UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

SYLLABUS DEL CORSO

Quantum Information and Algorithms

2627-2-F9103Q026

Aims

(DdD 1) Knowledge and understanding
The student acquires an in-depth understanding of the foundations of quantum information, open quantum systems and decoherence, the main quantum cryptographic protocols, and models of distributed and advanced quantum computation, including quantum machine learning approaches.

(DdD 2) Applying knowledge and understanding
The student is able to analyze and classify advanced quantum algorithms — from fundamental subroutines to variational algorithms for QML — and to implement them using appropriate formalisms, including quantum channels, variational circuits, and distributed protocols.

(DdD 3) Making judgements
The student is able to critically assess the potential and limitations of quantum algorithms and protocols — from error correction to cryptography, from distributed computation to quantum machine learning — with respect to specific computational problems and concrete application scenarios.

(DdD 4) Communication skills
The student is able to present theoretical and applied results across the different areas of the course — cryptography, quantum communication, advanced algorithms, and QML — with clarity, precision, and appropriate technical language, including in interdisciplinary contexts and before an academic audience.

(DdD 5) Learning skills
The student develops the ability to independently keep up to date in a rapidly evolving field, integrating theoretical and practical competencies through advanced scientific literature and emerging platforms in quantum computation, cryptography, and quantum machine learning.

Contents

The course provides an introduction to representative topics in the following thematic areas:

1. Open Quantum Systems
2. Quantum Cryptography
3. Distributed Quantum Computation
4. Advanced Quantum Algorithms
5. Quantum Machine Learning

Detailed program

0. Review of the foundational methods and tool

Pauli and Clifford operators and gates
Entanglement vs. Interference
The Bell state basis
Density matrix theory
Pure vs. Mixed states

1. Open Quantum Systems (modelling Decoherence)

Composite systems and Reduced states
Expansion, Evolution and Reduction.
Quantum Channels: Stinespring, Kraus and Choi representations
Decoherence and non-ideal channels: Qubit Reset, Dephasing, Depolarizing channels
Elements of Quantum Error-Correction
Shannon Entropy and Mutual Information in classical systems
Von Neumann Entropy and Mutual Information in Quantum Systems

2. Quantum Cryptography (representative protocols)

Quantum Cryptography Primitives
Quantum Key Distribution Protocols: Bennet & Brassard 84, Bennet 92, Ekert 91
Quantum Homomorphic Encryption
Quantum Secret Sharing
Quantum Encrypted Cloning

3. Quantum Communication and Distributed Quantum Computing (DQC)

Quantum Teleportation and Dense coding
The non-local CNOT
The DQC primitives
The Quantum Internet

4. Advanced Quantum Computation (selected advanced algorithms)

Quantum “Subroutines” (e.g. phase kick-back)
Review of “the Canon”, well-known algorithms and some variants (ex. Fixed-Point Grover)
Further notable algorithms: Shor factorization algorithm

5. Quantum Machine Learning (selected advanced algorithms)

Information Encoding in Quantum Systems
Quantum Neural Networks (QNNs) and Variational Quantum Circuits (VQCs)
Quantum Kernel Methods and Support Vector Machines
Quantum Principal Component Analysis (qPCA) and Quantum Linear Algebra (HHL)

Prerequisites

Linear algebra, and mathematical topics covered in undergraduate courses held in STEM bachelor degrees. Understanding of basic concepts in statistics and machine learning.

Attendance of the course Fundations of Quantum Computing (1st year M.Sc.), or an equivalent course.

Teaching form

The course consists of

- classroom lectures (DE 32 hours)
- interactive laboratory exercises and programming activity (DI 24 hours)

All activities will be held in presence.

The course will be delivered in English.

Textbook and teaching resource

Lecture notes and scientific papers provided by the lecturer.

To further explore the topics in greater detail, the following texts are useful:

- Vathsan - Introduction to Quantum Physics and Infromation Processing - CRC Press 2016
- Hayashi - Introduction to Quantum Information Science - Springer-Verlag Berlin Heidelberg 2015
- Wolfgang Polak, Eleanor Rieffel: Quantum Computing : A Gentle Introduction. MIT Press, 2011
- Schuld & Petruccione: Machine Learning with Quantum Computers. Springer 2021
- Schuld & Petruccione: Supervised Learning with Quantum Computers. Springer 2018

Semester

Second Year, First Semester

Assessment method

The learning assessment is based on an oral interview, on the subjects exposed in class during the course and on the evaluation of the lab project deliverables.

Evaluation criteria:

- Understanding of Concepts (in-depth and comprehensive understanding of course topics)
- Problem-Solving Skills (application of theoretical knowledge and creativity)
- Ability to Explain and Discuss (clarity, synthesis and critical thinking)

Office hours

Upon appointment.

Sustainable Development Goals

QUALITY EDUCATION | INDUSTRY, INNOVATION AND INFRASTRUCTURE