Prospects of quantum informatics and studying its basics in school courses

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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. A survey was conducted among 26 computer science teachers to assess the relevance and feasibility of introducing a "Fundamentals of quantum informatics and programming" course for lyceum students. The proposed 17-hour sample module covers key concepts of quantum computing, quantum circuits, quantum gates, and basic quantum algorithms. Expected learning outcomes and methodological support are discussed. The study concludes that quantum computer science has significant potential and proposes starting to study its basics in the school computer science course in grades 10-11, using universal software and Internet services like IBM Quantum Experience and Jupyter Notebooks with Python.

Keywords

quantum computing, quantum computer, quantum circuit, quantum algorithm, IBM Quantum Experience, Python, Jupyter Notebook

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) [1].

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 [2, 3, 4]. 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.

2. Background

2.1. 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

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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. [5]

2.2. Need for quantum education

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 to all interested parties [6, 7, 8]. 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 [9, 10, 11], we consider it appropriate and possible to generalize, systematize, and adapt the basics of quantum informatics for mastering it by lyceum students.

3. Methodology

For effective studying of the training material, 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 1, [6]);
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 2);
3) for studying the mathematical foundations of quantum calculations and the implementation of basic quantum algorithms remotely using Collaborative Calculation and Data Science (CoCalc).

CoCalc (figure 3, [12, 13, 14]) 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,

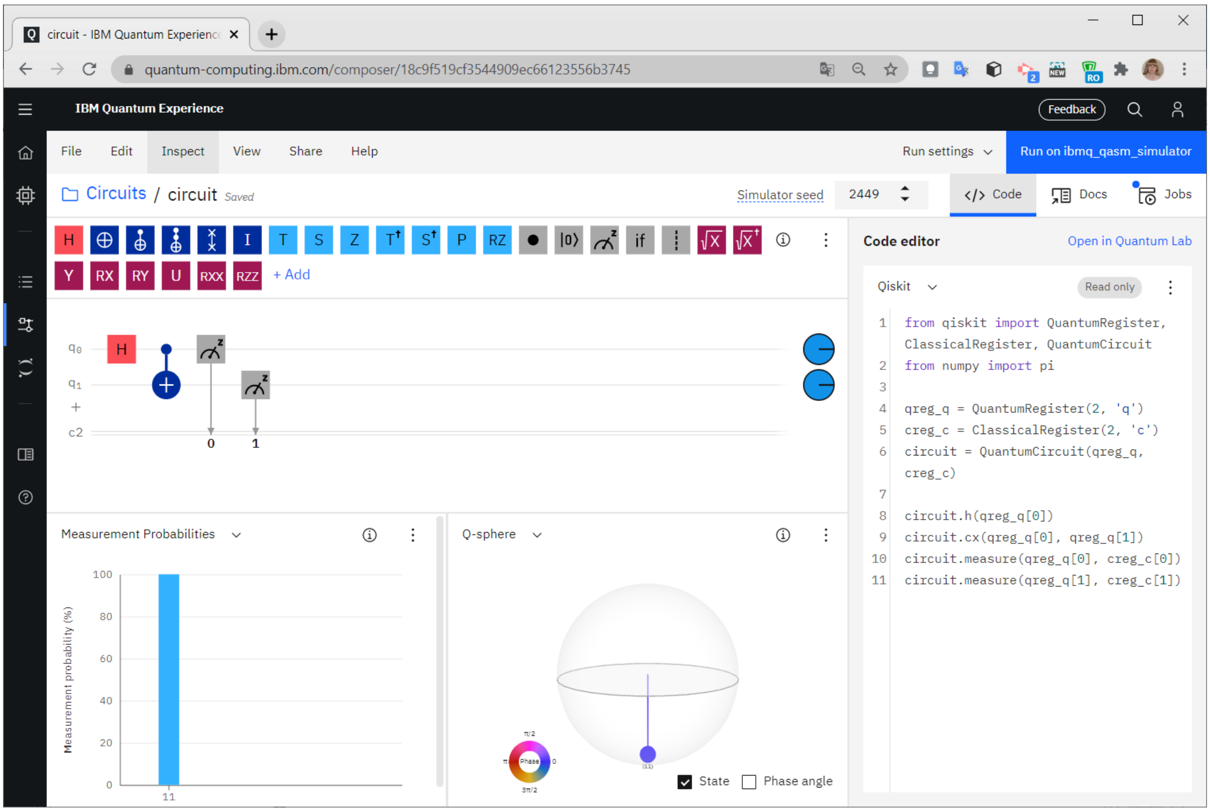

Figure 1: Page with quantum circuit composer from IBM Quantum Experience.

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”.

4. Proposed course content

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.

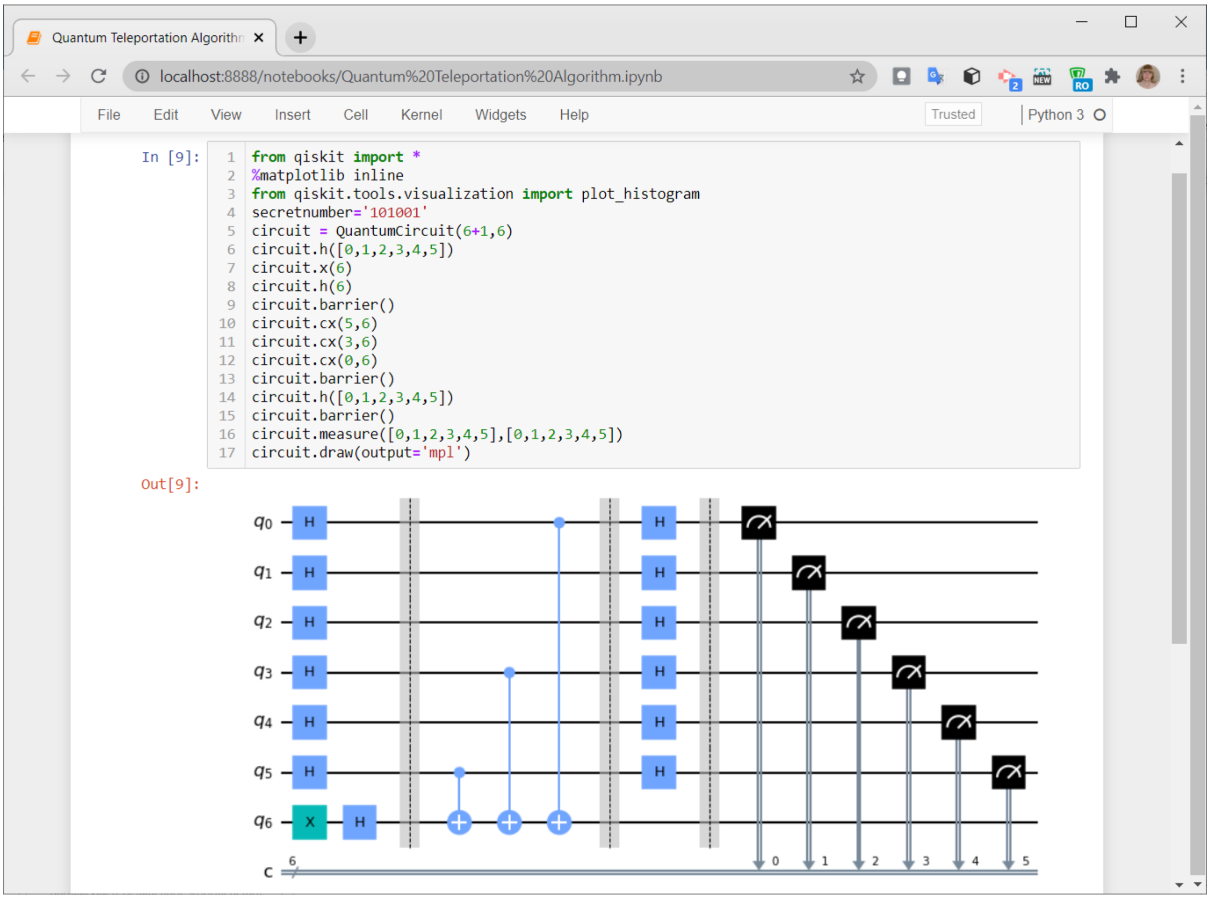

Figure 2: Jupyter notebook page in local access.

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

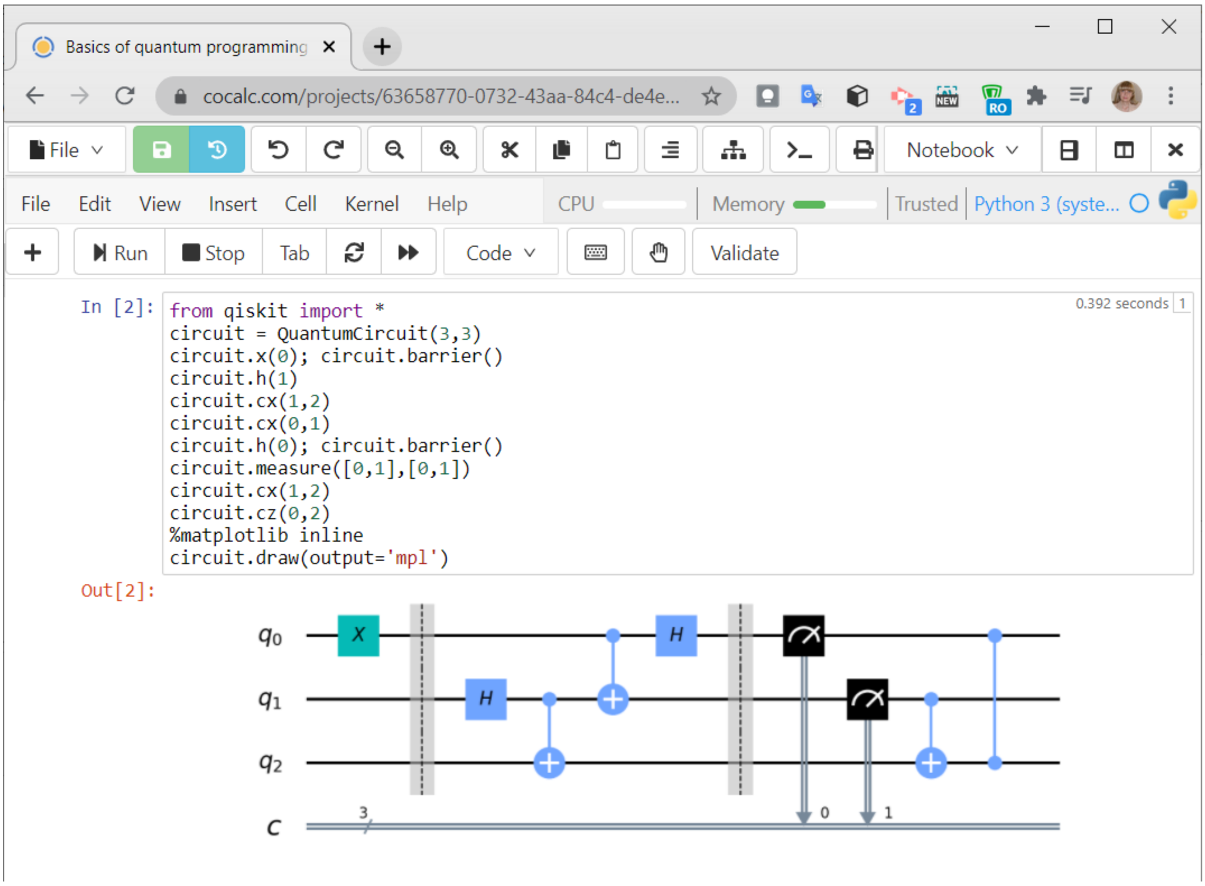

Figure 3: Jupyter notebook page in the CoCalc cloud environment.

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.

5. 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.

Table 1
"Fundamentals of quantum informatics and programming": draft content of the sample module (17 hours)

N	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

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

[1] A. S. Sigov, E. G. Andrianova, D. O. Zhukov, S. V. Zykov, I. Y. Tarasov, Quantum informatics: overview of the main achievements, Russian Technological Journal 7 (2019) 5–37. URL: https://www.rtj-mirea.ru/jour/article/view/138/139. doi:10.32362/2500-316X-2019-7-1-5-37.

[2] D. Rotman, We're not prepared for the end of Moore's Law, 2020. URL: https://www.technologyreview.com/2020/02/24/905789/were-not-prepared-for-the-end-of-moores-law/.

[3] A. Fog, Moores law hits the roof, 2015. URL: https://www.agner.org/optimize/blog/read.php?i=417#417.

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

[5] C. Bernhardt, Quantum Computing for Everyone, MIT Press, 2019.

[6] Start coding with Python in Quantum Lab, 2021. URL: https://quantum-computing.ibm.com/jupyter.

[7] Microsoft, Azure Quantum documentation, 2024. URL: https://learn.microsoft.com/en-us/azure/quantum/.

[8] Amazon Web Services, Inc., Amazon Braket: Accelerate quantum computing research, 2024. URL: https://aws.amazon.com/braket/?nc2=type_a.

[9] D. Ackerman, Transforming quantum computing's promise into practice, 2021. URL: https://news.mit.edu/2021/william-oliver-quantum-computing-0119.

[10] Quantum Chemistry. Predictors | The Big Leap, 2020. URL: https://youtu.be/gWg5toDzSw4.

[11] Quantum Cryptography | Science Question with Alexei Semihatov, 2019. URL: https://youtu.be/omkP_ipZT_Y.

[12] Collaborative Calculation and Data Science, 2024. URL: https://cocalc.com/.

[13] K. Vlasenko, O. Chumak, D. Bobyliev, I. Lovianova, I. Sitak, Development of an Online-Course Syllabus "Operations Research Oriented to Cloud Computing in the CoCalc System", in: A. Bollin,

H. C. Mayr, A. Spivakovsky, M. V. Tkachuk, V. Yakovyna, A. Yerokhin, G. Zholtkevych (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume I: Main Conference, Kharkiv, Ukraine, October 06-10, 2020, volume 2740 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 278–291. URL: https://ceur-ws.org/Vol-2740/20200278.pdf.

[14] P. V. Merzlykin, M. V. Marienko, S. V. Shokaliuk, CoCalc: an integrated environment for open science education in informatics and mathematics, in: O. Y. Burov, S. H. Lytvynova, S. O. Semerikov, Y. V. Yechkalo (Eds.), Proceedings of the VII International Workshop on Professional Retraining and Life-Long Learning using ICT: Person-oriented Approach (3L-Person 2022), Virtual Event, Kryvyi Rih, Ukraine, October 25, 2022, volume 3482 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 39–53. URL: https://ceur-ws.org/Vol-3482/paper025.pdf.