Quantum Annealing & Its Applications for Simulation in Science & Industry, ISC 2017

At ISC 2017, the international supercomputing conference held in Frankfurt am Main June 18–22, Prof. Dr. Kristel Michielsen from the Jülich Supercomputing Centre hosted the special conference session "Quantum Annealing & Its Applications for Simulation in Science & Industry". The goal of the session was to introduce the general principles of quantum annealing and quantum annealer hardware to the global HPC community and to discuss the challenges of using quantum annealing to find solutions to real-world problems in science and industry. These topics were addressed in four presentations:

- An Introduction to Quantum Annealing
  Prof. Dr. Kristel Michielsen, Jülich Supercomputing Centre (JSC)
  Summary and YouTube video: http://primeurmagazine.com/live/LV-PL-06-17-36.html

- Qubits, Couplers & Quantum Computing in 2017
  Dr. Denny Dahl, D-Wave Systems
  Summary and YouTube video: http://primeurmagazine.com/weekly/AE-PR-08-17-7.html

- Quantum Annealing for Aerospace Planning Problems
  Dr. Tobias Stollenwerk, Deutsches Zentrum für Luft- und Raumfahrt (DLR)
  Summary and YouTube video: http://primeurmagazine.com/weekly/AE-PR-08-17-27.html

- Maximizing Traffic Flow Using the D-Wave Quantum Annealer
  Dr. Christian Seidel, Volkswagen (VW)
  Summary and YouTube video: http://primeurmagazine.com/live/LV-PL-06-17-37.html

Session speakers, from left: Christian Seidel, Denny Dahl, and Tobias Stollenwerk.
Right: session host Kristel Michielsen.

Quantum annealing and discrete optimization

New computing technologies, like quantum annealing, open up new opportunities for solving challenging problems including, among others, complex optimization problems. Optimization challenges are omnipresent in scientific research and industrial applications. They emerge in planning of production processes, drug-target interaction prediction, cancer radiation treatment scheduling, flight and train scheduling, vehicle routing, and trading. Optimization is also playing an increasingly important role in computer vision, image processing, data mining and machine leaning.

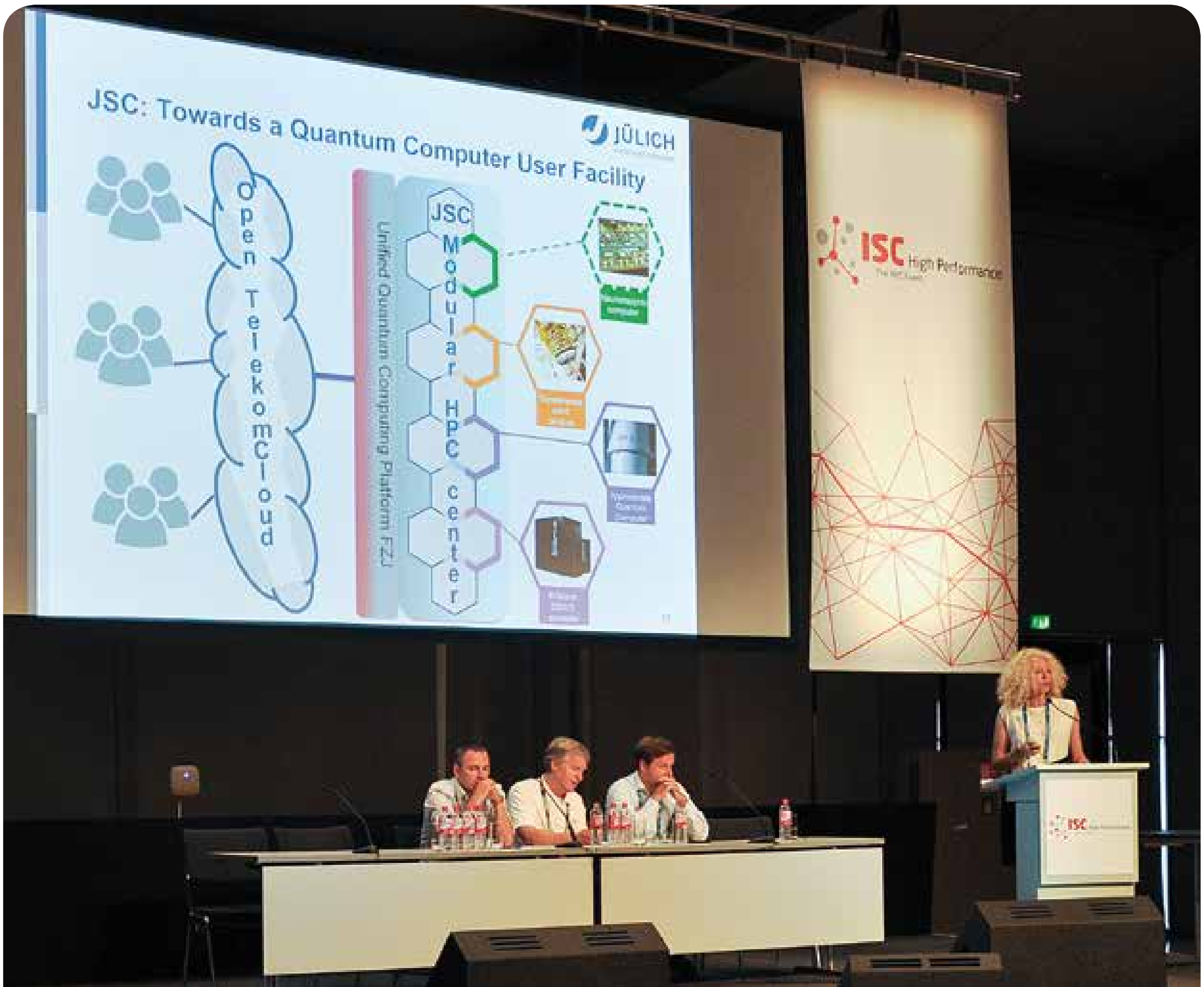
The task in many of these optimization challenges is to find the best solution among a finite set of feasible solutions. In mathematics, optimization deals with the problem of finding numerically minima of a cost function, while in physics it is formulated as finding the minimum energy state of a physical system described by a Hamiltonian, or energy function. Quantum annealing is a new technique, exploiting quantum fluctuations, for solving those optimization problems that can be mapped to a quadratic unconstrained binary optimization problem (QUBO). A QUBO can be mapped onto an Ising Hamiltonian and the simplest physical realizations of quantum annealers are those described by an Ising Hamiltonian in a transverse field, inducing the quantum fluctuations. Many challenging optimization problems playing a role in scientific research and in industrial applications naturally occur as or can be mapped by clever modeling strategies onto QUBOs.

Denny Dahl from D-Wave Systems and Kristel Michielsen from JSC answer questions from the audience interested in benchmarking D-Wave quantum annealers.

D-Wave Systems

Founded in 1999, D-Wave Systems is the first company to commercialize quantum annealers, manufactured as integrated circuits of superconducting qubits which can be described by the Ising model in a transverse field. The currently available D-Wave 2000Q™ systems have more than 2000 qubits (fabrication defects and/or cooling issues render some of the 2048 qubits inoperable) and 5600 couplers connecting the qubits for information exchange. The D-Wave 2000Q™ niobium quantum processor, a complex superconducting integrated circuit with 128,000 Josephson junctions, is cooled to less than 15 mK and is isolated from its surroundings by shielding it from external magnetic fields, vibrations and external radiofrequency fields of any form. The power consumption of a D-Wave 2000Q™ system is less than 25 kW, most of which is used by the refrigeration system and the front-end servers.

Roughly speaking, programming a D-Wave machine for optimization consists of three steps: (i) encode the problem of interest as an instance of a QUBO; (ii) map the QUBO instance on the D-Wave Chimera graph architecture connecting a qubit with at most six other qubits, which in the worst case requires a quadratic increase in the number of qubits; (iii) specify all qubit coupling values and single qubit weights (the local fields) and perform the quantum annealing, a continuous time (natural) evolution of the quantum system, on the D-Wave device. The solution is not guaranteed to be optimal. Typically a



Kristel Michielsen explains the plans of JSC to move towards a Quantum Computer User Facility in which a D-Wave quantum annealer, a universal quantum computer without error correction and some smaller experimental quantum computing devices form special computing modules within a modular HPC center.

user performs thousands of annealing runs for the problem instance to obtain a distribution of solutions corresponding to states with different energy.

The potential of quantum annealing for some applications in science and industry

The exploration of quantum annealing's potential for solving some real-world problems on D-Wave Systems' hardware is a challenge that nowadays is taken up not only in the US, but also in Europe. For these exploratory endeavors, it is essential that users from science and industry have easy access to this new computing technology at an early stage. As explained by Kristel Michielsen, JSC aims to establish a Quantum Computer User Facility hosting a D-Wave quantum annealer and various other quantum computing systems. The development of applications in the field of quantum computers by research groups in science and industry in Germany and the rest of Europe will largely profit from opportunities of being able to access the various available technologies.

In his presentation, Denny Dahl from D-Wave Systems focused on the possible benefits of new annealing controls, introduced with the latest-generation system, that allow the user to have more control over the annealing process. These controls help improve performance in finding solutions to certain problems or simulating particular quantum systems. As sample problems, he considered prime factorization and the simulation of a three-dimensional Ising model in a transverse field.

Tobias Stollenwerk from DLR reported on a research project pertaining to an aerospace planning problem, which he performed in close collaboration with researchers from NASA Ames. There are about 1,000 transatlantic flights per day. In order to fit more flights in the limited airspace, one considers wind-optimal or fuel saving trajectories which might lead to conflicts (airplane collisions). To solve the deconflicting problem with minimum flight delays, it was first formulated as a QUBO and then solved on a D-Wave machine. Problem instances with up to 64 flights and 261 conflicts were solved.

Christian Seidel from VW showed how to maximize traffic flow using the D-Wave quantum annealer. For this project the VW team used a public data set containing data of 10,000 taxi's driving in Beijing during one week. They restricted the traffic flow maximization problem, in which the travel time for each car has to be smaller than the one in the un-optimized traffic flow, using a trajectory from Beijing city centre to the airport for 418 cars thereby allowing each car to take three possible routes. They formulated this constrained optimization problem as a QUBO and solved it on the D-Wave machine.

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