AFC – An Introduction to Quantum Computing

Dipartimento di Informatica, Università di Roma “La Sapienza”

Paolo Zuliani (zuliani@di.uniroma1.it)

https://pzuliani.github.io

General goals:
The course aims at equipping students with the foundational concepts of quantum computing that will enable learners to purse further studies or taking up jobs in the quantum IT industry.

Specific goals:
This course has four specific goals:
1. to introduce the mathematical foundations of quantum computing that are necessary to understand the counter-intuitive features of quantum algorithms;
2. to present the fundamental notions of quantum computing;
3. to introduce several non-trivial quantum algorithms and quantum communication protocols, and analyze their behavior;
4. to show how simple quantum algorithms and protocols can be implemented and run on a simulator or a on quantum computer.

Knowledge and understanding:
At the end of the course, students should be aware of and fully understand the main differences between classical and quantum computers, the quantum circuit and bra-ket formalisms, and the main quantum algorithms (Grover’s, Shor’s, HHL, etc.) and protocols (e.g., BB84 and teleportation). In addition, students should be aware of the different technologies for quantum hardware implementation.

Application of knowledge and understanding:
Students will be able to use the theoretical notions presented in class for developing and/or implementing quantum solutions to problems. The computer practicals will give students hands-on experience with quantum circuits run on simulators or quantum computers, to reinforce the theoretical concepts delivered in the lectures. In addition, students will be able to deepen their studies independently by consulting other material on the subject, including the scientific literature.

Critical and judgment skills:
Students will refine these skills through regular problem-solving tasks to do at home. The acquired knowledge and skills will enable students to critically select or adapt existing quantum approaches for solving the problem at hand, or to develop new quantum techniques as necessary. Students will be able to evaluate efficiency and identify pros and cons of their quantum solutions.

Communication skills:
Students will be stimulated to collaborate with their peers through developing and documenting a simple project, and solving the homework assignments.

Ability to follow up on learning:
The course will equip students with the necessary technical background to study at doctoral (PhD) level both relevant topics in cognate fields such as quantum communication and quantum simulation, and specific aspects of quantum computing.

Syllabus

- Status of the quantum computing field
- Review of complex linear algebra
- Linear operators on Hilbert spaces
- Qubits and measurements
- Single-qubit unitary operations (NOT, Hadamard, Pauli matrices)
- Quantum registers (tensor products)
- Entangled states and the EPR paradox
- Multi-qubit operations (CNOT, Toffoli)
- Tensor product of unitary operations
- Schrödinger's equation and the rules of quantum mechanics
- No cloning theorem and teleportation protocol
- Deutsch-Jozsa's and Grover's algorithms
- Quantum phase estimation and Shor's algorithm
- Quantum algorithm for linear systems
- Post-quantum cryptography
- The BB84 and E91 quantum key-exchange protocols
- Bell inequalities and quantum nonlocality
- Basics of quantum information theory (density matrices, superoperators)
- Holevo's bound
- Approximation of single-qubit unitaries
- Approximation of general unitaries (Solovay-Kitaev theorem)
- Quantum programming languages (Silq)

Activities

Language: English.

Lectures: 36 hours (first semester, 2024-25).

CFU: 6.

Reading List

Recommended textbook: *Quantum Computation and Quantum Information*. M.A. Nielsen, I.L. Chuang. Cambridge University Press, 2010.

Other textbooks:

- *Classical and Quantum Computation* (Graduate Studies in Mathematics). A. Yu. Kitaev, A.H. Shen, M.N. Vyalyi. AMS, 2002.
- *Lectures on Quantum Theory: Mathematical and Structural Foundations*. C.J. Isham. Imperial College Press, 1995.
- *Quantum Computing for Computer Scientists*. N.S. Yanofsky, M.A. Mannucci. Cambridge University Press, 2008.
- *Mathematical Foundations of Quantum Mechanics* (New Edition). J. von Neumann. Princeton University Press, 2018.