Federal State Autonomous Educational Institution of Higher Education "Moscow Institute of Physics and Technology (National Research University)"

APPROVED
Head of Landau Phystech-School of Physics & Research
A.V. Rogachev

Work program of the course (training module)

course:	Quantum Information Processing/Обработка квантовой информации
major:	Photonics and Optical Informatics
specialization:	Photonics, Quantum Technologies & 2D Materials/Фотоника, квантовые технологии и двумерные материалы
	Landau Phystech-School of Physics & Research
	Chair of the Russian Quantum Centre
term:	1
qualification:	Master

Semester, form of interim assessment: 1 (fall) - Exam

Academic hours: 45 AH in total, including:
lectures: 30 AH.
seminars: 15 AH.
laboratory practical: 0 AH.

Independent work: 60 AH.

Exam preparation: 30 AH.

In total: 135 AH, credits in total: 3

Author of the program: E.O. Kiktenko, candidate of physics and mathematical sciences

The program was discussed at the Chair of the Russian Quantum Centre 04.04.2022

Annotation

The course is devoted to an introduction to the vast field of processing and transmission of quantum information. The course examines the basic ideas of using individual quantum objects to solve computational problems, introduces the basic concepts of quantum and classical information theory, formulates the principles of constructing quantum algorithms and the functioning of quantum computers, analyzes the main approaches to transmitting information through quantum channels.

Special attention is paid to the phenomenon of quantum entanglement, which is an important resource for the implementation of quantum information technologies. The course also focuses on the latest world advances in quantum computing.

1. Study objective

Purpose of the course

to acquaint students with the basics of quantum information processing theory, necessary for starting their own research activities.

Tasks of the course

give a general idea of the formalization of information concept from the view point of the probability theory;

introduce the basic ideas of classical information processing;

introduce the formalism of positive operator-valued measures;

introduce the basic concepts of quantum information transfer;

introduce the basic algorithms of quantum computing, as well as modern algorithms of quantum machine learning.

2. List of the planned results of the course (training module), correlated with the planned results of the mastering the educational program

Mastering the discipline is aimed at the formation of the following competencies:

Code and the name of the competence	Competency indicators
Gen.Pro.C-1 Gain fundamental scientific knowledge in the field of physical and mathematical sciences	Gen.Pro.C-1.1 Apply fundamental scientific knowledge in the field of physical and mathematical sciences
	Gen.Pro.C-1.3 Understands the interdisciplinary links in mathematics and physics and is able to apply them to problems in photonics and opto-informatics
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.2 Assess the relevance and practical importance of research in professional settings
	Gen.Pro.C-2.3 Understand professional terminology used in modern scientific and technical literature and present scientific results in oral and written form within professional communication
Gen.Pro.C-3 Select and/or develop approaches to professional problem-solving with consideration to the limitations and specifics of different solution methods	Gen.Pro.C-3.1 Analyze problems, plan research strategy to achieve solution(s), propose, and combine solution approaches
	Gen.Pro.C-3.2 Employ research methods to solve new problems, and apply knowledge from various fields of science (technology)
	Gen.Pro.C-3.3 Gain knowledge of analytical and computational methods of problem-solving, understand the limitations for applying the obtained solutions in practice
Gen.Pro.C-4 Successfully perform a task, analyze the results and present conclusions, apply knowledge and skills in the field of physical and mathematical sciences and ICTs	Gen.Pro.C-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results

Pro.C-1 Assign, formalize, and solve tasks, develop and research mathematical models of the studied phenomena and processes, systematically analyze scientific problems and obtain new scientific results	Pro.C-1.2 Make hypotheses, build mathematical models of the studied phenomena and processes, evaluate the quality of the developed model

3. List of the planned results of the course (training module)

As a result of studying the course the student should:

know:

- the basic concepts of quantum and classical information theory and the fundamental differences between quantum and classical information theory;
- principles for constructing quantum algorithms and the functioning of quantum computers;
- basic approaches to the transmission of information through quantum channels.

be able to:

- calculate the entropy characteristics for classical probability distributions and quantum states;
- perform operations on bra- and ket- vectors;
- purify mixed quantum states;
- calculate quantum states of the qubit register after applying a given set of quantum gates;
- construct elementary quantum algorithms;
- to design the simplest quantum communication protocols.

master:

- the mathematical apparatus of classical and quantum information theory;
- formalism of the quantum channels description.

4. Content of the course (training module), structured by topics (sections), indicating the number of allocated academic hours and types of training sessions

4.1. The sections of the course (training module) and the complexity of the types of training sessions

№	Topic (section) of the course	Types of training sessions, including independent work			
		Lectures	Seminars	Laboratory practical	Independent work
1	Review of the foundations of quantum mechanics formalism for finite-dimensional spaces	4			6
2	Quantum measurement and quantum evolution	6	3		9
3	Quantum entanglement	4	2		6
4	Quantum information theory	4	2		12
5	Universal quantum computing	8	4		12
6	Variational and adiabatic quantum computing	4	4		15
AH in total		30	15		60
Exam preparation		30 AH.			
Total complexity		135 AH., credits in total 3			

4.2. Content of the course (training module), structured by topics (sections)

Semester: 1 (Fall)

1. Review of the foundations of quantum mechanics formalism for finite-dimensional spaces

Review of the foundations of quantum mechanics formalism for finite-dimensional spaces. Hilbert spaces, bra and ket vectors, unitary, Hermitian, semi-positive operator. Matrix multiplication, trace, eigen values and eigen vectors. Calculation of mean values of the observables. Pure and mixed states, tensor product and partial trace.

2. Quantum measurement and quantum evolution

Quantum measurement and quantum evolution. Quantum measurements and quantum evolution. Formalism of positive operator-valued measures. Naimark's theorem. Completely positive trace-preserving mappings. Representations of quantum channels in terms of Kraus operators. Stinespring representation.

3. Quantum entanglement

Quantum entanglement. The concept of quantum entanglement of pure and mixed states. Measures of quantum entanglement and witnesses of quantum entanglement. The use of entangled states in the protocol of quantum teleportation and super-dense coding.

4. Quantum information theory

Quantum information theory. Foundations of classical information theory. Generalization of classical information theory to quantum states. Information transmission through quantum channels, Holevo bound.

5. Universal quantum computing

Universal quantum computing. Basic quantum gates, universal set of quantum gates, Solovey-Kitaev theorem. Principles of constructing quantum algorithms. Deutsch’s, Deutsch-Jozsa’s, Simon’s, Shore’s, Grover’s algorithms. Demonstration of “quantum supremacy”.

6. Variational and adiabatic quantum computing

Variational and adiabatic quantum computing. The principle of constructing variational quantum algorithms. Examples of using variational quantum algorithms. Using variational algorithms for quantum simulation. The principle of constructing adiabatic quantum algorithms. The relationship between variational and adiabatic algorithms.

5. Description of the material and technical facilities that are necessary for the implementation of the educational process of the course (training module)

A classroom equipped with multimedia-projector and projection screen.

6. List of the main and additional literature, that is necessary for the course (training module) mastering

Main literature

1. Квантовая информация и квантовые вычисления [Текст] : в 2 т/Дж. Прескилл , -М. : Регулярная и хаотическая динамика ; Ижевск, 2011

Additional literature

1. Введение в квантовую теорию информации [Текст] : [лекции для студентов вузов] / А. С. Холево ; Независимый Моск. ун-т ; Высший колледж математ. физики .— М : МЦНМО, 2002 .— 128 с.
- A. S. Holevo, "Quantum Systems, Channels, Information. A Mathematical Introduction" De Gruyter (2013)
- M. A. Nielsen and I. L. Chuang "Quantum Computation and Quantum Information" Cambridge University press (2010)

7. List of web resources that are necessary for the course (training module) mastering

- http://www.theory.caltech.edu/~preskill/ph219/index.html Lecture notes on Quantum Computation by John Preskill
- https://arxiv.org/abs/1907.09415 Quantum Computing: Lecture Notes

8. List of information technologies used for implementation of the educational process, including a list of software and information reference systems (if necessary)

Multimedia technologies can be employed during lectures, including presentations.

Online LaTeX Editor Overleaf (https://www.overleaf.com/). Cloud IBM quantum processor (https://quantum-computing.ibm.com/)

9. Guidelines for students to master the course

Students should learn the basic concepts of quantum information processing, as well as how to apply their theoretical knowledge in practice.

For the successful assimilation of the course, in addition to attending classes, students are required to perform homework whose amount in hours should be not less than the number of hours specified in the curricula of the faculties. Studying at home includes:

- reading the recomended literature and making notes;
- processing and analysis of lecture materials (using notes, textbooks and scientific articles), answering questions, proving some statements;
- solving problems given on lectures and seminars for self-study;
- preparing for the tests and exams.

SUPPLEMENT

Assessment funds for course (training module)

major:	Photonics and Optical Informatics
specialization:	Photonics, Quantum Technologies & 2D Materials/Фотоника, квантовые технологии и двумерные материалы
	Landau Phystech-School of Physics & Research
	Chair of the Russian Quantum Centre
term:	1
qualification:	Master

Semester, form of interim assessment: 1 (fall) - Exam

Author:	E.O. Kiktenko, candidate of physics and mathematical sciences

1. Competencies formed during the process of studying the course

Code and the name of the competence	Competency indicators
Gen.Pro.C-1 Gain fundamental scientific knowledge in the field of physical and mathematical sciences	Gen.Pro.C-1.1 Apply fundamental scientific knowledge in the field of physical and mathematical sciences
	Gen.Pro.C-1.3 Understands the interdisciplinary links in mathematics and physics and is able to apply them to problems in photonics and opto-informatics
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.2 Assess the relevance and practical importance of research in professional settings
	Gen.Pro.C-2.3 Understand professional terminology used in modern scientific and technical literature and present scientific results in oral and written form within professional communication
Gen.Pro.C-3 Select and/or develop approaches to professional problem-solving with consideration to the limitations and specifics of different solution methods	Gen.Pro.C-3.1 Analyze problems, plan research strategy to achieve solution(s), propose, and combine solution approaches
	Gen.Pro.C-3.2 Employ research methods to solve new problems, and apply knowledge from various fields of science (technology)
	Gen.Pro.C-3.3 Gain knowledge of analytical and computational methods of problem-solving, understand the limitations for applying the obtained solutions in practice
Gen.Pro.C-4 Successfully perform a task, analyze the results and present conclusions, apply knowledge and skills in the field of physical and mathematical sciences and ICTs	Gen.Pro.C-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
Pro.C-1 Assign, formalize, and solve tasks, develop and research mathematical models of the studied phenomena and processes, systematically analyze scientific problems and obtain new scientific results	Pro.C-1.2 Make hypotheses, build mathematical models of the studied phenomena and processes, evaluate the quality of the developed model

2. Competency assessment indicators

As a result of studying the course the student should:

know:

the basic concepts of quantum and classical information theory and the fundamental differences between quantum and classical information theory;
principles for constructing quantum algorithms and the functioning of quantum computers;
basic approaches to the transmission of information through quantum channels.

be able to:

calculate the entropy characteristics for classical probability distributions and quantum states;
perform operations on bra- and ket- vectors;
purify mixed quantum states;
calculate quantum states of the qubit register after applying a given set of quantum gates;
construct elementary quantum algorithms;
to design the simplest quantum communication protocols.

master:

the mathematical apparatus of classical and quantum information theory;
formalism of the quantum channels description.

3. List of typical control tasks used to evaluate knowledge and skills

1. Calculate the average fidelity of restoring a random pure qubit state in the projective measurement
2. Get the SIC-POVM elements for the qubit case

3. Calculate the reduced density matrices for Bell states
4. Get the resulting unitary matrix of the CNOT gate acting on the 1st and 3rd qubits of the three-qubit system
5. Get the required operations on the side of Alice and Bob in the quantum teleportation protocol based on an arbitrary Bell state
6. Get the required operations on the side of Alice and Bob in the superdense coding protocol based on an arbitrary Bell state
7. Get a unitary matrix of a quantum oracle for an arbitrary Boolean function
8. Get a decomposition of a multi-qubit gate of a controlled unitary rotation
9. Calculate the von Neumann entropy for a given quantum state
10. Calculate the quantum mutual information for a two-part quantum state

4. Evaluation criteria

Checking questions:
1. Give definitions of Shannon's entropy and classical mutual information. Formulate the coding theorem for a classic channel.
2. Describe the main tasks of the classic post-processing procedure in quantum key distribution systems. Describe the procedures of information reconciliation, verification and privacy amplification. Explain how an authenticated channel is established.
3. Define pure and mixed quantum states. Define the von Neumann entropy and the method of its calculation. Define positive operator-valued measures and their connection with projective quantum measurements.
4. Describe the sequence of operations in the protocols of quantum teleportation, and quantum superdense coding
5. Write matrices of basic quantum gates. Present a universal set of quantum gates. Formulate the principle of implementation of functions in the paradigm of reversible quantum computation.
6. Formulate the mathematical problems underlying the algorithms of Simon and Shor. Describe the basic principles of the construction of these algorithms.
7. Formulate the mathematical problems underlying the algorithms of Deutsch and Grover. Describe the basic principles of the construction of these algorithms.
8. Define the quantum channel. Explain the difference between the requirements of positivity and complete positivity. Give concepts of Steinspring representation and Kraus operators.
9. Define the decoherence process. Give the concept of a dephasing, depolarizing and damping channels.
10. Give the concept of a quantum error correction code. Explain the principle of the Shor code.
11. Define stabilizing quantum error correction codes. Explain the principles for the operation of fault-tolerant quantum computing.
12. Define the quantum entanglement witness. Define concurrence and negativity. Give the concept of quantum discord.
13. Explain the principles of operation of quantum machine learning variation algorithms.

Examples of checking tasks:
1. Obtain local operators in the quantum teleportation protocol based on the specified two-qubit entangled state
2. To obtain the state vector, which is the purification of a given mixed state
3. Calculate the reduced density matrix for a given multi-partite quantum state
4. Build a quantum gate that implements the specified classical function
5. Get the optimal number of iterations for the Grover algorithm.
6. Prove that the given mixed state is entangled
7. Obtain the Kraus operators for a given interaction of a quantum system with the environment
8. To get the Choi-Jamiołkowski state for a given quantum channel
9. Calculate quantum mutual information for a given two-qubit state
10. Calculate the concurrence for a given two-qubit state.

Examples of test tickets:

Test 1.
1. Calculate the reduced density matrix for a given multi-partite quantum state.
Test 2
1. Get the optimal number of iterations for the Grover algorithm.
Test 3
1. Obtain the Kraus operators for a given interaction of a quantum system with the environment.

Assessment “excellent (10)” is given to a student who has displayed comprehensive, systematic and deep knowledge of the educational program material, has independently performed all the tasks stipulated by the program, has deeply studied the basic and additional literature recommended by the program, has been actively working in the classroom, and understands the basic scientific concepts on studied discipline, who showed creativity and scientific approach in understanding and presenting educational program material, whose answer is characterized by using rich and adequate terms, and by the consistent and logical presentation of the material;

Assessment “excellent (9)” is given to a student who has displayed comprehensive, systematic knowledge of the educational program material, has independently performed all the tasks provided by the program, has deeply mastered the basic literature and is familiar with the additional literature recommended by the program, has been actively working in the classroom, has shown the systematic nature of knowledge on discipline sufficient for further study, as well as the ability to amplify it on one’s own, whose answer is distinguished by the accuracy of the terms used, and the presentation of the material in it is consistent and logical;

Assessment “excellent (8)” is given to a student who has displayed complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently performed all the tasks stipulated by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (7)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in the answer, has independently performed all the tasks provided by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (6)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently carried out the main tasks stipulated by the program, studied the basic literature recommended by the program, showed systematic character of his knowledge of the discipline, which is sufficient for further study;

Assessment “good (5)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, mastered the basic literature recommended by the program, made some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors by himself;

Assessment “satisfactory (4)” is given to a student who has discovered knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, learned the main literature but allowed some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors under the guidance of a teacher;

Assessment “satisfactory (3)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, not showed activity in the classroom, independently fulfilled the main tasks envisaged by the program, but allowed errors in their implementation and in the answer during the test, but possessing necessary knowledge for elimination under the guidance of the teacher of the most essential errors;

Assessment “unsatisfactory (2)” is given to a student who showed gaps in knowledge or lack of knowledge on a significant part of the basic educational program material, who has not performed independently the main tasks demanded by the program, made fundamental errors in the fulfillment of the tasks stipulated by the program, who is not able to continue his studies or start professional activities without additional training in the discipline in question;

Assessment “unsatisfactory (1)” is given to a student when there is no answer (refusal to answer), or when the submitted answer does not correspond at all to the essence of the questions contained in the task.

5. Methodological materials defining the procedures for the assessment of knowledge, skills, abilities and/or experience

The course is graded at an oral grading test. The grading starts with a random task assigned to each student and time given for completion of the task. No aids are allowed. The student then proceeds to a chat with the examiner, at which he/she presents his/her solution to the assigned task. The examiner then asks the student several questions that evenly cover the course content. A final grade is assigned based on the quality of answers and demonstrated level of understanding.