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XXXIV Cycle

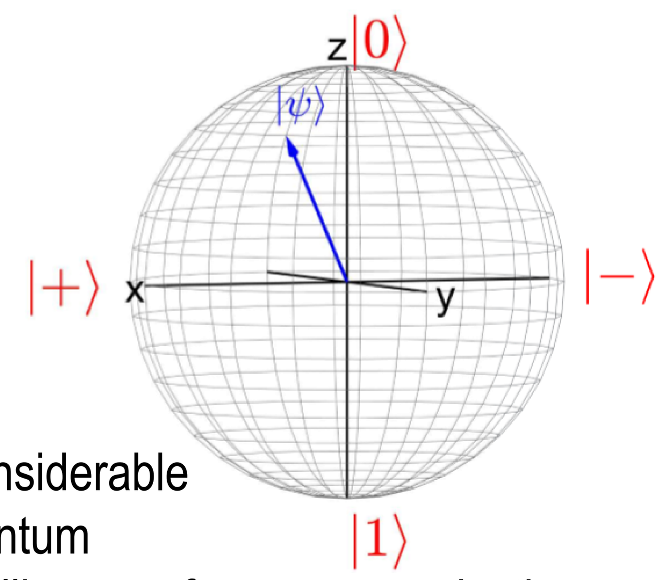
Emerging technologies for Quantum Computing: characterization and potential architectures

Giovanni Amedeo Cirillo

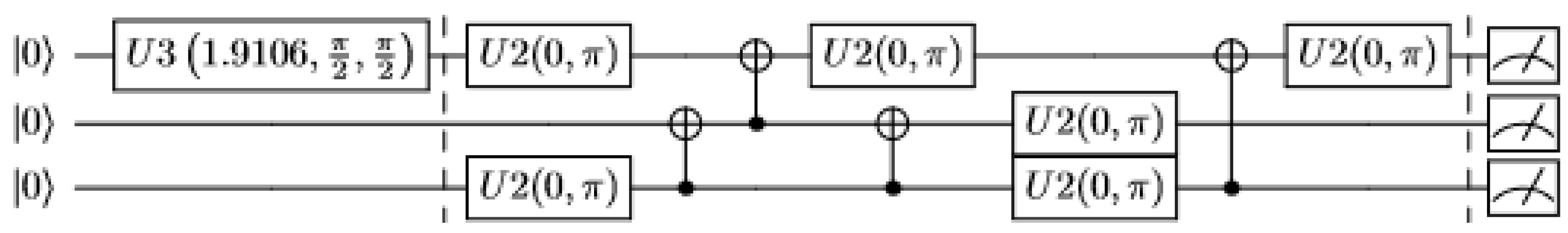
Supervisor: Prof. Mariagrazia Graziano

Research context and motivation

- Quantum Computing (QC) is a new computational paradigm where the unit of information, named qubit, is mapped on a quantum physical quantity. Since quantum states are characterized by superposition, the qubit theoretically has a non-null probability of being in two different states (encoding 0 and 1) at the same time.
- Superposition permits to define an equivalent parallel computation model, involving algorithms faster than the corresponding classical ones. Quantum Computing Devices can potentially solve problems that classical computers practically cannot (quantum advantage), *e.g.* for the simulation of quantum systems.
- Academic and private research activities are providing considerable efforts in studying potential contests of application of Quantum Computers: from optimization problems to artificial intelligence, from communications to quantum simulation.



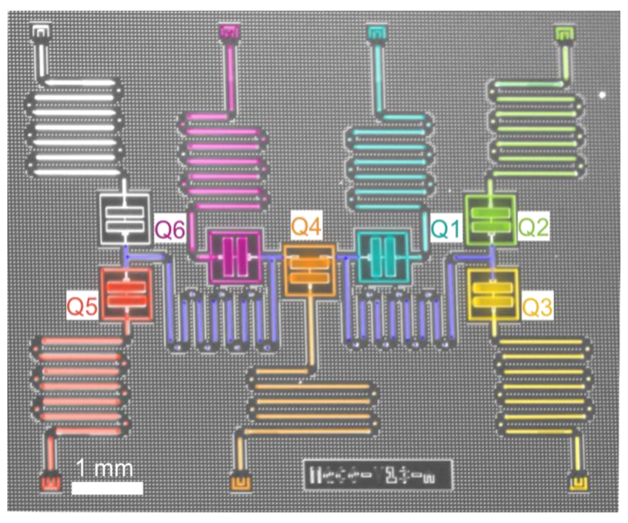
- Quantum computation is based on the so-called quantum circuit model, where all the operations are implemented as sequences of quantum gates changing the probability amplitudes of the Quantum Computer basis vectors, *i.e.* its potential results.

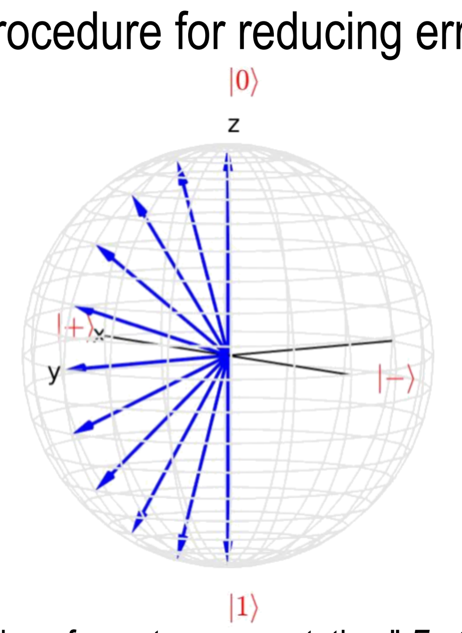


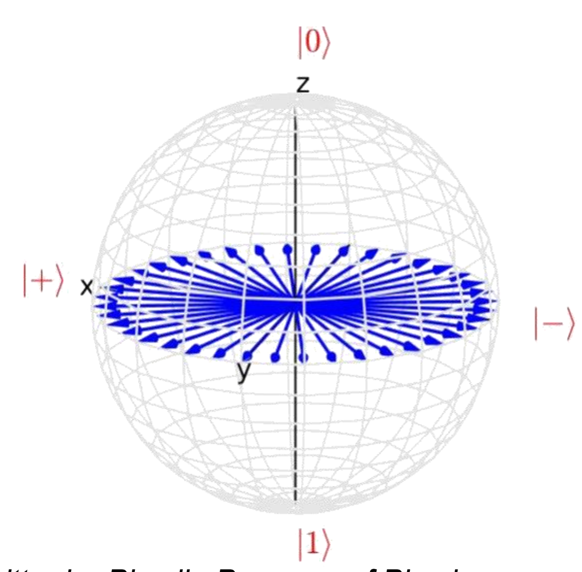
- Some fabricated Quantum Computers (*e.g.* by IBM) are nowadays available via-cloud, even though they are inherently affected by errors; for these reasons, these are defined Noisy Intermediate Scale Quantum (NISQ) Computers.

Addressed research questions/problems

- Many potential technologies for making a Quantum Computer have been proposed in the last twenty years: superconductor, trapped ions, photons, ultracold atoms in optical lattices and spin systems as quantum-dots, silicon and molecules, which can be as organic as inorganic.
- The main limitations for the development and fabrication of quantum computers are related to the difficulties in satisfying the DiVincenzo criteria for candidate QC technologies [1].
- A mechanism for comparing the contemporary NISQ technologies is required, in order to establish which is the best technology capable for solving a given problem.
- A necessary preliminary operation is building simulation models for each quantum technology which take into account the useful properties and the drawbacks of theirs.
- The development of efficient quantum circuit transpilers, *i.e.* modification procedures for the quantum gates/circuits to be applied on a certain hardware according to its limitations and constraints, is another important procedure for reducing errors on NISQ devices.







[1] DiVincenzo, David P. "The physical implementation of quantum computation." *Fortschritte der Physik: Progress of Physics* 48.9-11 (2000): 771-783.

Awards

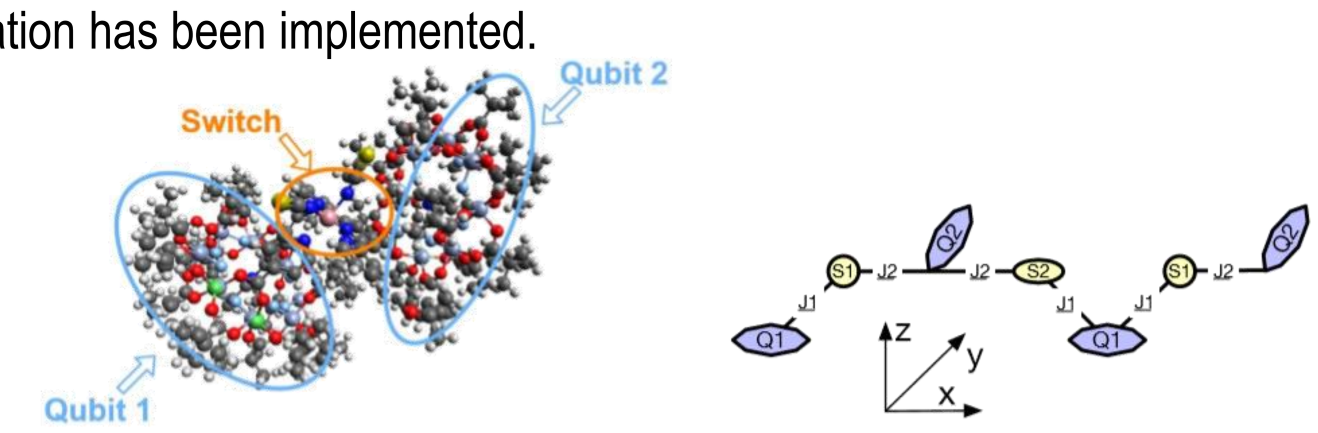
Costa Hamido, O., Ghazi Vakili, M., Giusto, E., Baiardi, A., and Cirillo, G.A., "*Quantum Synth: a quantum-computer-based music synthesizer*", **Qiskit Camp Europe 2019, Schilthorn, Switzerland, 13-14 sept. 2019, Community Choice Award**.

Submitted and published works

- Cirillo, G. A. , Turvani, G., and Graziano, M., "*A quantum computation model for molecular nanomagnets*", IEEE Transactions on Nanotechnology, 2019, DOI:10.1109/TNANO.2019.2939910
- Garlando, U., Riente, F., Cirillo, G. A., Graziano, M., and Zamboni, M., "*Design and Characterization of Circuit based on Emerging Technology: the MagCAD Approach*", IEEE 18th International Conference on Nanotechnology (IEEE-NANO), Cork, Ireland, 2018, pp. 1-4
- Riente, F., Turvani, G., Ranone, P., Cirillo, G. A., Vacca, M., Zamboni, M., and Graziano, M., "Topology optimization and Monte Carlo multithreading simulation for fault-tolerant nanoarrays", Journal of Computational Electronics, vol. 17, no. 3, September 2018, pp. 1356-1369

Novel contributions

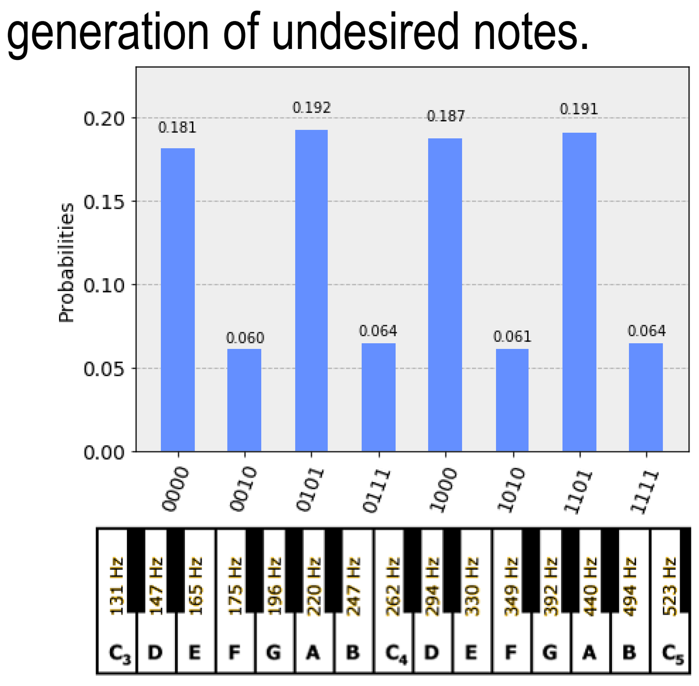
1) Development of a MATLAB model (up to four qubits) for Cr7Ni-Co-Cr7Ni molecular nanomagnets, a technology theoretically scalable which has been proved to implement a universal set of quantum gates. A technology-dependent simulator – programmable with the quantum Hardware Description Language OpenQASM - has been developed for testing the computational capabilities of the molecule. Virtual-Z quantum circuit optimization has been implemented.

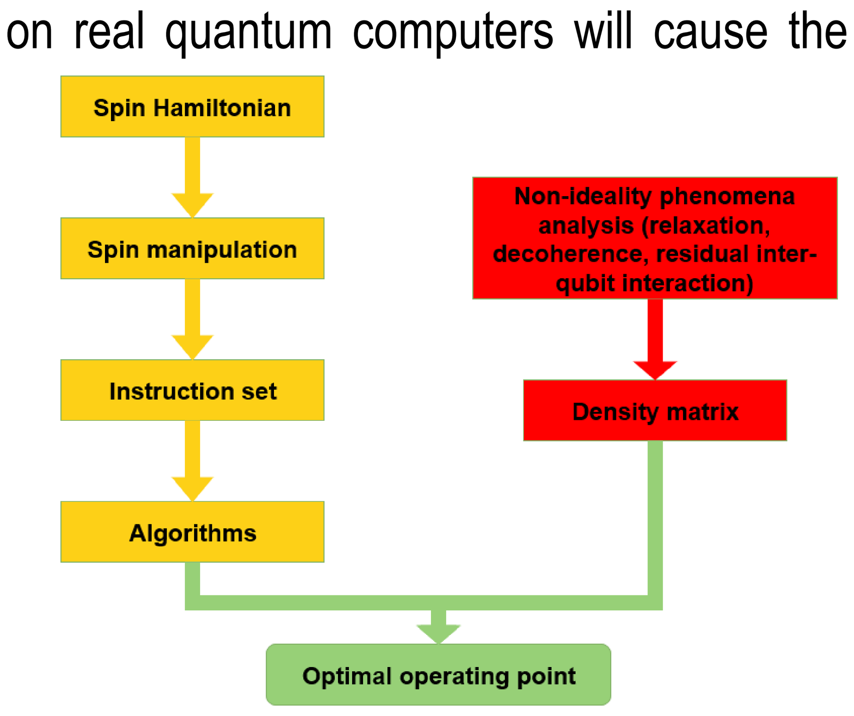


2) Development of "Quantum Synth", an interface between superconducting IBM quantum computers and a professional audio synthesizer. The platform stands in the context of analysis of real quantum hardware non-idealities (measurement errors, noise, *etc.*). Sound generation depends on the results of quantum circuits applied on quantum hardware. A "phonic" interpretation of Grover's search algorithm has been proposed.

Adopted methodologies

1) Cr7Ni-Co-Cr7Ni molecular nanomagnets:
   a) Bottom-up methodology, starting from the molecule's Hamiltonian up to the analysis of elementary algorithms in presence of non-idealities (relaxation, decoherence, undesired qubits interaction), extendable to other technologies.
   b) Defintion of an optimal operating point, where non-idealities provide negligible contributions.
2) «Quantum synth»: generate superposition of notes encoded on the basis states of a quantum computer. Each result providable by the quantum computer is associated to a specific harmonic. The presence of noise on real quantum computers will cause the generation of undesired notes.





Future work

- Analysis of quantum computation technologies different from Cr7Ni-Co-Cr7Ni molecular nanomagnets (superconducting qubits, trapped ions, silicon qubits, *etc.*).
- Design of optimized, technology-dependent quantum circuit transpliers (gate-level compilers).
- Optimization of the simulation procedure on classical hardware for systems with many qubits (≥ 20)
- Development of a unique simulation environment, reliably employable on classical computers, for comparing different backend technologies given the same quantum circuit or algorithm.
- Integration of the technology-dependent simulator systems inside Qiskit, the open-source framework for quantum computing founded by IBM Research.
- Exploit "Quantum synth" for studying the noise properties of the real quantum computers, fundamental for improving their fabrication processes and computational capabilities.

List of attended classes

- CHI0056 – Chimica computazionale Università degli Studi di Torino (14/2/2019, 30 hours)
- 01SOKOQ – Integrazione di sistemi embedded (1/3/2019, 60 hours)
- 01SFURV – Programmazione scientifica avanzata in matlab (27/3/2019, 28 hours)
- 01TAHIU – Quantum computing (29/4/2019, 20 hours)
- 03SGVRV – Entrepreneurship and start-up creation from University Research (9/5/2019, 40 hours)
- 01LDVRU – Magnetismo nei materiali e misure magnetiche(12/6/2019, 20 hours)
- Quantum Information for Developers Summer School ETH Zürich (19/9/2019, 24 hours)

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