JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

QUANTUM INFORMATION PROCESSING

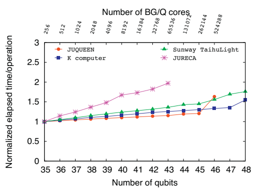
SIMULATION ON/OF QUANTUM COMPUTERS

- **High performance computing for simulating the real-time dynamics of spin-1/2 quantum computers up to 48 qubits**
- **Simulation of physical models of multi-qubit systems**
- **Analysis and exploration of D-Wave quantum annealers**
- **Exploration and performance tests of the IBM Quantum Experience with 5 qubits**

Ideal quantum computer with spin-1/2 qubits

Massively parallel quantum spin dynamics simulator simulates $N \geq 40$ qubit quantum computer on JURECA, JUQUEEN, K and Sunway TaihuLight

- Simulator to develop and test quantum algorithms and applications
- Nearly perfect scaling with increasing problem size and number of cores
- Beats exponential scaling: wall clock time O(N)



Weak scaling behavior for executing a Hadamard gate on each qubit. The elapsed time is normalized by the values for running the 35-qubit circuit.

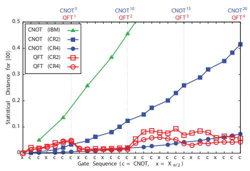
H. De Raedt, et al., Massively parallel quantum computer simulator, eleven years later, arXiv:1805.04708

Superconducting qubits

Simulation of the real-time dynamics of a system of

- two superconducting flux qubits (rf-SQUIDS) coupled by an rf-SQUID, the building blocks of the D-Wave quantum processors, shows that the system can be well described by two spin-1/2 qubits coupled by an harmonic oscillator
- two transmon qubits coupled by a resonator, the building blocks of the 5-qubit IBM QX device, shows that the system modelled as the lowest eigenstates of two Cooper Pair Boxes in the transmon regime coupled to an harmonic oscillator cannot be represented by two spin-1/2 qubits coupled to an harmonic oscillator

Simulation and IBM QX results show that gate metrics provide insights into errors of the implemented gate pulses, but this information is not enough to assess the error induced by repeatedly using the gate in quantum algorithms.



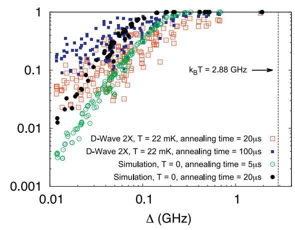
On a transmon qubit device a CNOT gate can be implemented as a two-pulse (four-pulse) echoed cross-resonance gate CR2 (CR4). One Quantum Fourier Transform (QFT) consists of 5 CNOT gates and two $X_{\pi/2}$ gates.

D. Willsch et al., Gate error analysis in simulations of quantum computers with transmon qubits, Phys. Rev. A 96, 062302 (2017)

D-Wave quantum annealer

Solve small but hard 2-SAT problems, characterized by a known unique ground state and a highly degenerate first excited state, on a D-Wave system and on a simulated ideal quantum annealer modelled as a quantum spin-1/2 system

- Selected 2-SAT problems have minimal spectral gaps $\Delta \leq k_B T$, where T denotes the operating temperature
- Measured frequency distribution as a function of the minimal spectral gap shows Landau-Zener (= quantum) behavior for 2-SAT problems with 18 Boolean variables
- Scattering in the measured distribution can be explained by coupling the ideal quantum annealing system to a heat bath

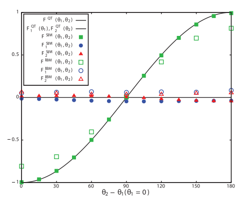


K. Michielsen et al., Solving 2-satisfiability problems on a quantum annealer (in preparation)

IBM Quantum Experience (IBM QX)

Performance test of a quantum computer device with 5 transmon qubits by means of very simple algorithms (identity operations, 2+2 qubit adder, measurement of singlet state, error correction)

- In some cases qualitative agreement with quantum theory for qubit systems is observed
- Errors cannot be identified by the user and they cannot be attributed to the specified gate errors
- Sequences of identity operations provide simple, scalable algorithms to validate the correct operation of the device
- The current IBM QX device does not meet the elementary requirements for a computing device



Measurement results of the singlet state obtained from quantum theory (QT), from simulation of a 2-qubit transmon system (SIM) and with the IBM QX (IBM)

K. Michielsen et al., Benchmarking gate-based quantum computers, Comp. Phys. Comm. 220, 44 (2017)

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