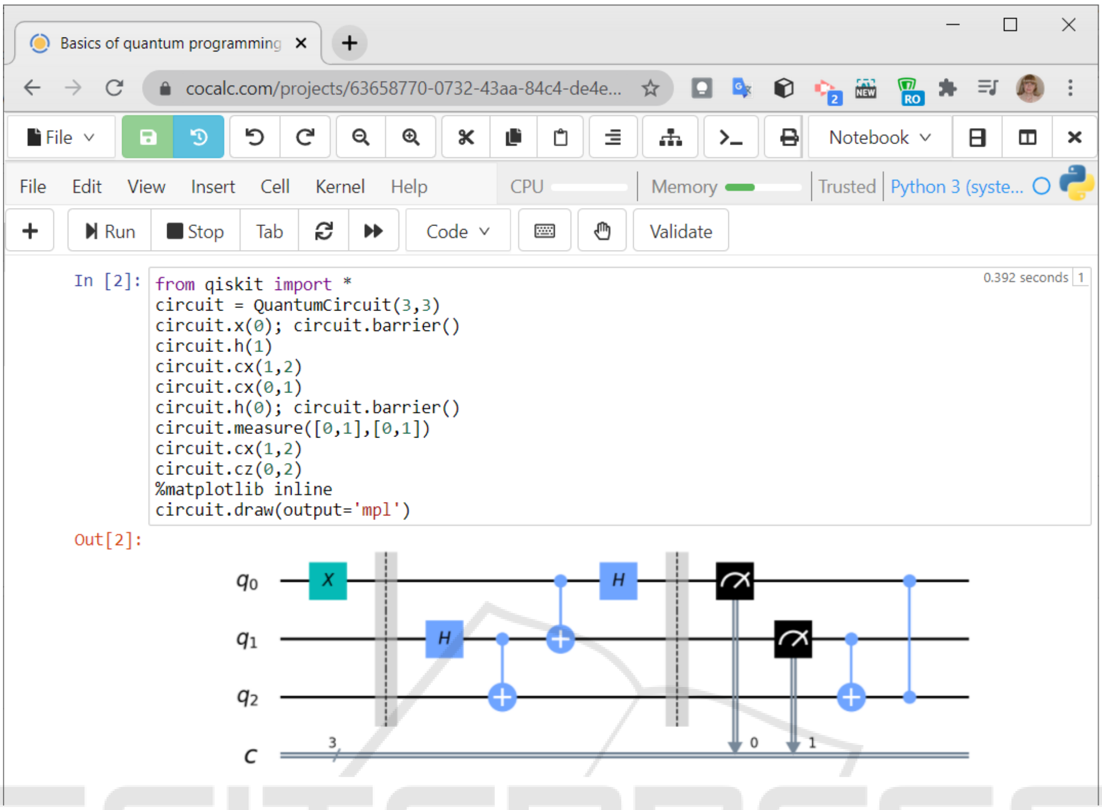

Figure 4: Jupyter notebook page in the CoCalc cloud environment.

3 CONCLUSIONS

1. The new branch of computer science – quantum computer science – has significant potential for increasing the productivity of cumbersome and secure computing, for reliable storage of their results in scientific fields, in the spheres of logistics, safe trade, and finance.
2. It is proposed to start studying the basics quantum computer science and programming in the school computer science course (obligatory-selective for students of grades 10-11) within the framework of a new (experimental) module (17 hours) according to the lyceum curriculum of the standard level or an elective course (35 hours) of the profile level curriculum.
3. For effective studying of the training material, students are offered to work with universal and special software and Internet-services – IBM Quantum Experience, Jupyter Notebook using Python programming language (in remote or local access).

REFERENCES

Ackerman, D. (2021). Transforming quantum computing's promise into practice. https://news.mit.edu/2021/william-oliver-quantum-computing-0119.

Al-Kilani, V. and Umkeeva, B. (2016). Budushchee vychislitelnykh tekhnologii. Budet li rabotat zakon Mura dalshe? (Future of computing technologies. Will work on Moore's law?). *Internauka*, 12(1):33–36. http://nbuv.gov.ua/UJRN/mnj_2016_12%281%29__7.

Amazon (2021). Amazon Braket: Explore and experiment with quantum computing . https://aws.amazon.com/braket/?nc2=type_a.

Bernhardt, C. (2019). *Quantum Computing for Everyone*. MIT Press.

CoCalc (2021). Collaborative calculation and data science. https://cocalc.com/.

Fog, A. (2015). Moores law hits the roof. https://www.agner.org/optimize/blog/read.php?i=417\#417.

IBM (2021). Start coding with Python in Quantum Lab. https://quantum-computing.ibm.com/jupyter.

Microsoft (2021). Azure Quantum Documentation (preview). https://docs.microsoft.com/en-us/azure/quantum/.

Rotman, D. (2020). We're not prepared for the end of Moore's Law. https://www.

technologyreview.com/2020/02/24/905789/were-not-prepared-for-the-end-of-moores-law/.

Sigov, A. S., Andrianova, E. G., Zhukov, D. O., Zykov, S. V., and Tarasov, I. Y. (2019). Quantum informatics: overview of the main achievements. *Russian Technological Journal*, 7(1):5–37. https://www.rtj-mirea.ru/jour/article/view/138/139.

YouTube (2019). Quantum Cryptography — Science Question with Alexei Semihatov. https://youtu.be/omkP_ipZT_Y.

YouTube (2020). Quantum Chemistry. Predictors — The Big Leap. https://youtu.be/gWg5toDzSw4.

Zahorodko, P. V., Semerikov, S. O., Soloviev, V. N., Striuk, A. M., Striuk, M. I., and Shalatska, H. M. (2021). Comparisons of performance between quantum-enhanced and classical machine learning algorithms on the IBM quantum experience. *Journal of Physics: Conference Series*, 1840(1):012021.