DEMOCRITUS UNIVERSITY OF THRACE | DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

MSc in QUANTUM COMPUTING AND QUANTUM TECHNOLOGIES

NATIONAL CENTRE FOR SCIENTIFIC RESEARCH "DEMOKRITOS"

MSc. in QUANTUM COMPUTING AND QUANTUM TECHNOLOGIES

Student Guide 2024-2025

International M.Sc. Program in Quantum Computing and Quantum Technologies

The M.Sc. will provide postgraduate students with cutting-edge knowledge in Quantum Mechanics, Quantum Computing and Quantum Technologies, as well as skills and abilities that will enable them to program quantum computers and to develop novel quantum algorithms. Graduates of this program will also be able to use and apply the acquired knowledge not only in science and research but also to tackle problems that companies face in their operation as well as to create new enterprises. Graduates of the program may also continue their studies towards a PhD degree.

In the MSc program participate:

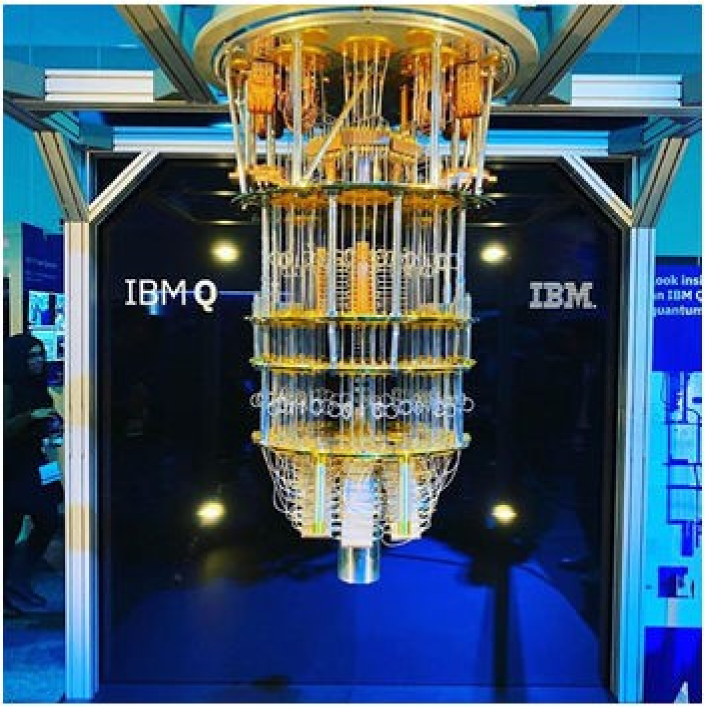
1. The Department of Electrical and Computer Engineering, Democritus University of Thrace (DECE), and
2.
   2. The Institute of Nanoscience and Nanotechnology, National Centre of Scientific Research "Demokritos" (INN-D)

IBM **Quantum**

The M.Sc. program participates in both the "IBM Quantum Educators Program" and the "IBM Quantum Researchers Program".

IBM Quantum System One (credit: IBM)

Quantum computers are novel computers that use quantum mechanical properties, such as state superposition and entanglement to execute computations and solve complex problems, which are impossible to be solved using classical supercomputers, no matter how much computation power they provide. Quantum technologies use quantum mechanical principles and properties to design, implement and develop novel quantum systems, such as quantum bits, quantum computer circuits, quantum sensors, quantum communications and teleportation, quantum metrology, and quantum cryptography systems.



IBM Quantum computer (Credit IBM)

Quantum computers and quantum technologies are at the core of the second quantum revolution, which is expected to have a significant impact on all sciences, in the industry as well as in health and everyday life.

Students will acquire in-depth knowledge and skills in the following specific areas:

Quantum computing
Quantum and quantum bit devices
Quantum Solid-state devices
Quantum communications
Quantum algorithms
Quantum machine learning

No previous knowledge of Quantum Mechanics is required. Courses in Quantum Mechanics and Linear Algebra for Quantum Mechanics are part of the M.Sc. curriculum.

Courses in areas in which quantum computing and quantum technologies have already made an impact on, are also included in the M.Sc. curriculum:

Natural and Unconventional Computing
Computational Biology
Artificial Intelligence
Big Data Handling

Curriculum

In the first and second semesters, the post-graduate students will take four courses, two compulsory and two elective courses. The total number of courses required is eight. The third semester is dedicated to the MSc dissertation. Total MSc ECTS: 90

1st SEMESTER			
CODE	COURSE TITLE	TYPE	ECTS
QY1	Quantum Computing	C	9
QY2	Quantum Devices	C	9
Two (2) of the following courses should be elected:			
QE1	Optical and Quantum Communications	E	6
QE2	Computational Biology	E	6
QE3	Nanoelectronics	E	6
QE11	Linear Algebra for Quantum Mechanics	E	6
QE5	Applied Quantum Mechanics	E	6
QE6	Artificial Intelligence and Applications	E	6
QE7	Python Programming and Applications	E	6
QE8	Quantum Control	E	6
1st SEMESTER TOTAL ECTS			30
2nd SEMESTER			
CODE	COURSE TITLE	TYPE	ECTS
QY3	Quantum Algorithms and Quantum Information	C	9
QY4	Qubit devices	C	9
Two (2) of the following courses should be elected:			
QE9	Quantum Machine Learning	E	6
QE10	Natural and Unconventional Computing	E	6
QE4	Quantum Solid-state Physics	E	6
QE14	Quantum Optics	E	6
2nd SEMESTER TOTAL ECTS			30

3rd SEMESTER			
CODE	COURSE TITLE	TYPE	ECTS
QMD	MSc Dissertation	C	30
3rd SEMESTER TOTAL ECTS			30

C: Compulsory, E: Elective

Course descriptions

QY1. Quantum Computing

Elements of Quantum Mechanics. States of quantum systems. Vectors and operators in Hilbert space. Two-state quantum systems. Bras and Kets. The quantum bit (qubit). Qubit representation in the Bloch sphere. Quantum registers. Basis states of qubits and quantum registers. One-qubit quantum gates: The Hadamard, the phase-shift and the inertial quantum gates. Pauli quantum gates. Two-qubit quantum gates: The controlled-not (CNOT) and the controlled-phase-shift quantum gates. Three-qubit quantum gates: The controlled-controlled-Not (CCNOT) and the Fredkin quantum gates. The circuit model of quantum computation. Quantum circuits and the principle of quantum computation. Quantum computations. The Deutsch quantum algorithm. The Grover quantum algorithm. Quantum Fourier transform. Entanglement. The Shor quantum algorithm. Quantum teleportation. The quantum computer simulator (QCS). The Qiskit quantum simulator. Quantum algorithms on real quantum computers.

QY2. Quantum Devices

Semiconducting devices: quantum wells - 2DEG devices (HEMT) -quantum dots - Coulomb blockade- Single Electron Transistor (SET) - Tunnel FET. Superconducting devices: Josephson effect - Josephson junctions - superconducting electronic circuits - dc and ac squid sensors. Molecular Magnets: definition (description of the compounds) - organic molecules - transition metal and rare earth ions mono-and poly-nuclear compounds - molecular spins (endohedral fullerenes and/or encapsulated atoms) - impurities in solids

QY3. Quantum Algorithms and Quantum Information

Quantum computing in noisy environments. Quantum error correction. The nine-qubit error correcting code. Stabilizer codes. Surface error correcting codes. The density operator. The reduced density operator. Pure and mixed quantum states. Measurement and partial measurement of quantum states. Ensembles of quantum states. Quantum simulators. Quantum algorithms. Entropy and quantum information. Von Neumann entropy. Elements of quantum cryptography: quantum key distribution. The BB84 and novel quantum key distribution protocols. The quantum walk model of quantum computation. Quantum walks in one and two dimensions. Adiabatic quantum computation. The quantum Ising model for optimization. Variational quantum algorithms and eigensolvers. Applications of quantum computing.

QY4. Qubit devices

CMOS qubits (QD FET - P-dopants in Si devices – Nitrogen vacancies in Diamond – topological insulators) - Superconducting qubits - Molecular magnets – Atom traps

QE1. Optical and quantum communications

Essential basics: Wave nature of light, E/M waves, physical optics, optical waveguiding. Key components and modules: Optical fiber (operation, characteristics, types), passive elements (couplers, isolators, filters, multiplexers/demultiplexers), active devices (sources, modulators, amplifiers, photodetectors). Optical signal processing: Optical nonlinearities, nonlinear media, modern switching and limitations, optical switches and gates, applications to sequential and combinational circuits, optical interconnects, photonic integration. Optical communications systems: Basic parts, technological evolution, performance limitations and characterization, design of real systems. Optical communications networks: Topologies, Wavelength Division Multiplexing, optical data centers, optical access networks, passive optical networks. Optical quantum communications: Concept, infrastructure, networks, limitations, challenges.

QE2. Computational Biology

What is life? From molecules to organisms and back. Fundamentals of evolution. Genomes, sequencing, sequences, and their databases. Homology and similarity: sequence alignments. Database searches: BLAST and friends. Protein families, motifs, and their databases. Connecting the dots: sequence-based phylogenetic analysis and clustering. Gene expression, networks, pathways and their databases. Genetic variation: characterization, analysis and databases. Atoms, molecules and energy: getting up-close-and-personal with life. Structures illustrated: from the double helix to the ribosome. Making structures: homology modelling, docking and drug design. Protein folding: energy, structure, function and evolution.

QE3. Nanoelectronics

Quantum mechanical description of nanomaterials - Nanoelectronic and spintronic devices: quantum dots, nanowires, nanopillars, quantum transport and tunneling effects, magnetoresistance, spin-dependent electron transport, molecular electronics, and graphene and 2D nanomaterials.

QE4. Quantum Solid State Physics

Semiconductor nanostructures – Quantum confinement – Semiconductor heterostructures – Quantum Hall effect – Semiconductor/dielectric tunnel junctions – Superconductivity and physics of superconductors - Static Magnetic properties (Hyperfine interactions, Spin orbit coupling and single ion anisotropy, Exchange coupling) - Dynamic Magnetic properties (Real and imaginary magnetic susceptibility, Spin Relaxation times, Rabi oscillations).

QE5. Applied Quantum Mechanics

Basic features: Schrödinger's equation, operators, expectation values, probability density and probability current density, superposition principle, eigenvalues, uncertainty principle. One dimensional problems: free-particle, symmetric quantum wells, combination of infinite and finite-barrier potential well, delta function potential, combination of delta function potentials and heterostructures or quantum wells, triangular potential. Scattering in one dimension:

transmission and reflection coefficients, tunneling and resonant tunneling in simple and complex barriers, the propagation matrix method, WKB approximation for tunneling. Periodic potential and the Kronig-Penney model. Additional mathematical issues: More on operators, eigenstates and the measurement problem, Dirac notation. Harmonic oscillator: Algebraic method of the harmonic oscillator, creation and annihilation operators, calculation of the wavefunctions with the algebraic method and calculation of expectation values, Stark effect in the harmonic oscillator, quantization of the LC circuit, quantization of lattice vibrations-phonons, free electron in a magnetic field - Landau states and connection to the semiclassical orbit. Electron in a central potential: angular momentum, application to spherical "hard" potential and finite spherical potential, solution for hydrogen-like systems and applications in excitons in semiconductors. Spin: an intrinsic angular momentum and its description, addition of angular momentum. Approximation methods: time-independent non-degenerate perturbation theory and time-independent degenerate perturbation theory and their applications, the variational method, WKB approximation for stationary states and its applications, the sudden approximation. Identical particles, Pauli exclusion principle and the symmetry of the wavefunctions. Applications in atoms, molecules, nanostructures, and solids.

QE6. Artificial Intelligence and Applications

Overview of the current Artificial Intelligence (AI) domain. AI applications. Current and future AI challenges in a Quantum Computing world. The interaction of Quantum Physics and AI. Introduction to the scientific method for AI. Hypothesis testing as a research tool. Risks and pitfalls in hypothesis testing Scientific error and lies. Scientific reviewing. Communicating research results. Legal and ethical challenges of AI. Societal impact of AI and Quantum Computing.

QE7. Python Programming and Applications

Introduction to data programming. Python programming. Data stream processing. Data acquisition: web services, streams, data transfer. Octave/Matlab/R for data analysis. Optimisation considerations, vectorisation, GPUs. Use-case combining batch processing, streaming and analysis; quantum physics data analysis use case. Open quantum computing in Python (ProjectQ).

QE8. Quantum Control

The purpose of this course is to introduce the student to basic quantum dynamics and to different methods for its control using external fields, as well as to show the connection of the quantum control methods in applications in quantum technologies. The course syllabus include: Coherent vs incoherent dynamics. Incoherent dynamics and rate equations. Coherent dynamics, time-dependent Schrödinger equation, and probability amplitudes. Open quantum systems and the relevant equations for the density operator. Dynamics of specific quantum systems, for example, the two-level quantum system. Weak field dynamics, time-dependent perturbation theory, and coherent control of weak excitation by a field and its harmonics. Fermi's golden rule. Exactly solvable models for the control of quantum dynamics in two and three-level systems and their applications. Adiabatic methods for the control of quantum dynamics, rapid adiabatic passage (RAP) and stimulated Raman adiabatic passage (STIRAP), and their applications. Shortcut to adiabaticity and its applications. Optimal control and its applications. Other methods of quantum control and their applications. Examples of applications of quantum control methods in quantum technologies and connection to current research.

QE9. Quantum Machine Learning

What is machine learning, data mining and quantum computing? Preliminaries from Probability and Stochastic Processes. Learning theory: Data-Driven Models, Feature Space, Classification, Regression, Supervised and Unsupervised Learning, Generalization Performance, Model Complexity. Brief review on quantum mechanics and quantum computations. Unsupervised Learning: Principal Component Analysis, K-Means and K-Medians Clustering, Hierarchical Clustering, Density-Based Clustering. Pattern Recognition and Neural Networks: The Perceptron, Feed-forward Networks, Deep Learning, Computational Complexity. Supervised Learning and Support Vector Machines: K-Nearest Neighbors, Optimal Margin Classifiers, Soft Margins, Nonlinearity and Kernel Functions, Least-Squares Formulation, Generalization Performance, Multiclass Problems, Computational Complexity. Regression Analysis: Linear Least Squares, Nonlinear Regression, Nonparametric Regression, Computational Complexity. Clustering and Quantum Computing: Quantum Random Access Memory, Calculating Dot Products, Quantum Principal Component Analysis, Quantum K-Means, Quantum K-Medians, Quantum Hierarchical Clustering, Computational Complexity. Quantum Pattern Recognition: The Quantum Perceptron, Quantum Neural Networks, Computational Complexity. Quantum Classification: Nearest Neighbors, Support Vector Machines with Grover's Search, Support Vector Machines with Exponential Speedup, Computational Complexity.

QE10. Natural and Unconventional computing

Cellular automata. Rules and evolution of cellular automata. Quantum Cellular Automata. Computing processes in biological systems. The computing amoeba. Bio-inspired computation systems. Memristors and memristive circuits. In-Memopry-Computing. Memristive computation architectures and systems. Memristive learning cellular automata. Memristive Quantum Simulators and Circuits. Neurons and Neuromorphic computation. Emergent computing. Crowd dynamics. Swarm intelligence. Cytosceleton computing models. Random walks. Cellular ants computing.

QE11. Linear Algebra for Quantum Mechanics

Eigenvalues and eigenvectors. Matrix diagonalization. Jordan canonical form. Vector spaces and vector subspaces. Linear dependence and linear independence. Basis of a vector space. Dimension of a vector space. Inner products. Inner product spaces. Best approximation. Orthogonal projection. Gram-Smidt orthonormalization. Linear operators. Adjoint operators. Operators in inner product spaces. Orthonormal operators. Isomorphisms. Normal operators. Transformation of symmetric matrices to diagonal form.

QE14. Quantum Optics

The purpose of this course is to introduce the student to basic quantum optics phenomena and connect them with applications in quantum technologies. The course syllabus include: Semiclassical light-matter interaction, probability amplitude approach, two-level system, and Rabi oscillations. Optical Bloch equations. Nonlinear optical response of the two-level system. Three-level systems, CPT and EIT. Quantization of the electromagnetic field, (Fock states, coherent states, squeezed states and their properties). Correlations and photon statistics.

Spatial and temporal coherence. Intensity fluctuations, Hanbury Brown & Twiss Experiment. Quantized light-matter interaction and the Jaynes-Cummings model. Dressed state picture. Quantum Rabi oscillations and collapse and revival. Wigner-Weisskopf theory of spontaneous emission. Resonance fluorescence and the Mollow triplet. Cavity quantum electrodynamics, quantum systems in cavities. Applications of quantum optics in quantum technologies.

Learning outcomes

After completing this MSc. Program the post-graduate students will be able to:

1. Use quantum simulators
2. Program quantum computers
3. Develop novel quantum algorithms
4. Understand and use quantum communication technologies
5. Apply quantum computers to machine learning
6. Design qubit devices and quantum circuits
7. Understand and use quantum key distribution protocols

Faculty

Democritus University of Thrace

Department of Electrical and Computer Engineering

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Courses and Instructors 2024-2025

CODE	COURSE TITLE	SEMESTER	INSTRUCTORS
QY1	Quantum Computing	Winter	Ioannis Karafyllidis
QY2	Quantum Devices	Winter	Panagiotis Dimitrakis (Coordinator) George Mitrikas Michalis Pissas Ioannis Sanakis
QE1	Optical and Quantum Communications	Winter	Kyriakos Zoiros
QE2	Computational Biology	Winter	Petros Kolovos (Coordinator) Raphail Sandaltzopoulos Nicolaos Glykos Aristotelis Papageorgiou Antonios Gianakakis
QE3	Nanoelectronics	Winter	Panagiotis Dimitrakis (Coordinator) Michalis Pissas
QE11	Linear Algebra for Quantum Mechanics	Spring	Christos Schinas
QE5	Applied Quantum Mechanics	Winter	Emmanuel Paspalakis
QE6	Artificial Intelligence and Applications	Winter	Ioannis Boutalis
QE7	Python Programming and Applications	Winter	Georgios Dimitrakopoulos
QE8	Quantum Control	Winter	Emmanuel Paspalakis (Coordinator) Ioannis Thanopulos Dionisios Stefanatos

CODE	COURSE TITLE	SEMESTER	INSTRUCTORS
QY3	Quantum Algorithms and Quantum Information	Spring	Ioannis Karafyllidis
QY4	Qubit Devices	Spring	Panagiotis Dimitrakis (Coordinator) George Mitrikas Michalis Pissas Ioannis Sanakis
QE9	Quantum Machine Learning	Spring	Ioannis Boutalis
QE10	Natural and Unconventional Computing	Spring	Georgios Sirakoulis
QE4	Quantum Solid-state Physics	Winter	Panagiotis Dimitrakis (Coordinator) George Mitrikas Michalis Pissas Ioannis Sanakis
QE14	Quantum Optics	Spring	Emmanuel Paspalakis

MSc. In Quantum Computing and Quantum Technologies
Academic Calendar 2024-2025

Winter Semester -15 weeks

Lecture period – 13 weeks

From Monday, October 14, 2024, until Friday, December 20, 2024 (Ten (10) weeks)

From Monday, January 6, 2025, until Friday, January 24, 2025 (Three (3) weeks)

Winter semester exams: Monday, January 27, 2025, until Friday, February 7, 2025 (Two (2) weeks)

Christmas holidays: From Monday, December 23, 2024, until Friday, January 3, 2025.

Spring Semester – 15 weeks

Lecture period – 13 weeks

From Monday, February 10, 2025, until Friday, April 11, 2025 (Nine (9) weeks)

From Monday, April 28, 2025, until Friday, May 23, 2025 (Four (4) weeks)

Spring semester exams: Monday, May 26, 2025, until Friday June 6, 2025 (Two (2) weeks)

Easter holidays: From Monday, April 14, 2025, until Friday, April 25, 2025.

September Exams for all courses in all semesters.

Monday, September 1, 2025, until Friday, September 26, 2025.

Holidays

Monday, October 28, 2024 (National Holiday)
Monday, March 3, 2025 (Monday of Lent, Religious Holiday)
Tuesday, March 25, 2025 (National Holiday)
Thursday, May 1, 2025 (Labor Day)