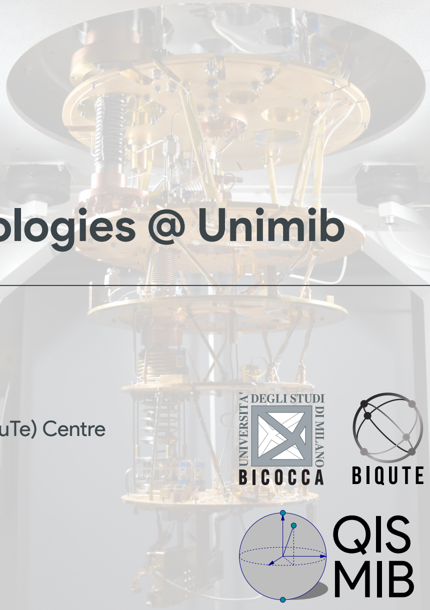


Quantum technologies @ Unimib

Andrea Giachero

University of Milano-Bicocca
INFN - Milano-Bicocca
Bicocca Quantum Technologies (BiQuTe) Centre

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

BIQUTE

NQSTI
National Quantum Science and Technology Institute

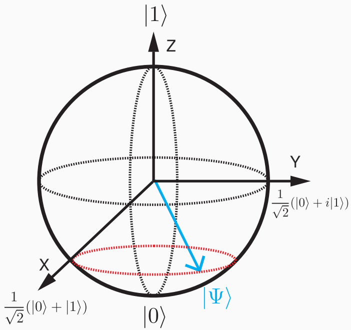
QIS MIB

INFN
Istituto Nazionale di Fisica Nucleare

CSN5
Ricerca
Tecnologica

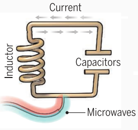
Quantum Information Science and Technology (QIST)

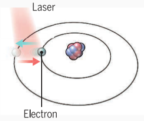
Quantum Information Science and Technology harnesses the power of quantum mechanics for understanding, design, construction and investigation of quantum information processing systems, such as quantum computers, quantum communication networks, and quantum sensors;

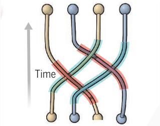


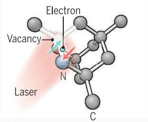
- A bit is the most basic unit of classical logic and can occupy one of two discrete states, 0 or 1
- A quantum bit is the arbitrary superposition of the eigenstates $|0\rangle$ and $|1\rangle$ or $|\Psi\rangle = a_0 |0\rangle + a_1 |1\rangle$ where $|a_0|^2$ and $|a_1|^2$ are the occupation probabilities of the $|0\rangle$ and $|1\rangle$ state, respectively
- n classical bits can only exist in one of the 2^n possible states;
- n qubits can be placed in a complex superposition state of all 2^n permutations,
- a quantum processor can contain exponentially more information than a conventional processor;
- certain classically intractable problems that benefit from known quantum algorithms;

Technologies used to build quantum computers





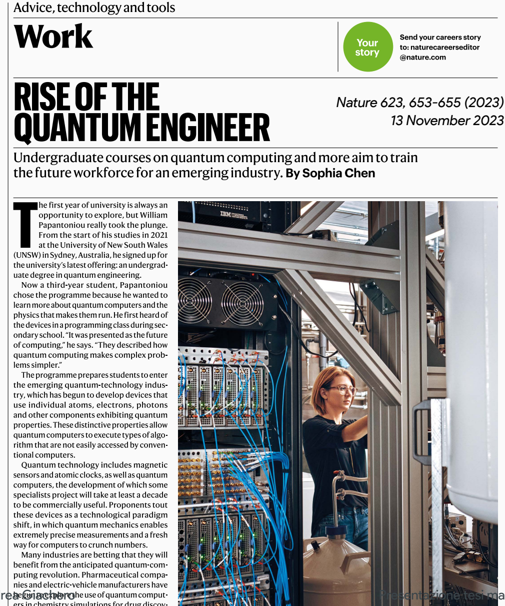




	Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
⊕ **Pros**	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
⊖ **Cons**	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Science 354 (2016) 1090-1093

The future is quantum



Advice, technology and tools

Work

Your story

Send your careers story to: naturecareerseditor@nature.com

RISE OF THE QUANTUM ENGINEER

Nature 623, 653-655 (2023)
13 November 2023

Undergraduate courses on quantum computing and more aim to train the future workforce for an emerging industry. **By Sophia Chen**

The first year of university is always an opportunity to explore, but William Papantoniou really took the plunge. From the start of his studies in 2021 at the University of New South Wales (UNSW) in Sydney, Australia, he signed up for the university's latest offering: an undergraduate degree in quantum engineering.

Now a third-year student, Papantoniou chose the programme because he wanted to learn more about quantum computers and the physics that makes them run. He first heard of the devices in a programming class during secondary school. "It was presented as the future of computing," he says. "They described how quantum computing makes complex problems simpler."

The programme prepares students to enter the emerging quantum-technology industry, which has begun to develop devices that use individual atoms, electrons, photons and other components exhibiting quantum properties. These distinctive properties allow quantum computers to execute types of algorithm that are not easily accessed by conventional computers.

Quantum technology includes magnetic sensors and atomic clocks, as well as quantum computers, the development of which some specialists project will take at least a decade to be commercially useful. Proponents tout these devices as a technological paradigm shift, in which quantum mechanics enables extremely precise measurements and a fresh way for computers to crunch numbers.

Many industries are betting that they will benefit from the anticipated quantum-computing revolution. Pharmaceutical companies and electric-vehicle manufacturers have begun to explore the use of quantum computers in chemistry simulations for drug discov-

- Technology companies such as Google, Microsoft, IBM, Amazon and smaller start-ups (Rigetti, IQM, Quantinuum, IonQ, etc) invests resources and funds to developed quantum-technology industry;
- Governments, including the European Union and Italy, have collectively pledged billions of dollars for the same purpose;
- Universities have the mission of adequately preparing students to become qualified job candidates;
- ... and the University of Milano-Bicocca is actively playing its role in fulfilling this mission

Google
QUANTINUUM
IBM
rigetti
XANADU
D-Wave The Quantum Computing Company
IONQ
atom computing

Quantum technologies at Unimib

The University of Milano-Bicocca and the Department of Physics are member and leads project funded by

- the Bicocca Quantum Technologies (BiQuTe) centre;
- the National Quantum Science and Technology Institute (NQSTI);
- the National Centre for HPC, big data and quantum computing (ICSC);
- the Italian Institute of Nuclear Physics (INFN) with two active projects;
- the European Union with two active projects;
- the CERN DRD5/RDq roadmap for quantum sensing for particle physics;

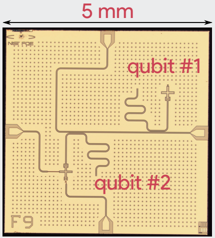
The main activities carried out at the department of physics are:

- Design and simulation of single or coupled qubit for quantum computing;
- Design and simulation of qubit optimized for quantum sensing (light dark matter detection);
- Measurement and characterization of qubit with innovative electronics;
- Design and simulation of quantum limited parametric amplifier for qubit and detector read out;
- Design and simulation of quantum limited parametric amplifier as squeezed microwave radiation source;
- Development of quantum algorithms for simulations, classification, key distribution and error correction/mitigation;

Available Experimental Theses

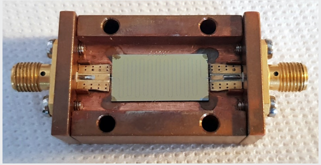
Development of qubits

- Design and simulations of qubit by using dedicated python packages (qiskit-metal and KQCircuits) and commercial software (Ansys HFSS and Ansys Q3D);
- Fully characterization of qubit (qubit and resonator Spectroscopy, Ramsey, and Rabi measurements, etc)
- Contact: Andrea Giachero andrea.giachero@mib.infn.it
  Angelo Nucciotti angelo.nucciotti@mib.infn.it
  Marco Faverzani marco.faverzani@mib.infn.it

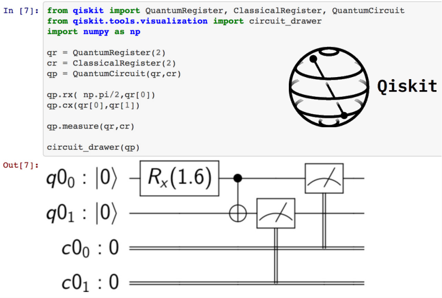


Development of parametric amplifiers

- Design and simulations of traveling wave parametric amplifier (TWPA) by using custom python packages and commercial software (Sonnet);
- Fully characterization of the devices (gain, noise, compression point, etc)
- Contact: Andrea Giachero andrea.giachero@mib.infn.it
  Angelo Nucciotti angelo.nucciotti@mib.infn.it
  Elena Ferri elena.ferri@mib.infn.it



Quantum Computing on the cloud



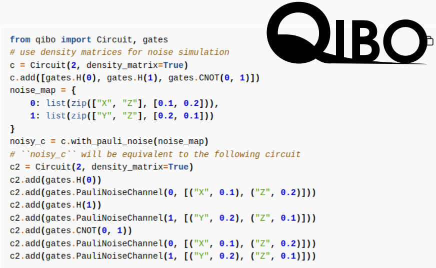
```
In [7]: from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
        from qiskit.tools.visualization import circuit_drawer
        import numpy as np

        qr = QuantumRegister(2)
        cr = ClassicalRegister(2)
        qp = QuantumCircuit(qr,cr)

        qp.rx( np.pi/2,qr[0])
        qp.cx(qr[0],qr[1])

        qp.measure(qr,cr)

        circuit_drawer(qp)
Out[7]:
```



```
from qibo import Circuit, gates
# use density matrices for noise simulation
c = Circuit(2, density_matrix=True)
c.add([gates.H(0), gates.H(1), gates.CNOT(0, 1)])
noise_map = {
    0: list(zip(["X", "Z"], [0.1, 0.2])),
    1: list(zip(["Y", "Z"], [0.2, 0.1]))
}
noisy_c = c.with_pauli_noise(noise_map)
# ``noisy_c`` will be equivalent to the following circuit
c2 = Circuit(2, density_matrix=True)
c2.add(gates.H(0))
c2.add(gates.PauliNoiseChannel(0, [("X", 0.1), ("Z", 0.2)]))
c2.add(gates.H(1))
c2.add(gates.PauliNoiseChannel(1, [("Y", 0.2), ("Z", 0.1)]))
c2.add(gates.CNOT(0, 1))
c2.add(gates.PauliNoiseChannel(0, [("X", 0.1), ("Z", 0.2)]))
c2.add(gates.PauliNoiseChannel(1, [("Y", 0.2), ("Z", 0.1)]))
```

Goal: development of quantum applications exploiting cloud framework for quantum computing (qiskit, Qibo, PennyLane, and Yao)

Possible Topics:

- Quantum simulations of quantum chemistry systems on quantum computers;
- Quantum noise characterization and development of reduction techniques;
- Quantum communication, quantum cryptography, and quantum encryption;
- Quantum machine learning: hybrid quantum classical methods, quantum neural networks, etc,
- Qubits calibration and characterization by pulse interface;

Available Quantum Computing Theses

The primary mission of the Quantum Information Science Milano-Bicocca (QISMIB) initiative at the University of Milano-Bicocca is to introduce undergraduate and master students to the main foundational concepts of quantum computing, as well as to provide them with the necessary theoretical and experimental tools to pursue research in this field.

Contact: Andrea Giachero andrea.giachero@mib.infn.it

Available works

- **Quantum Simulations:** Variational Quantum Eigensolver (VQE) allows to simulate molecular systems in a computational efficient way
- **Quantum Machine Learning:** combines the principles of quantum mechanics and machine learning to create new algorithms and models that can solve problems in a more efficient;
- **Quantum Key Distribution:** method for secure communication that uses the principles of quantum mechanics to establish a secret key between two parties;
- **Quantum Error Mitigation:** a series of techniques aimed at reducing (mitigating) the errors that occur in quantum computing algorithms;

more information at qismib.github.io

Other proposal

Inclusion of error mitigation routines in Variational Quantum Circuit model training

State-of-the-art quantum error mitigation methods cannot address the exponential concentration loss induced by noise in current devices. We propose to test and combine different routines to enhance Variational Quantum Circuit s trainability by reducing the corruption of the loss function. The algorithm under consideration could be the fit of a mono - dimensional Parton Distribution Function (PDF) on a superconducting single - qubit device. Starting from the paper arXiv:2309.03279 [quant-ph], we would test its applicability under a real noisy scenario.

In collaboration with CERN, with a potential visiting period.

Contact: Pietro Govoni pietro.govoni@unimib.it

Particles Tracking with Quantum Algorithms

The reconstruction of particle trajectories in high-energy physics experiments at a hadron collider is a computing-intensive task due to the high multiplicity of particles in the final state. Particles tracking is classically performed with global (Hough transforms, Hopfield neural networks) or local (Kalman filter) algorithm approaches. Heterogeneous computing models are now taking place to exploit a high degree of parallelism in the calculations. In this scenario, quantum computing algorithm are worth checking since they may offer computation advantages with respect to the currently used classical ones.

Contact: Maurizio Martinelli maurizio.martinelli@unimib.it

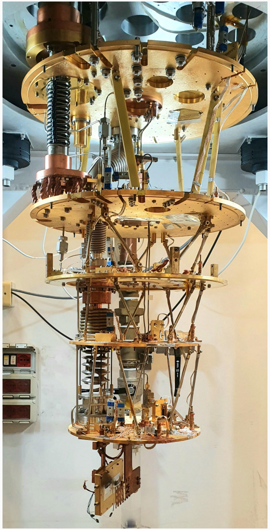
Master Classes

Corsi per la Laurea Magistrale in Fisica

- Theory of Quantum Information and Quantum Computing
- Applied Quantum Technologies
- Quantum Materials
- Laboratory of Solid State and Quantum Technologies I
- Laboratory of Solid State and Quantum Technologies II

Collaborazione per tesi magistrali

- Chalmers University of Technology (Gothenburg, Sweden);
- Aalto University (Espoo, Finland);
- Institut Neel (Grenoble, France);
- National Institute of Standards and Technology (Boulder, Colorado, USA);
- University of Colorado Boulder (Boulder, Colorado, USA);
- Stanford University / SLAC National Accelerator Laboratory (Silicon Valley, California, US)
- École Polytechnique Eédérale de Lausanne (Lausanne, Switzerland)



Quantum Horizons: Unveiling Expertise through a Thesis Journey

- **Advanced Expertise:** a thesis allows you to deepen your knowledge and expertise in quantum technologies, positioning you as a specialist in this cutting-edge field;
- **Practical Implementation Skills:** engaging in a thesis provides hands-on experience in implementing quantum concepts, translating theoretical knowledge into practical applications;
- **Career Advancement:** completing a thesis in quantum technologies enhances your resume and opens up diverse career opportunities, as industries increasingly seek professionals with expertise in this field;
- **Contributing to Research:** through a thesis, you have the chance to contribute to the ongoing research in quantum technologies, adding valuable insights and advancements to the growing body of knowledge;
- **Networking Opportunities:** pursuing a thesis in quantum technologies exposes you to a network of experts, researchers, and professionals in the field, providing valuable connections for future collaborations and career growth;

Master Classes

Corsi per la Laurea Magistrale in Fisica

- Theory of Quantum Information and Quantum Computing
- Applied Quantum Technologies
- Quantum Materials
- Laboratory of Solid State and Quantum Technologies I
- Laboratory of Solid State and Quantum Technologies II

Collaborazione per tesi magistrali

- Chalmers University of Technology (Gothenburg, Sweden);
- Aalto University (Espoo, Finland);
- Institut Neel (Grenoble, France);
- National Institute of Standards and Technology (Boulder, Colorado, USA);
- University of Colorado Boulder (Boulder, Colorado, USA);
- Stanford University / SLAC National Accelerator Laboratory (Silicon Valley, California, US)
- École Polytechnique Eédérale de Lausanne (Lausanne, Switzerland)

Grazie per l’attenzione!!!

Contatti

- Andrea Giachero andrea.giachero@mib.infn.it
- Angelo Nucciotti angelo.nucciotti@mib.infn.it
- Marco Faverzani marco.faverzani@mib.infn.it
- Elena Ferri elena.ferri@mib.infn.it

Ulteriori Informazioni

- Descrizione tesi su quantum computing *https://qismib.github.io*
- Sito per il Bicocca Quantum Technologies Centre *https://biqute.unimib.it*
- Sito per il National Quantum Science and Technology Institute *https://nqsti.it*
- Sito per il progetto DARTWARS *https://dartwars.unimib.it*
- Sito per il progetto Qub-IT *https://web.infn.it/qub-it/*