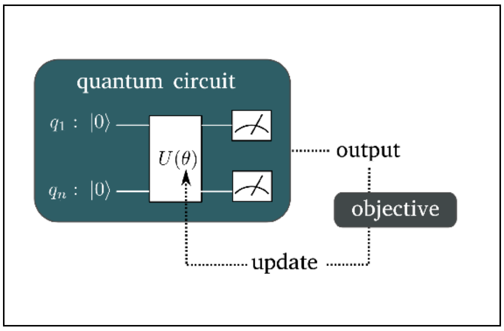

1. ***Title***

   Quantum Machine Learning

2. ***Lecturer(s)***

   Oleksandr Kyriienko

3. ***Assistance(s)***

   Igor Lobanov

4. ***Course Language***

   English

5. ***Credits and assessment form (exam, ungraded credit test, graded credit test)***

   3 ECTS, exam

6. ***Educational program and semester***

   Master: Quantum Materials, 3 semester

7. ***Prerequisites (courses and topics, skills and abilities, as a prerequisite for studying the discipline - specify the basic or advanced courses, whether they are present in the Department of Physics and Engineering programs, since under different names of courses there may be different content)***

   Quantum Mechanics. Optionally: Quantum Optics, Quantum Computing

8. ***Brief annotation (in simple and understandable language with the obligatory indication of the points below):***

Course goal and main objectives:

This course aims to provide the state-of-the-art knowledge in the field of quantum computing and its application to quantum machine learning (ML). The goal is to introduce quantum computing, explain its difference from classical computing, and learn the way in which quantum algorithms in application to machine learning can be developed. First major objective is to familiarize students with paradigmatic algorithms of quantum computing, and explain the difference between fault-tolerant and near-term quantum computing. Next objective is to learn and understand modern variational quantum algorithms, and code them for quantum hardware and simulators. Finally, the-state-of-the-art quantum machine learning (QML) tools will be introduced, with objective to understand and develop extensions to existing QML protocols.

Expected learning outcomes:

After the course you will have a base in quantum computing, understanding state-of-the-art quantum protocols, and being able to implement it in code for quantum hardware and simulators. You will understand the modern quantum techniques and will learn how to develop variational quantum-classical algorithms. You will learn the goals of machine learning, and apply quantum computing to machine learning, developing quantum machine learning software.

Relevance, novelty, significance, and uniqueness:

The course targets understanding of the quantum computing approach to information processing and state-of-the-art of machine learning, so it combines the significance of quantum paradigm of computation with novel solutions inspired by the artificial intelligence. It has a unique and specialized curriculum that is based on the contemporary research, giving access to knowledge available only in best research centers. The course teaches the way computing will be performed tomorrow.

9. *Course content*

The course consists of the lecture series, where quantum computing and machine learning algorithms are described and explained. The large part of the course includes practical assignments (independent work), to be completed before each lecture, and discussed after lectures in the round table format. The course is also supplemented with weekly seminars where questions on practical assignments can be asked.

The structure of the course comprises of **three modules**:

1. Quantum computing
2. Variational quantum computing for modern devices
3. Machine learning and state-of-the-art quantum techniques

№ section	Section title	The main topics of the section, divided into lectures, practices, laboratory	Classes format	Estimated date (if known)
1	Introduction to Quantum Computing	1 Bits and qubits. Dirac notation. Entanglement. Quantum measurement. Classical computing and reversible computing. Quantum gates.	Lecture	
		2 Coding quantum gates and checking identities in the programming language of choice	Independent study/Seminars	
		3 Physical platforms for quantum computing. Quantum software infrastructure and simulation tools. QuASM. Quantum packages from IBM (qiskit), Rigetti (forest), Google (circ), Microsoft (Q#), and others.	Lecture	
		4 Implementing a gate sequence using one of existing quantum packages	Independent study/Seminars	
		5 Quantum teleportation and Bells states. Deutsch algorithms and Deutsch–Jozsa algorithm.	Lecture	
		6 Quantum complexity. Simon's algorithm. Quantum phase estimation.	Lecture	
		7 Factoring and Shor's algorithm. Quantum search and Grover's algorithm.	Lecture	

		8 Quantum simulation and linear combination of unitaries. Quantum computing for linear algebra, HHL and beyond.	Lecture	
		9 Quantum linear algebra (cont.) Future algorithms for quantum machine learning.	Lecture	
		10 Project: software realization for a quantum protocol of choice	Independent study/Seminars	
2	Variational Quantum Algorithms for modern quantum devices	11 Current hardware for quantum computing, NISQ vs. FTQC protocols. Hybrid quantum-classical workflow. Variational quantum eigensolver (VQE).	Lecture	
		12 VQE (cont.) Quantum chemistry and material science.	Lecture	
		13 Coding VQE with chemically motivated ansatz	Independent study/Seminars	
		14 Classical optimization and gradient descent. Variational ansatz.	Lecture	
		15 Coding VQE with hardware efficient ansatz	Independent study/Seminars	
		16 Initial state choice. Measurement and Hamiltonian averaging. Barren plateaus. Quantum state comparator.	Lecture	
		17 Variational quantum algorithms for linear algebra. Automatic differentiation and analytical gradients.	Lecture	
		18 Quantum approximate optimization algorithm and QAOA-type quantum ansatz. Embedding of NP-hard problems and financial modelling. MaxCut and unsupervised machine	Lecture	

		learning (clustering).		
		19 Coding the embedding for NP-hard problem and using QAOA to solve it	Independent study/Seminars	
		20 Coding the VQE for chemistry/material problem and benchmarking	Independent study/Seminars	
3		21 Tasks of machine learning. Supervised and unsupervised learning. Classical neural networks. Quantum neural networks and variational circuits.	Lecture	
		22 Amplitude encoding and feature map encoding. ML-inspired quantum computing. Quantum circuit learning.	Lecture	
		23 Coding data using amplitude and feature maps.	Independent study/Seminars	
		24 Quantum clustering and regression. Quantum support vector machines. Quantum Principal Component Analysis.	Lecture	
		25 Generative modelling. Quantum GANs.	Lecture	
		26 Variational Quantum Autoencoder. Phase transition detection and convolutional neural networks. Quantum Deep Learning.	Lecture	
		27 Open problems of Quantum Machine Learning (Input, Output, Costing, and Benchmarking problems). Perspectives.	Lecture	
		28 Coding one of the QML approaches as a final project. Presenting code and benchmarking.	Independent study/Seminars	

The course is taught in the online format, with possibility to attend virtual lecture in the campus. More details can be found in shared *gitlab* group (open to students only) https://gitlab.com/qml-msc-course-2020/quantum-machine-learning-course-2020

10. Resources and references (required and recommended - be sure to add at least 2 links to an electronic source available at ITMO, as well as to an online course, if used)

1. Quantum Computation and Quantum Information: book / M. A. Nielsen and I. L. Chuang — Cambridge Univ. Press, 2010. — http://mmrc.amss.cas.cn/tlb/201702/W020170224608149940643.pdf

2. Introduction to Quantum Computing: lecture notes / John Watrous — Waterloo, 2006. — https://cs.uwaterloo.ca/~watrous/LectureNotes/CPSC519.Winter2006/all.pdf

3. Quantum machine learning: review / Jacob Biamonte et al. — Nature 549, 195–202, 2017. — https://www.nature.com/articles/nature23474

4. Parameterized quantum circuits as machine learning models: review / M. Benedetti, E. Lloyd, S. Sack, and M. Fiorentini. — Quantum Science and Technology 4, 043001, 2019. — https://iopscience.iop.org/article/10.1088/2058-9565/ab4eb5

11. Evaluation of course progress (grading policy) and examples of assignments

Choose the types of tasks from the list below or fill in your own in the table indicating the weight of the task in points and possible comments. The table must be filled in completely (comments if desired or if there are important details), and in the deadlines indicate the approximate expected dates or study weeks.

Форма контроля	Assignments type	Score %	Minimum threshold for attestation (grade E or credit)%	Deadlines	Comments
Current attestation for Module 1 (Monitoring of progress)	Mini-project	20	5	Mid-Oct 2020	Score includes homeworks, and presentation on the Module 1 mini-project
Current attestation for Module 2 (Monitoring of progress)	Mini-project	30	10	Nov 2020	Score includes homeworks, and presentation on the Module 2 mini-project
Mid-term attestation	Presentation of results in Modules 1 and 2 (counts towards total score for M1 and M2)				
Current attestation for Module 3 (Monitoring of progress)	Project	50	15	Dec 2020	Presentation on the Module 3 project and benchmarking
Admission to	Complete minimum 25% of homework				

attestation (if any)					
Attestation	Presentation of results in Module 3 and final project (counts towards total score for M3)				
∑		100			

<u>Tasks examples</u>

- Homework
- Project
- Presentation

Scoring includes the implementation of proof-of-concept (minimal requirement), coding solutions, performance (advanced), presentation and questions answered.

12. Additional comments

<u>The information will become available only for those registered for the course:</u> details will be communicated at the official course page at https://gitlab.com/qml-msc-course-2020/quantum-machine-learning-course-2020 and over emails with course lecturer and assistant.