Digital Quantum Simulations with Superconducting Circuits

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Superconducting circuits are a promising quantum technology for the implementation of quantum information protocols. In particular, digital quantum simulations are an efficient method for reproducing quantum dynamics that are not produced naturally in available quantum platforms. We propose a method for simulating efficiently the dynamics of prototypical spin and fermionic models in circuit quantum electrodynamics architectures with either qubit-qubit pairwise interactions, or resonators acting as quantum buses. We show how to implement Ising and Heisenberg spin models, and the Fermi-Hubbard model, making use of the Jordan-Wigner mapping and Mølmer-Sørensen gates. Furthermore, we propose digitized adiabatic quantum computing protocols for spin Hamiltonians where the generality of the adiabatic algorithm and the universality of the digital approach are combined.

Motivation

Digital methods allow one to reproduce dynamics that do not appear naturally in controllable quantum technologies and are unfeasible in analog quantum simulations. Superconducting circuits have turned into one of the most advanced quantum technologies in the last decades due to its high controllability. Spin and fermionic system dynamics represent interesting problems in the fields of condensed matter and quantum information, and optimization problems can be encoded in adiabatic quantum evolutions.

Trotter expansion

Simulating a Hamiltonian H when the system does not provide it, while a set of Hamiltonians $\{H_1, H_2, \dots, H_N, H_{N+1}, \dots\}$ is accessible

$$H = \sum_{i=1}^{N} H_i \qquad e^{-iHt} \sim \left(e^{-iH_1 t/l} \cdots e^{-iH_N t/l}\right)^l + \sum_{i<j} \frac{[H_i, H_j]t^2}{2l}$$

Simulation of spin models

Models

Heisenberg

$$H_H = J\sum_{\langle i,j\rangle} \sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y + \sigma_i^z\sigma_j^z$$

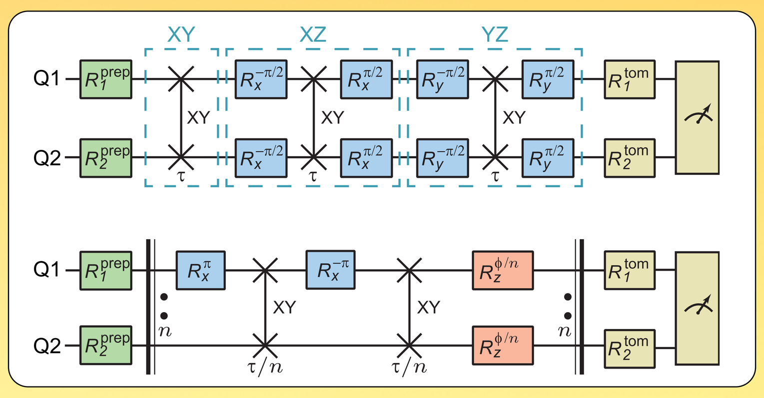
Ising with transverse field

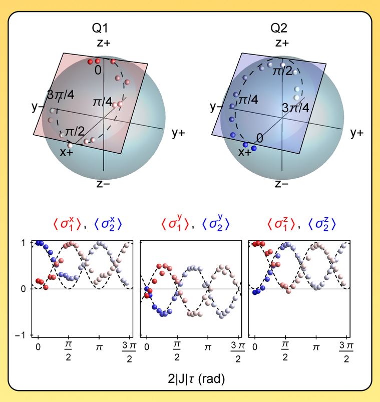
$$H_I = J\sum_{\langle i,j\rangle} \sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z$$

Experiment by ETH Zurich/Bilbao

Using resonators as quantum buses

Gates: XY & single qubit rotations





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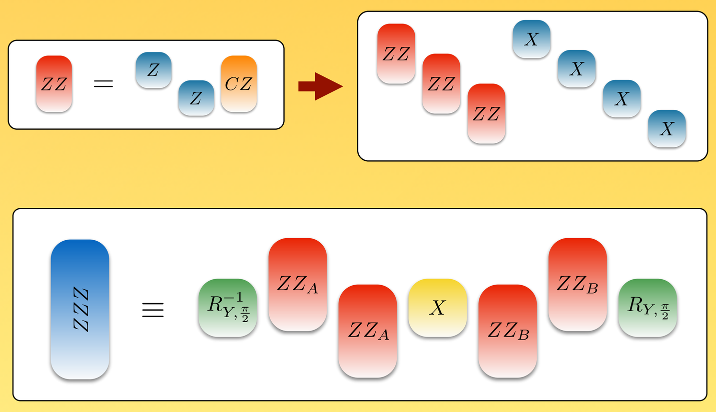
Pairwise coupled qubits

Gates: C-Phase & single-qubit rotations

ZZ gate building block

N-body interactions



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Simulation of Fermi-Hubbard model

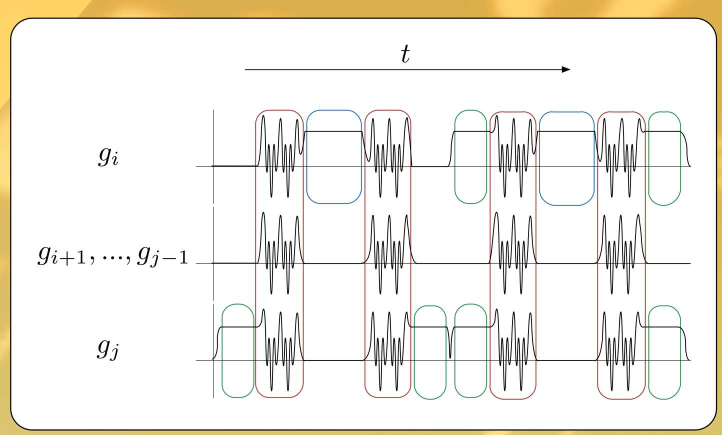
Jordan-Wigner mapping

Encoding fermionic interactions in quantum bits with non-local operations

$$b_i^\dagger b_j + b_j^\dagger b_i$$

$$\downarrow$$

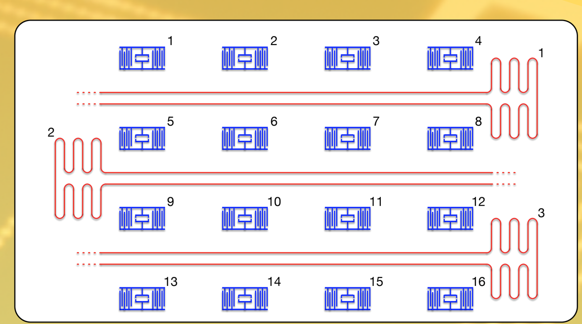
$$-(\sigma_i^x \otimes \sigma_{i+1}^z \otimes \cdots \otimes \sigma_{j-1}^z \otimes \sigma_j^x + \sigma_i^y \otimes \sigma_{i+1}^z \otimes \cdots \otimes \sigma_{j-1}^z \otimes \sigma_j^y)/2$$



Mølmer-Sørensen/*N*-body gates required (can be decomposed digitally)

2D fermionic lattices

Proposals for simulating nearest and next-nearest neighbor interactions with optimized superconducting circuit architectures



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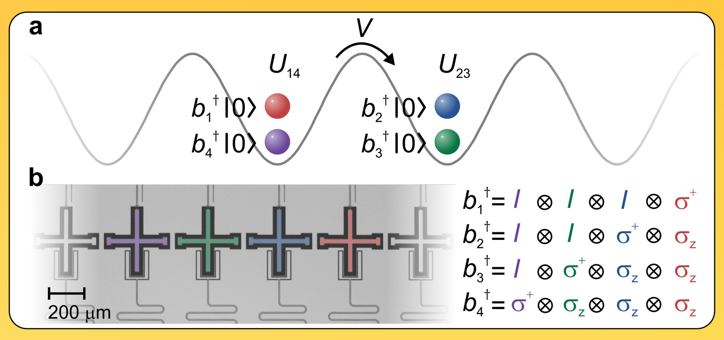
Experiment by Google/UCSB/Bilbao



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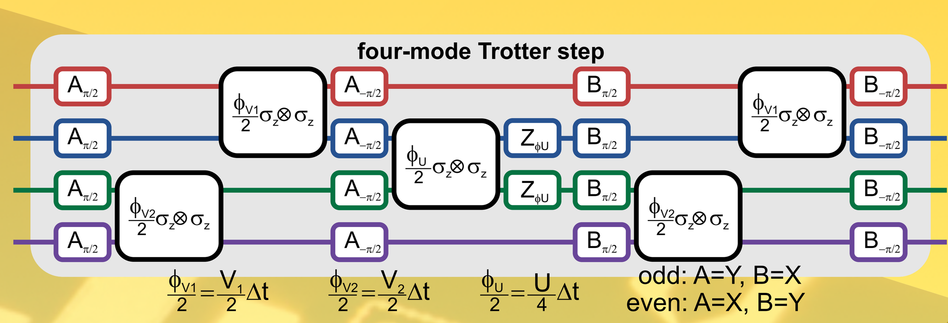
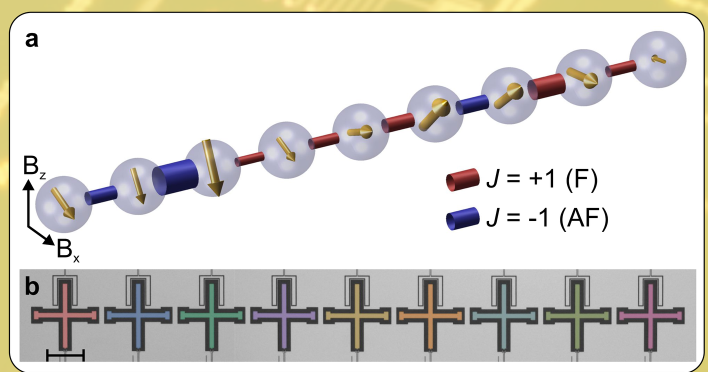


Digitized adiabatic quantum computing

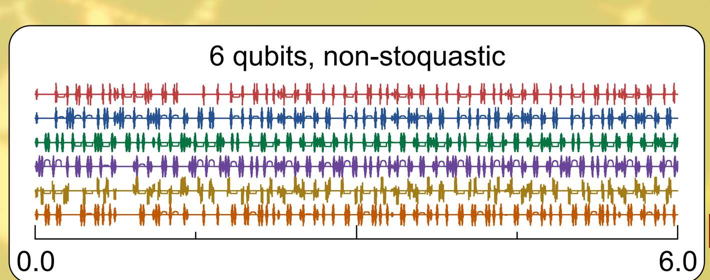
Experiment by Google/UCSB/Bilbao

$$H_I(t) = J(t)\sum_{\langle i,j\rangle} \sigma_i^z\sigma_j^z + B(t)\sum_i \sigma_i^x$$

Couplings are artificially modified in each Trotter step achieving an adiabatic evolution of the ground state in a 9-qubit superconducting chip



Real pulse sequence in the experiment



Total number of gates $>10^3$ with 52 entangling gates

[6]

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[2] Y. Salathé, et al., Phys. Rev. X 5, 021027 (2015).
[3] U. Las Heras, L. García-Álvarez, A. Mezzacapo, E. Solano, L. Lamata, Mathematics for Industry 11, arXiv:1507.02553 (2015).
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[7] U. Las Heras, U. Alvarez-Rodriguez, E. Solano, and M. Sanz, Phys. Rev. Lett. 116, 230504 (2016).
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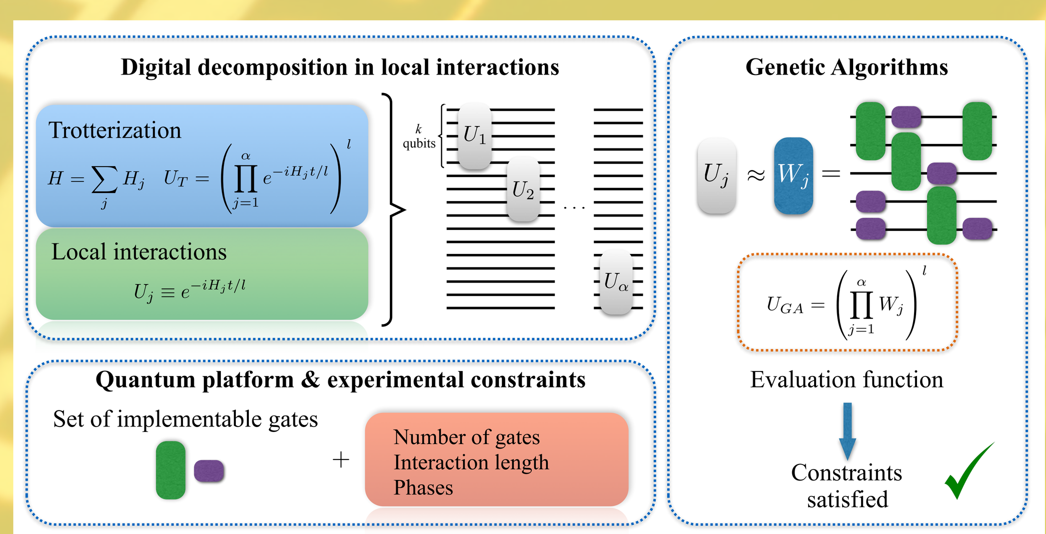
Unconventional approaches to DQS

Genetic Algorithms for DQS



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Algorithmic Quantum Simulations

An Algorithmic Quantum Simulator (AlQS) is a classical algorithm on top of which, we can make use of a Analog Quantum Simulator (AnQS). This increases the flexibility of the AnQS, allowing to solve many different problems. We have employed a Markovian AnQS to solve a large variety of memory (Non-Markovian) effects, and even use it as a solver of integro-differential equations.

[8]

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