AQC2017, Tokyo, June 26-29, 2017

Monday, June 26

8:30 Registration

9:20 Opening

Chair: H. Nishimori

9:30 **William Oliver (MIT Lincoln Lab)** **[Invited]**
Quantum engineering of superconducting qubits

10:10 **Yu Chen (Google)**
Progress towards building quantum annealer V2.0

10:50 Break

Chair: D. Lidar

11:10 **Gabriel O. Samach (MIT Lincoln Lab)**
Engineering quantum annealing architectures
Beyond the transverse-field Ising model

11:30 **David Ferguson (Northrop Grumman)**
Component concepts for super-classical quantum annealing

11:50 **Trevor M. Lanting (D-Wave)**
The D-Wave 2000Q processor

12:10 Lunch

13:40 **Poster Session 1**

Chair: W. Vinci

15:10 **Seth Lloyd (MIT)** **[Invited]**
(TBA)

15:50 **Jaw-Shen Tsai (Tokyo Univ. Science and RIKEN)** **[Invited]**
Superconducting circuit QED for
quantum annealing, computing, and simulation

16:30 **Hirotaka Tamura (Fujitsu Labs)**
An architecture for parallel-trial hardware accelerator
for Ising-model MCMC search

16:50 Break

Chair: E. Farhi

17:10 **Mohammad Amin (D-Wave)** **[Invited]**
Is quantum annealing efficiently simulatable?

17:50 **Helmut G. Katzgraber (Texas A&M Univ., 1QBit, Santa Fe Inst.)**
Test and evaluation in quantum annealing:
Raising the bar for novel architectures

18:10 **Masoud Mohseni (Google)**
Inhomogeneous Quantum Annealing

Tuesday, June 27

Chair: H. G. Katzgraber

9:00 **Richard G Harris (D-Wave)** **[Invited]**
Simulation of a 3-dimensional transverse Ising system
with a D-Wave quantum annealing processor

9:40 **Salvatore Mandrà (NASA Ames Research Center, SGT)**
Exponentially biased ground-state sampling of quantum
annealing machines with transverse-field driving Hamiltonians

10:00 **Andrew D. King (D-Wave)**
Mitigating perturbative anticrossings with
nonuniform driver Hamiltonians

10:20 **Daniel A. Lidar (USC)**
Evidence for a limited quantum speedup
on a quantum annealing device

10:40 Break

Chair: I. Hen

11:00 **Barbara Terhal (RWTH Aachen Univ.)** **[Invited]**
The power and use of stoquastic Hamiltonian

11:40 **Elizabeth Crosson (Caltech)**
Ground state geometry and the energy spectrum of
local Hamiltonians

12:00 Lunch

13:30 **Poster Session 2**

Chair: H. Neven

15:00 **Walter Vinci (USC)** **[Invited]**
Towards scalable quantum annealing correction for
optimization and sampling

15:40 **Paolo Zanardi (USC)**
Relaxation vs. adiabatic quantum steady state preparation:
Which wins?

16:00 Break

Chair: S. Adachi

16:30 **John Realpe-Gomez (NASA Ames Research Center)** **[Invited]**
Quantum assisted learning of graphical models with
arbitrary pairwise connectivity

17:10 **Shinichi Takayanagi (Recruit Communications)**
Display advertising optimization by quantum annealing processor

17:30 **Dan D. Padilha (QxBranch)**
Training L0-Regularised Linear Regression and Classification Models
with a quantum annealer

17:50 **Kotaro Tanahashi (Recruit Communcations)**
Feature selection by quantum annealing processor
- An extension of the QBoost -

18:40 Banquet

Wednesday, June 28

Chair: E. Rieffel

9:00 **Itay Hen (Information Sciences Inst., USC)** **[Invited]**
Limitations of physical quantum annealers

9:40 **Nike Dattani (Hertford College, Oxford Univ.)**
Truly adiabatic quantum annealing in novel NMR systems which do not leave their ground state

10:00 **Steven J. Weber (MIT Lincoln Lab)**
Coherent coupled qubits for next generation quantum annealing

10:20 **Ryan M. Hamerly (National Institute of Informatics)**
Quantum vs. optical annealing: the coherent Ising machine and D-Wave

10:40 Break

Chair: M. Amin

11:00 **Gianni Mossi (SISSA)**
Quantum Annealing and Localization on the Regular Random Graph

11:20 **Eleanor Rieffel (NASA Ames Research Center)**
Investigations of quantum heuristics for optimization

11:40 Lunch

Chair: B. Terhal

14:00 **Stephen P. Jordan (NIST, Univ. Maryland)** **[Invited]**
Quantum and stochastic optimization

14:40 **Maritza L. Hernandez-Gaete (1QBit)**
Enhancing quantum annealing performance for the molecular similarity problem

15:00 **Davide Venturelli (NASA Ames Research Center)**
Deterministic embedding methods for integer linear programming on chimera graphs and beyond

15:20 **Masaaki Maezawa (AIST)**
Technology integration for practical-scale quantum annealing machine

15:40 Break

Chair: E. Crosson

16:10 **Edward Farhi (MIT)** **[Invited]**
How to run a near term gate model quantum computer

16:50 **Alejandro Perdomo-Ortiz (NASA Ames Research Center)**
Model-based diagnosis in combinational digital circuits: An application with potential for quantum speedup

16:50 **Jack Raymond (D-Wave)**

17:10 Quantum and classical estimators for quantum Boltzmann statistics

17:30 Break

17:50 **Panel Discussion**
What will be the future society with quantum computers?
Eleanor Rieffel (Moderator)
Helmut Katzgraber, Daniel Lidar, Seth Lloyd
Norio Murakami, Hartmut Neven, Paul Warburton

Thursday, June 29

Chair: P. A. Warburton

9:00 **Shunji Matsuura (1QBit)** **[Invited]**
Non-stoquastic Hamiltonian in QAC and spin glass

9:40 **Andrea Rocchetto (Univ. Oxford)**
Stabilizers as a design tool for new forms of
the Lechner-Hauke-Zoller annealer

10:00 **Shruti Puri (Univ. Sherbrooke)**
A quantum Ising machine based onoscillators
parametrically driven nonlinear

10:20 **Hidetoshi Nishimori (Tokyo Tech)** **[Invited]**
Analyses of non-stoquastic Hamiltonians by the mean-field theory

AQC2017, Tokyo, June 26-29, 2017

Poster Session: Day 1 (June 26)

1 **Sei Suzuki (Saitama Med. Univ.)**
Quantum annealing of an open quantum system

2 **Jun Takahashi (Univ. Tokyo)**
Detection of Phase Transition in Quantum Annealing using Fidelity Susceptibility

3 **Andrew J. Ochoa (Texas A&M University)**
Approximating continuous coupler distributions on devices with limited precision

4 **Pooya Ronagh (1QBit)**
Reinforcement Learning Using Quantum Boltzmann Machines

5 **Yuki Susa (Tokyo Institute of Technology)**
Relation between quantum fluctuations and the performance enhancement of quantum annealing in a non-stoquastic Hamiltonian

6 **Hamed Karimi (1QBit)**
Effective optimization using sample persistence: a case study on quantum annealers, simulated annealing and simulated quantum annealing

7 **Manuel Pino Garcia (Insituto Física Fundamental)**
Non-ergodic metallic and insulating phases of Josephson junction chains

8 **Jie Sun (Huazhong University of Science and Technology)**
On the failure of the general models of adiabatic evolutions for quantum search

9 **Hayato Goto (R&D Center, Toshiba Corporation)**
Adiabatic quantum computation and Boltzmann sampling with a network of driven nonlinear oscillators

10 **Hitoshi Ishikawa (PEZY Computing, K.K.)**
A strategic scheme of quantum Monte Carlo implementation bringing out the potential in a supercomputer with many-core processors

11 **Steve Reinhardt (D-Wave Systems, Inc.)**
Graph Embedding by Filtering Pre-embeddings via a Distance-Aware Metric

12 **Gabriel M. Bianconi (QxBranch)**
Quantum-Assisted Learning for Convolutional Deep Belief Networks

13 **Maxwell P. Henderson (QxBranch)**
Leveraging adiabatic quantum computation for election forecasting

14 **Yoichiro Hashizume (Tokyo University of Science)**
A construction method of initial Hamiltonian for singular value decomposition by quantum annealing

15 **Songfeng Lu (Huazhong University of Science and Technology)**
Assisted driving Hamiltonian can be not unique in adiabatic evolution

16 **Tomohiko Abe (Nextremer Co., Ltd.)**
Batch-learning self-organizing map with quadratic unconstrained binary optimization -- toward application to Ising machine --

17 **Yoshihiro Osakabe (Tohoku University)**
Comparison between Ising Hamiltonian and Neuro-inspired Hamiltonian for Quantum Associative Memory

18 **Mutsuo Hidaka (National Institute of Advanced Industrial Science and Technology)**
Fabrication Process and Device Structure for Nb-based Quantum Annealing Devices

19 **Zhigang Zhang (Huazhong University of Science and Technology)**
Study the structure of local Hamiltonian on adiabatic quantum computation

20 **Gianni Mossi (SISSA)**
Many-body localization in quantum spin glasses

21 **Ryo Tamura (National Institute for Materials Science)**
Quantum annealing for clustering of artificial data set by
quantum Monte Carlo methods

22 **Toshiyuki Ohki (Tokyo Institute of Technology)**
Verification of the performance of the quantum Boltzmann machine

23 **Masaki Ookuwa (Tokyo Institute of Technology)**
Application of the discrete WKB method to the ferromagnetic p-spin model
with antiferromagnetic transverse interactions

24 **Nicholas Chancellor (Durham University)**
Modernizing Quantum Annealing (and beyond) using Local Search

25 **Tomomitsu Motohashi (Recruit Life Style)**
Optimize Combination of Recommendation Items by
Quantum Annealing Processor

26 **Taichi Itoh (BrainPad Inc.)**
Quantum annealing for combinatorial optimization problems with
multiple constraints

27 **Kohji Nishimura (Tokyo Institute of Technology)**
Inference of the ground state of spin-glass Hamiltonians
using quantum fluctuations

28 **Tadashi Kadowaki**
A design of annealer dynamics with quantum and thermal effects

29 **Masaaki Maezawa (National Institute of Advanced Industrial Science and Technology)**
Thermal Annealing of Classical Bits

Poster Session: Day 2 (June 27)

30 **Tobias Stollenwerk (German Aerospace Center)**
Quantum Annealing for Air Traffic Management

31 **Joaquin Ossorio-Castillo (ITMATI)**
Solving energy-related scheduling problems with column generation and an adiabatic quantum computer

32 **Kabuki Takada (Tokyo Institute of Technology)**
Behavior of Spin Systems with a First-Order Phase Transition under Dissipation

33 **Chihiro H. Nakajima (Tohoku university)**
Minimal energy gap of adiabatic quantum computing of multi-state extended Simon's problem

34 **Shunta Arai (Tohoku University)**
Detection of phase transition in transverse-field Ising model by neural network

35 **Tomoyuki Obuchi (Tokyo Institute of Technology)**
Complex semiclassical analysis of the Loschmidt amplitude and dynamical quantum phase transitions

36 **Steve Adachi (Lockheed Martin)**
Application of Quantum Annealing to Training of Deep Neural Networks

37 **Joseph S. Dulny (Booz Allen Hamilton)**
Quantum Annealing Enabled Cluster Analysis

38 **Takuya Hatomura (University of Tokyo)**
Fast quantum annealing for the infinite-range Ising model by mean-field counterdiabatic driving

39 **Yuya Seki (Tohoku University)**
Effect of State transition of multi level systems to Performance of Quantum Annealing

40 **Tatsuro Yuge (Shizuoka University)**
Appearance of a superposition of macroscopically distinct states in adiabatic quantum computation

41 **Hikaru Wakaura (University of Tsukuba)**
Quantum Error Correction using spin-vortex induced loop currents as qubits

42 **Hiroyasu Koizumi (University of Tsukuba)**
Proposal for spin-vortex-induced loop current quantum computer

43 **Zhaokai Li (University of Science and Technology of China)**
Experimental Adiabatic Quantum Factorization Based on a Single Spin System

44 **Shuntaro Okada (DENSO Corporation)**
Reconsideration of adiabatic theorem toward efficient quantum annealing

45 **Aniruddha A. Bapat (University of Maryland)**
Bang-Bang control of Classical and Quantum Optimization Algorithms

46 **Taro Yamashita (National Institute of Information and Communications Technology)**
Development of ferromagnetic Josephson junction based on niobium nitride

47 **Shoji Taime (The University of Tokyo)**
Quantum Simulation of Coherent Ising Machines with Positive-P Representation

48 **Ryoji Miyazaki (National Institute of Informatics)**
Application of coherent Ising machine to compressed sensing

49 **Meysam Namdari (Technische Universität Dresden)**

Ising machine using integrated photonics:
Feasibility study for the realization of OPOs in silicon waveguides

50 **Neris I. Sombillo (University of the Philippines)**
Fixed-point quantum search as implemented in an Ising spin system

51 **Denny Lane B. Sombillo (University of the Philippines)**
Tunneling time operator in quantum time of arrival formalism

52 **Atsushi Yamamura (The University of Tokyo)**
Theoretical Analysis on the Measurement Feedback Coherent Ising Machine

53 **Estelle Maeva Inack (ICTP/SISSA)**
Simulating quantum Ising models using the Diffusion Monte Carlo method

54 **Stefano Varotti (University of Trento)**
New methods for encoding SAT for an adiabatic quantum computer

55 **Matteo Michele Wauters (SISSA)**
Comparing simulated annealing with quantum annealing on
a fully-connected Ising ferromagnet

56 **Richard Li (USC)**
Quantum annealing versus classical machine learning applied to
a simplified computational biology problem

57 **Mario S. Könz (ETH Zurich)**
Comparing embedding penalties between minor-embedding, chimaera and
the paqo-scheme (lhz-scheme) as well as to direct SQA

58 **Manaka Okuyama (Tokyo Institute of Technology)**
Quantum-Classical Correspondence of Shortcuts to Adiabaticity

59 **Andriyan Bayu Suksmono (The School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Indonesia)**
Finding a Hadamard matrix by simulated quantum annealing

Title and Abstract of Oral Presentations

Monday, June 26

Morning Session

William Oliver, MIT Lincoln Lab

Quantum Engineering of Superconducting Qubits

We revisit the design, fabrication, and control of the superconducting flux qubit. By adding a high-Q capacitor, we dramatically improve its reproducibility, anharmonicity, and coherence, achieving T1 = 55 us and T2 = 90 us [1]. We identify quasiparticles as a leading cause of temporal variability in T1. We introduce and demonstrate a stochastic control technique that effectively pumps away these quasiparticles and thereby stabilizes and improves T1 [2]. We discuss the 3D integration of this qubit into architectures of interest for quantum annealing applications.

For more information:

[1] F. Yan et al., Nature Communications 7, 12964 (2016)

[2] S. Gustavsson et al., Science 354, 1573 (2016)

Yu Chen, Google

Progress towards building quantum annealer V2.0

A quantum annealer holds promises for improving solutions to hard optimization problems using quantum enhancement. Constructing a quantum annealer, however, stands as an outstanding challenge.

Here, we are reporting our recent progresses towards building quantum annealer V2.0 in Google. Constructed from coplanar waveguide-based ‘fluxmon’ qubits, quantum annealer V2.0 is aiming to have enhanced connectivity and coherence, yet, on a smaller scale. We will discuss the key features of our annealer architecture, which is being built as a multi-layer circuit structure with airbridge crossovers and flip chip technology. We will discuss why such an architecture can allow for a good balance between strong coupling, low crosstalk and coherence.

Gabriel O. Samach, MIT Lincoln Lab

Engineering Quantum Annealing Architectures Beyond the Transverse-Field Ising Model

The first generation of quantum annealers based on Josephson junction technology successfully represent arrays of spins in the quantum transverse-field Ising model. However, to date, no annealing architecture has emulated the more sophisticated non-stoquastic Hamiltonians of interest for next generation quantum annealing. Here, we present our recent results for tunable ZZ- and XX-coupling between high coherence superconducting flux qubits, as well as robust simulations of future coupled qubit systems. We consider the capabilities and limitations of annealing architectures based on these two-qubit building blocks, and we address specifically our efforts to engineer strong XX-coupling in the absence of local qubit fields, an inherent limitation of all existing flux qubit-based annealing systems. This research was funded by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA) and by the Assistant Secretary of Defense for Research & Engineering under Air Force Contract No. FA8721-05-C-0002. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of ODNI, IARPA, or the US Government.

David Ferguson, Northrop Grumman

Component Concepts for Super-Classical Quantum Annealing

The design of hardware components for application-relevant quantum annealing systems presents many difficult design challenges. Central to these challenges are the many disparate properties that are conjectured to be critical. These include qubit couplers that are high precision, non-stoquastic, high weight, long range, and compatible with high-degree connectivity. Further, these properties may need to be simultaneously implementable, and may need to be compatible with high coherence flux qubits. This talk will present two innovative designs developed by Northrop Grumman—a non-stoquastic XX coupler and a weight-three ZZZ coupler—that address some of these challenges. We will also discuss some of the design trade-offs that are likely to be important in the design of advanced, super-classical quantum annealing systems.

Trevor M. Lanting, D-Wave

The D-Wave 2000Q Processor

We have developed a series of tunable processors that run the quantum annealing algorithm on networks of coupled superconducting flux qubits. We discuss the most recent generation of processor with 2000 qubits and expanded control over the annealing process. In particular, we describe the per-qubit in situ tunable annealing offset control and the more flexible control over global annealing trajectories. This expanded capability allows for more sophisticated examination of the behaviour of the quantum annealing algorithm running on a practical processor.

Monday, June 26

Afternoon Session

Seth Lloyd, MIT

(TBA)

Jaw-Shen Tsai, Tokyo University of Science and RIKEN

Superconducting Circuit QED for Quantum Annealing, Computing, and Simulation

In this talk, our circuit schemes towards quantum annealing, quantum computing, and quantum simulation are described where circuit QEC is actively employed. In the quantum annealing, a qubit coupling scheme using resonator is considered. Cluster state quantum computing and boson sampling are also discussed.

Hirotaka Tamura, Fujitsu Laboratories LTD.

An Architecture for Parallel-Trial Hardware Accelerator for Ising-Model MCMC Search

We developed an architecture for parallel-trial hardware that minimizes the energy of Ising models, and implemented it in a system using an FPGA. The system can handle Ising models with 1,024 state variables forming a complete graph connected through 16-bit fixed-point signed binary weights. The bias terms (i.e., the values of the external field) in the Ising model are expressed in 26-bit signed binary and configurable for each bit. The system uses an accelerator engine that performs a Markov-chain Monte-Carlo search with a parallel evaluation of the energy increment prior to selection of a single state variable to be flipped, achieving a speedup while guaranteeing a convergence. The engine is implemented in Arria 10 GX FPGA and solved 32-city traveling salesman problems 12,000 times faster than a simulated annealing running on a 3.5-GHz Intel Xeon E5-1620v3 processor.

This work was done in collaboration with S. Matsubara*, T. Ahmed*, M. Takatsu*, D. Yoo**, B. Vatankhahghadim**, H. Yamasaki*, T. Miyazawa*, S. Tsukamoto*, Y. Watanabe*, K. Takemoto*, Y. Koyanagi*, and A. Sheikholeslami**.

* Fujitsu Laboratories Ltd., Kawasaki, Japan

** University of Toronto, Toronto, Canada

Mohammad Amin, D-Wave Systems Inc.

Is quantum annealing efficiently simulatable?

Past research on quantum annealing (QA) has primarily focused on optimization, and therefore the commercially available quantum annealers have been mainly designed to that end. In this talk, I will present sampling from the Boltzmann distribution of a quantum Hamiltonian as another use of quantum annealers, with applications in quantum machine learning. I will show that the equilibration dynamics of a quantum annealer cannot be simulated efficiently by classical means and argue that the existence of highly entangled eigenstates can lead to quantum advantage at some points during the annealing. I will end by showing preliminary experimental evidence of this advantage.

Helmut G. Katzgraber, Texas A&M University; 1QB Information Technologies (1QBit); Santa Fe Institute, New Mexico

Test and evaluation in quantum annealing: Raising the bar for novel architectures

Because recent evidence that native random spin-glass problems are not well suited for benchmarking purposes of quantum annealers, efforts in the search for quantum speedup have shifted to carefully tailored problems, such as Google Inc.'s weak-strong clusters problems or D-Wave Systems Inc.'s frustrated-loop cluster problems. Here we demonstrate how carefully tailored, as well as non-tailored classical algorithms continuously raise the bar for new quantum annealing technologies.
Work done in collaboration with S. Mandra (NASA), A. J. Ochoa (TAMU), C. Thomas, W. Wang (TAMU), Z. Zhu (TAMU)

Masoud Mohseni, Google Quantum AI Labs

Inhomogeneous Quantum Annealing

In this work, we develop a programmable approach to non-adiabatic quantum annealing. Specifically, we demonstrate how one can engineer quantum phase transitions via constructing spatially inhomogeneous control Hamiltonians. We numerically investigate the optimal conditions for suppression of topological defects during quantum critical dynamics. We show that our algorithm can significantly outperform conventional schemes, such as standard (homogeneous) adiabatic quantum annealing and simulated annealing, for sampling low-energy states of quasi-1D Hamiltonian systems.

Tuesday, June 27

Morning Session

Richard G. Harris, D-Wave Systems Inc.

Simulation of a 3-dimensional transverse Ising system with a D-Wave quantum annealing processor

A prototype quantum annealing processor has been used to simulate an 8x8x8 cubic lattice of Ising spins subject to a transverse magnetic field Ht. The lattice was formed by representing the individual Ising spins using strongly coupled chains of flux qubits and choosing a subset of interqubit couplers to represent the nearest neighbour couplings of the cubic lattice. The low energy Hamiltonian of the processor then mapped onto that of the desired system. The ground state of the Ht=0 Ising spin system was tuned by choosing a fraction 1-p of the nearest neighbour interactions to be antiferromagnetic (AFM) and the remaining fraction p to be ferromagnetic (FM). Measurements of the antiferromagnetic order parameter, dc magnetic susceptibility, and hysteresis were used to identify paramagnetic (PM) to AFM and PM to spin glass (SG) phase transitions. The measurements were used to map the p-Ht phase diagram for this system. Quantitative agreement between key points in the experimentally determined phase diagram and numerical results found in the literature has been demonstrated. These results support the hypothesis that D-Wave quantum annealing processors can be used to perform quantum magnetism simulations.

Salvatore Mandrà, QuAIL, NASA Ames Research Center - SGT

Exponentially Biased Ground-State Sampling of Quantum Annealing Machines with Transverse-Field Driving Hamiltonians

While obtaining the ground state of a spin-glass benchmark instance represents a difficult task, the gold standard for any optimization algorithm or machine is to sample all solutions that minimize the Hamiltonian with more or less equal probability. In my talk I will present our latest results [Phys. Rev. Lett. 118, 070502] on the performance of the D-Wave 2X quantum annealing machine on systems with well-controlled ground-state degeneracy. More precisely, I will show that while naïve transverse-field quantum annealing on the D-Wave 2X device can find the ground-state energy of the problems, it is not well suited in identifying all degenerate ground-state configurations associated

with a particular instance. Even worse, some states are exponentially suppressed, in agreement with previous studies on toy model problems [New J. Phys. 11, 073021 (2009)]. These results suggest that more complex driving Hamiltonians are needed in future quantum annealing machines to ensure a fair sampling of the ground-state manifold.

Andrew D. King, D-Wave Systems

Mitigating perturbative anticrossings with nonuniform driver Hamiltonians

The presence of small-gap perturbative anticrossings has long been identified as a computational bottleneck in quantum annealing. This bottleneck can be severe when the same transverse driver Hamiltonian is naively applied to each qubit, and all qubits are annealed in unison. Previous research has sought to alleviate such anticrossings in simulation by adjusting the transverse driver Hamiltonians on each qubit according to a perturbation approximation operating on the lowest nontrivial degree.
We apply this principle to a physical implementation of quantum annealing in a D-Wave 2000Q system, using per-qubit anneal offsets to effect nonuniform driver Hamiltonians. Our perturbation-based approach yields a systematic increase in minimum eigengap, ground state success probability, and escape rates from metastable valleys. We use the same approach to improve fair sampling of degenerate ground states.

Daniel A. Lidar, University of Southern California

Evidence for a Limited Quantum Speedup on a Quantum Annealing Device

Barbara Terhal, RWTH Aachen University

The Power and Use of Stoquastic Hamiltonians

Elizabeth Crosson, California Institute of Technology

Ground state geometry and the energy spectrum of local Hamiltonians

By generalizing a standard framework from the analysis of Markov chains to arbitrary (non-stoquastic) Hamiltonians we are naturally led to see that the spectral gap can always be upper bounded by a geometric quantity that depends only on the ground state probability distribution and the range of the terms in the Hamiltonian, but not on any other details of the interaction couplings. This means that for a given probability distribution the inequality can constrain the spectral gap (and other low-lying eigenvalues) of any local Hamiltonian with this distribution as its ground state probability distribution in some basis. These constraints reveal that some probability distributions will take exponential time to be precisely reached by a purely adiabatic evolution, while also showing the necessity of removing bottlenecks in the ground state geometry to improve the performance within the adiabatic paradigm.

This talk is based on arXiv:1703.10133.

Tuesday, June 27

Afternoon Session

Walter Vinci, USC

Towards Scalable Quantum Annealing Correction for Optimization and Sampling

Quantum Error Correction is critical to ensure the success of quantum computation. However, we do not have a formal theory of fault-tolerance in the adiabatic scheme. In the context of finite-temperature quantum annealing, an important ingredient in achieving fault-tolerance is an error correcting scheme that provides a scalable reduction of the effective temperature at which a quantum annealer operates. I will discuss recent developments on Nested Quantum Annealing Correction (NQAC), the first error correction method that can be implemented on currently available quantum annealers and that allows to control the level of protection against thermal errors. Theoretical mean-field analyses suggest that NQAC has the potential to provide a scalable temperature reduction. This is supported by experimental data obtained from a fourth-generation D-Wave 2000Q quantum annealer. Data show that NQAC scales up to the size of the device. This effective temperature reduction can also be exploited for sampling applications.

Kostyantyn Kechedzhi, NASA Ames Research Center and USRA

Noise dependent tunneling action in quantum annealing of the weak-strong cluster problem (cancelled)

We consider the effect of realistic flux-qubit noise on the quantum annealing dynamics. We analyze the strong low frequency noise regime and the associated multi-qubit polaron effect, polarization of the system responsible for the noise by the field of the qubits, and the consequences for the efficiency of tunneling in the course of quantum annealing. The multi-qubit polaron effect gives rise to two additional energy scales in the system, the multi-qubit reconfiguration energy and the multi-qubit linewidth, these are generalizations of the single qubit parameters characterizing the Gaussian shape of the dependence of the tunneling amplitude on the detuning. The two additional energy scales renormalize the quasiclassical action, resulting in a weaker noise-dependent tunneling amplitude. We analyze this effect in detail in the setting of quantum annealing of the so called weak-strong cluster problem which consists of two ferromagnetic

clusters subject to opposite local z-fields and coupled to each other ferromagnetically. The polaron effect is weaker at larger transverse field which partially compensates the noise-induced reduction in the tunneling amplitude. We find the optimal tunneling amplitude in the course of the annealing schedule which corresponds to a noise-dependent time to solution characteristic of the quantum annealing algorithm which affects the scaling comparison with quantum Monte Carlo simulation.
Joint work with Vadim Smelyanskiy, Sergio Boixo, Hartmut Neven, John Martinis.

Paolo Zanardi, University of Southern California
Relaxation vs. adiabatic quantum steady state preparation: which wins?

Adiabatic preparation of the ground states of many-body Hamiltonians in the closed system limit is at the heart of adiabatic quantum computation, but in reality systems are always open. This motivates a natural comparison between, on the one hand, adiabatic preparation of steady states of Lindbladian generators and, on the other hand, relaxation towards the same steady states subject to the final Lindbladian of the adiabatic process. In this work we thus adopt the perspective that the goal is the most efficient possible preparation of such steady states, rather than ground states. Using known rigorous bounds for the open-system adiabatic theorem and for mixing times, we are then led to a disturbing conclusion that at first appears to doom efforts to build physical quantum annealers: relaxation seems to always converge faster than adiabatic preparation. However, by carefully estimating the adiabatic preparation time for Lindbladians describing thermalization in the low temperature limit, we show that there is, after all, room for an adiabatic speedup over relaxation. To test the analytically derived bounds for the adiabatic preparation time and the relaxation time, we numerically study three models: a dissipative quasi-free fermionic chain, a single qubit coupled to a thermal bath, and the "spike" problem of n qubits coupled to a thermal bath. Via these models we find that the answer to the "which wins" question depends for each model on the temperature and the system-bath coupling strength. In the case of the "spike" problem we find that relaxation during the adiabatic evolution plays an important role in ensuring a speedup over the final-time relaxation procedure. Thus, relaxation-assisted adiabatic preparation can be more efficient than both pure adiabatic evolution and pure relaxation.

John Realpe-Gomez, NASA Ames Research Center

Quantum assisted learning of graphical models with arbitrary pairwise connectivity

There is increasing interest in the potential advantages of using quantum computing technologies as sampling engines to speedup machine learning and probabilistic programming tasks. However, some pressing challenges in state-of-the-art quantum annealers have to be overcome before we can assess their actual performance. Most notably, the effective temperature at which samples are generated is instance-dependent and unknown, the interaction graph is sparse, the parameters are noisy, and the dynamic range of the parameters is finite. Of all these limitations, the sparse connectivity resulting from the local interaction between quantum bits in physical hardware implementations, is considered the most severe limitation to the quality of constructing powerful machine learning models. Here we show how to overcome or mitigate these limitations and illustrate our findings by training probabilistic generative models with arbitrary pairwise connectivity. Our model can be trained in quantum hardware without full knowledge of the effective parameters specifying the corresponding quantum Boltzmann-like distribution. Therefore, inference of the effective temperature is avoided and the effect of noise in the parameters is mitigated. We illustrate our findings by successfully training hardware-embedded models with all-to-all connectivity on a real dataset of handwritten digits and two synthetic datasets. In each of these datasets we show the generative capabilities of the models learned with the assistance of the quantum annealer in experiments with up to 940 quantum bits. Additionally, we show a visual Turing test with handwritten digit data, where the machine generating the digits is a quantum processor. Such digits, with a remarkable similarity to those generated by humans, are extracted from the experiments with 940 quantum bits.

Shinichi Takayanagi, Recruit Communications Co., Ltd.

Display Advertising Optimization by Quantum Annealing Processor

Display advertising is an advertisement appearing on websites.
To increase advertisement efficiency, the appropriate advertisement should be displayed according to the characteristics of viewers.
To formulate mathematically, the display advertising can be represented by an optimization problem, so-called, the edge-weighed and capacitated bipartite matching problem [2], in which the vertices are either advertisement or user cluster. The weight of nodes in the bipartite graph represents the benefit, e.g., the click-through rate

(CTR). Corresponding to the change of display advertising with time, the weights of nodes change with time.

The purpose of our research is to find the best matching such that CTR maximizes and the variation rate of CTR reduces. The reason is that most of the advertisers usually like to spend their budget smoothly over the time in order to reach a wider range of users.

Since to find the best matching becomes harder as the number of vertices increases, a scheme to overcome the difficulty in the display advertising is a major issue.

Quantum annealing (QA) is expected to be an efficient method to obtain the best solution for combinatorial optimization problems [1,2]. To use quantum annealing processor, we constructed a formulation from the display advertising to quadratic unconstrained binary optimization (QUBO) to use the QA. More precisely, we pruned edges and nodes with less impact to deal with as large problems as possible by quantum annealing processor with the limited number of qubits. We performed the quantum annealing version of display advertising to our advertising data sets by quantum annealing processor, D-Wave 2X. We confirmed that the quantum annealing finds a better solution to realize our purpose than the greedy method in a shorter time.

This work was done in collaboration with Kotaro Tanahashi (Recruit Communications Co., Ltd.) and Shu Tanaka (Waseda Institute for Advanced Study, Waseda University and JST, PRESTO).

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Dan D. Padilha, QxBranch, LLC

Training L0-Regularised Linear Regression and Classification Models with a Quantum Annealer

Feature selection is a critical element of many applications of machine learning models. By selecting an optimal subset of features (variables) that best explain the underlying realities of a given dataset, a model becomes simpler to understand, more computationally efficient, and less susceptible to overfitting and noise. For this project, QxBranch designed, implemented, and benchmarked quantum-based $L0$-regularised (Q$L0$) linear regression and classification models on real-world and synthetic datasets. The $L0$ regularisation, a form of feature selection which penalises selecting too many features for a given model, encourages greater sparsity than other classical regularisation methods, but is a computationally intractable problem. Our QL0 implementation used the DW2X hardware to demonstrate generalised configurable-precision predictive models with linear combinations of selected features. The hybrid classical-quantum algorithm for QL0 was implemented as a scikit-learn (commonly-used Python machine learning library) "estimator" interface, allowing for simple integration with existing machine learning and scientific analysis pipelines. Our research showed that across the tested regression and classification datasets, QL0 consistently resulted in high-accuracy sparse prediction models that selected sets of features approximating those selected by leading sparse non-linear models. Based on these results, it is possible that quantum-based L0 regularisation methods may perform well as sparse feature selection steps in many machine learning algorithms.

Kotaro Tanahashi, Recruit Communications Co., Ltd.

Feature Selection by Quantum Annealing Processor -- An Extension of the QBoost --

Feature selection is to extract important features in the data among many features, which is an NP-hard problem. Since feature selection is widely used in real-world data analysis, development of an algorithm to overcome the difficulty in feature selection is an important issue. Quantum annealing (QA) is expected to be an efficient method to obtain the best solution for combinatorial optimization problems [1,2]. Thus, we proposed a new quantum annealing algorithm for feature selection (QAFS). To use quantum annealing processor, besides, we developed a method to map QAFS to quadratic unconstrained binary optimization (QUBO). Our method is regarded as an extension of the QBoost [3]. QAFS finds the optimal combination of the weak classifiers by QA to minimize the error over the training data with the limited number of features. Since QAFS is composed of non-linear weak classifiers, it can capture non-linear interactions between features while conventional linear methods cannot. We performed QAFS to an actual online advertising problem and public data sets by quantum annealing processor, D-Wave 2X. We confirmed that QAFS outperforms the conventional methods such as L1 regularized logistic regression and feature selection by random forest. This work was done in collaboration with Shinichi Takayanagi (Recruit Communications Co., Ltd.) and Shu Tanaka (Waseda Institute for Advanced Study, Waseda University and JST, PRESTO).

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Wednesday, June 28

Morning Session

Itay Hen, Information Sciences Institute, USC

Limitations of physical quantum annealers

It is yet unclear whether even ideal quantum annealers perform certain tasks better or faster than their classical counterparts. In this talk I will discuss several aspects of physical quantum annealing devices that limit their performance.

Nike Dattani, Hertford College, Oxford University

Truly adiabatic quantum annealing in novel NMR systems which do not leave their ground state

Previous implementations of adiabatic quantum computing algorithms using spin systems were not absolutely adiabatic, since they relied on control pulses which could spuriously cause the system to exit the ground state, and further control pulses to return the system back. We have experimentally demonstrated a complete adiabatic quantum computation where we managed to keep the system in the ground state all the way from the beginning to the end of a fully adiabatic passage. This was possible because we used the natural Hamiltonian of our sample to realize the problem Hamiltonian, and extrinsic Hamiltonians induced by electromagnetic pulses to drive the system along the adiabatic passage. As a showcase example, we prime factorized 291311 experimentally at room temperature, and we used tomography to measure the populations in the computational basis at 11 different stages of the adiabatic passage to demonstrate that the system remained in the ground state the entire time. The fluctuation in our fidelity was ~ 0.0005, compared to what we get with the previous method for NMR annealing, which is ~ 0.02. In contrast to superconducting flux-based annealing, NMR annealing has already succeeded with 3-local terms [PRL (2009) 102, 104501], 2-local non-stoquastic terms XX, YY in addition to ZZ [PRA (2016) 93, 052116], and 4-local, non-stoquastic terms XYXY + YXYX [PRL (2014) 113, 080404]. We will therefore discuss prospects for scaling universal NMR annealers to numbers of qubits competing with non-universal superconducting annealers.

Co-authors: Zhaokai Li [1,2], Xi Chen [1], Xiaomei Liu [1], Hengyan Wang [1], Nathan

Bryans [3], Richard Tanburn [4], Hongwei Chen [4], Xinhua Peng [1,2], and Jiangfeng Du [1, 2]
[1] University of Science and Technology of China, Hefei 230026, China, [2] Synergetic Innovation Center of Quantum Information and Quantum Physics, Hefei 230026, China [3] University of Calgary, Calgary, T2N 1N4, Canada, [4] Oxford University, Department of Mathematics, Oxford, OX1 3BW, United Kingdom

Steven J. Weber, MIT Lincoln Laboratory
Coherent Coupled Qubits for Next Generation Quantum Annealing

Existing quantum annealers rely on coupled superconducting flux qubits with short coherence times, limited primarily by the use of large persistent currents. Here, we investigate the available design space for next-generation quantum annealers, exploring the tradeoff between, coherence, coupling, and connectivity. In particular, by reducing the qubit persistent current we demonstrate a significant improvement in coupled qubit coherence. Furthermore, we discuss coupler chains and parallel couplers, the basic building blocks of a proposed high-connectivity, high-coherence architecture for quantum annealing.

Ryan M. Hamerly, National Institute of Informatics
Quantum vs. Optical Annealing: the Coherent Ising Machine and DWAVE

Ryan Hamerly, Peter McMahon, Alireza Marandi, Davide Venturelli, Shoko Utsunomiya and Yoshihisa Yamamoto
We compare the performance of an optical Ising machine built from a network of parametric oscillators to the DWAVE quantum annealer. In the Ising machine, the spin network is represented by a synchronously-pumped fiber OPO that stores 100 pulses, and the Ising Hamiltonian is simulated with a measurement-feedback system, enabling all-to-all connectivity. While the quantum annealer outperforms the Ising machine for sparse graphs, we find that the Ising machine gives significantly better solutions for dense graphs, a fact that may be attributed to the sparse connectivity and embedding overhead of current quantum annealing architectures.

Alexander Glaetzle, University of Oxford and CQT Singapore
Adiabatic Quantum Computing with Ultra-Cold Rydberg Atoms

There is a significant ongoing effort in realizing quantum annealing with different physical platforms. The challenge is to achieve a fully programmable quantum device featuring coherent adiabatic quantum dynamics. In this seminar I will show show that combining the well-developed quantum simulation toolbox for Rydberg atoms with the recently proposed Lechner-Hauke-Zoller (LHZ) architecture allows one to build a prototype for a coherent adiabatic quantum computer with all-to-all Ising interactions and, therefore, a novel platform for quantum annealing and machine learning. In LHZ a infinite-range spin-glass is mapped onto the low energy subspace of a spin-1/2 lattice gauge model with quasi-local 4-body parity constraints. This spin model can be emulated in a natural way with Rubidium and Cesium atoms in a bipartite optical lattice involving laser-dressed Rydberg-Rydberg interactions, which are several orders of magnitude larger than the relevant decoherence rates. This makes the exploration of coherent quantum enhanced optimization protocols accessible with state-of-the-art atomic physics experiments.

Reference:

A. Glaetzle, R. van Bijnen, P. Zoller, W. Lechner, A Coherent Quantum Annealer with Rydberg Atoms, arXiv:1611.02594

Eleanor Rieffel, NASA Ames Research Center

Investigations of quantum heuristics for optimization

Wednesday, June 28

Afternoon Session

Stephen P. Jordan, NIST/U. Maryland

Quantum and stochastic optimization

Quantum and stochastic optimization algorithms are closely related. Loosely speaking, stochastic optimization algorithms can be obtained by removing the i from Schrodinger's equation, yielding a continuous time diffusion process. Here we investigate how quantum and stochastic optimization algorithms compare to each other and inform each other. In particular, we find that, by applying the control-theoretic framework introduced by Yang et al. for the optimization of adiabatic and QAOA algorithms, we obtain an exponential improvement in the performance of classical simulated annealing for certain problems. This is joint work with Aniruddha Bapat, Jake Bringewatt, and Bill Dorland.

Maritza L. Hernandez-Gaete, 1QBit

Enhancing Quantum Annealing Performance for the Molecular Similarity Problem

Quantum annealing is a promising technique which leverages quantum mechanics to solve hard optimization problems. In this work, we present a quantum annealing approach to measure similarity among molecular structures. In order to overcome the limited hardware connectivity, a problem must be reformulated using minor-embedding techniques. Using a real data set, we investigate the performance of a quantum annealer in solving the molecular similarity problem. We provide experimental evidence that common practices for embedding can be replaced by new alternatives which mitigate some of the hardware limitations and enhance its performance. Common practices for embedding include minimizing either the number of qubits or the chain length, and determining the strength of ferromagnetic couplers empirically. We show that current criteria for selecting an embedding do not improve the hardware's performance for the molecular similarity problem. Furthermore, we use a theoretical approach to determine the strength of ferromagnetic couplers. Such an approach removes the computational burden of the current empirical approaches, and also results in hardware solutions that can benefit from simple local classical improvement. Although our results are limited to the problems considered here, they can be generalized to guide future benchmarking studies.

Davide Venturelli, NASA QuAIL

Deterministic Embedding Methods for Integer Linear Programming on Chimera Graphs and beyond

Quantum Annealers are being considered as a possible platform to solve challenging Integer Linear Programming Problems (ILP). The current approaches to hard-code an ILP employ graph minor embedding algorithms that require a significant overhead of resources (number of qubits, computing power) with respect to the number of logical variables in the ILP. This overhead is arguably the primary problems for practitioners of quantum annealing. We present a new method to deterministically embed an arbitrary ILP in a generic class of annealing chip layouts such that the timings and performance beats the current methods. The method is flexible on the chip structure and it is based on directly crafting the optimization formulation by modifying the penalty functions and casting the instance into an intermediate form which is known to be embeddable. It is shown on the latest D-Wave chips to allow programming of problems, relevant for database and space sciences, which would not be embeddable in reasonable time or space with the current approaches. The discussed methods can be easily adapted to any chip that supports a tiling in unit cells, or to irregular chips by means of pre-processing techniques, and also inform the design of next-generation of quantum annealers.

Masaaki Maezawa, National Institute of Advanced Industrial Science and Technology

Technology Integration for Practical-Scale Quantum Annealing Machine

We propose a technology integration scheme for quantum annealing machine towards solving practical-scale problems. The manufacturability is discussed with an example application of a factoring machine consisting of superconducting qubits, inter-qubit couplers, and auxiliary circuits. A central idea is restriction of the functionality: the factoring machine is designed only for the factoring application. The simplification strategy, which we call an Application Specific Annealing Computing (ASAC) architecture, increases the available hardware budget and reduces the cost and time for development. The circuits consist of Josephson junctions and are implemented by using superconducting integrated circuit technology. We plan to fabricate the factoring machine in a 3-dimentional packaging structure, namely, a QUbit chips, Interposers and a Package substrate (QUIP) structure, which is essential to sufficiently large scale systems for practical applications.

Edward Farhi, MIT

How to run a near term gate model quantum computer

I will discuss quantum algorithms for optimization that can be run on near term gate model quantum computers. In particular I will discuss an approach to optimization that is a variant of the Quantum Approximate Optimization Algorithm and uses only gates that are available given the hardware layout. These algorithms can be tried without error correction or compilation so that the number of logical qubits is the number of physical qubits. The ultimate strength of this approach will be determined when actual quantum computers test them.

Alejandro Perdomo-Ortiz, NASA Ames Research Center

Model-based diagnosis in combinational digital circuits: An application with potential for quantum speedup

Only recently, it was demonstrated that optimization on the D-Wave 2X quantum annealer can outperform other sequential algorithms on CMOS-based hardware.
However, the benchmark problems were tailored to yield an advantage over classical local search algorithms. Furthermore, including state-of-the-art optimization techniques that are not sequential in nature closed the gap between quantum and classical optimization techniques. Therefore, the question arises if there are real-world application problems small enough in the number of variables such that they can be optimized on current quantum hardware, and where quantum annealing might excel over classical optimization techniques.
Here we demonstrate that model-based diagnosis in combinational circuits is an ideal problem for quantum enhanced optimization and the first application problem with potential for quantum speedup. Benchmark instances generated from this real-world application tend to be considerably harder than any specially-tuned random spin-glass instances (excluding post selection). We address the relevancy of many-body interactions beyond quadratic in current quantum annealers, as well as connectivity requirements to solve real-world problems.
Co-authors: A. Feldman, Z. Zhu, A. Ozaeta, S. Isakov, A. Diedrich, H. Katzgraber, H. Neven, V. Denchev, J. De Kleer, B. Lackey, and R. Biswas.

Jack Raymond, D-Wave systems

Quantum and classical estimators for quantum Boltzmann statistics

We apply three methods to the task of estimating statistics of quantum Boltzmann distributions in the transverse field Ising model.

The first is based on drawing samples from a physical implementation of quantum annealing (QA). The second is based on simulated quantum annealing (SQA) using continuous-time quantum Monte Carlo. The third is based on parallel-tempering quantum Monte Carlo (PT-QMC).

QA and SQA have qualitatively similar error patterns, but the rate required in SQA to match the QA error increases both with system size, and with the ratio of problem energy scale to transverse field energy scale (roughness of the energy landscapes). Our PT-QMC implementations are capable of establishing exact statistics for large systems over long runs, but require resources that increase with system size to match the errors achieved by QA. These results indicate that the QA-based estimator we propose may be a good candidate for approximate sampling of certain complex transverse field Ising models.

Thursday, June 29

Morning Session

Shunji Matsuura, 1Qbit

Non-stoquastic Hamiltonian in QAC and spin glass

The efficiency and the accuracy of the adiabatic quantum computation largely depend on energy gaps between energy levels. Recently it has been shown in some models that quantum error correction can increase an energy gap between the ground state and excited states, whereas non-stoquastic Hamiltonian can also allow to avoid strong phase transitions. In this talk I will present behaviour of non-stoquastic systems in quantum annealing correction as well as a spin glass model.

Andrea Rocchetto, University of Oxford

Stabilizers as a design tool for new forms of the Lechner-Hauke-Zoller annealer

In a recent paper, Lechner, Hauke, and Zoller (LHZ) described a means to translate a Hamiltonian of N spin-1/2 particles with “all-to-all” interactions into a larger physical lattice with only on-site energies and local parity constraints. LHZ used this mapping to propose a novel form of quantum annealing. We provide a stabilizer-based formulation within which we can describe both this prior approach and a wide variety of variants. Examples include a triangular array supporting all-to-all connectivity as well as arrangements requiring only 2N or N log N spins but providing interesting bespoke connectivities. Further examples show that arbitrarily high-order logical terms can be efficiently realized, even in a strictly two-dimensional layout. Our stabilizers can correspond to either even-parity constraints, as in the LHZ proposal, or odd-parity constraints. Considering the latter option applied to the original LHZ layout, we note that it may simplify the physical realization because the required ancillas are only spin-1/2 systems (that is, qubits rather than qutrits); moreover, the interactions are very simple. We make a preliminary assessment of the impact of these design choices by simulating small (few-qubit) systems; we find some indications that the new variant may maintain a larger minimum energy gap during the annealing process.

Shruti Puri, Université de Sherbrooke

A quantum Ising machine based on parametrically driven nonlinear oscillators

Quantum annealing exploits quantum fluctuations to solve combinatorial optimization problems that can be encoded into the couplings of Ising Hamiltonians. Protecting these machines against decoherence remains an outstanding challenge. In this talk I will introduce a new paradigm for quantum annealing which relies on continuous variable states. In this approach, quantum information is encoded in two coherent states that are stabilized by parametrically driving a nonlinear oscillator. I will show that a fully connected Ising problem can be mapped onto a network of such resonators. I will also outline an adiabatic annealing protocol during which the oscillators in the network evolve from vacuum to coherent states representing the ground state configuration of the encoded problem. Numerical simulations indicate substantial resilience to photon loss in this system. Finally, I will discuss realizations of these ideas in superconducting circuits. This continuous variable annealer provides new direction for exploring quantum phase transitions and non-stoquastic dynamics.

Hidetoshi Nishimori, Tokyo Institute of Technology

Analyses of non-stoquastic Hamiltonians by the mean-field theory

Non-stoquastic Hamiltonians cannot be easily simulated classically and are known to have the capacity to accelerate quantum annealing in some cases. I review our analyses of non-stoquastic Hamiltonians and present new results on the role of quantum effects in the mean-field-type non-stoquastic Hamiltonians.

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[4] Y. Susa, J. Jadebeck and H. Nishimori, Phys. Rev. A 95, 042321 (2017)

Title and Abstract of Poster Presentations

Day 1: Monday, June 26

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1. Sei Suzuki, Saitama Medical University

Quantum annealing of an open quantum system

In the practical situation of quantum annealing like in a D-Wave's computer, the effect of thermal environment is unavoidable. Therefore it is quite important to investigate the time evolution of a quantum spin system coupled to a thermal bath. Recently, we have developed a novel numerical method that can be applied to the time evolution of a disordered transverse Ising chain coupled to a bosonic bath. This method is based on the combination of the quasi-adiabatic path integral and the density matrix renormalization group. With the numerical results, we will discuss what happens to the spin state during quantum annealing. Our study will provide a hint on the design of an efficient quantum annealing in a thermal environment.

2. Jun Takahashi , University of Tokyo

Detection of Phase Transition in Quantum Annealing using Fidelity Susceptibility

Understanding phase transitions which occur during Quantum Annealing (QA) has both practical and fundamental importance. It not only provides the physical picture for the obstacle of efficient QA, but also suggests strategies to avoid the phase transition, resulting in speed up of QA.

In this work we focus on fidelity susceptibility (a.k.a., SLD Fisher information) which is a probe to detect drastic changes in the ground state of a varying Hamiltonian. It is known in several quantum spin models, that fidelity susceptibility captures topological phase transitions, where there are no local order parameters.

We study if fidelity susceptibility is useful also for quenched disorder systems, specifically in QA Hamiltonians for NP-hard problems.

NP-hard problems with unique solutions should have exponentially small energy gaps according to the computational complexity conjecture of NP ¥nsubset BQP (or P ¥neq NP, if you believe that stoquastic QA are actually within BPP). In this study, we numerically find that for the NP-hard maximum independent set problem, there is a phase transition that is only detectable by the divergence of the fidelity susceptibility, which leads to exponentially small energy gaps within the novel phase.

3. Andrew J. Ochoa, Texas A&M University

Approximating continuous coupler distributions on devices with limited precision

Special purpose computers, such as the D-Wave 2X quantum annealer or the FPGA-based Janus Computer, are typically restricted by memory constraints, limited precision or analog noise. This means that the study of problems with interactions drawn from continuous distributions can be difficult. Here we extend the approach introduced by Leuzzi {¥em et al.}~[Phys.~Rev.~Lett.~103, 267201 (2009)] to approximate a continuous Gaussian distribution by using quadratures. Our approach allows us to approximate any continuous distribution using only a few discrete weights. From a classical point of view, this reduces the simulation's memory footprint of continuous problems drastically, as well as the simulation time, because multiple quantities and expensive operations, such as exponentials, can be precomputed and tabulated. For quantum annealing architectures this means that problems that require continuous distributions can be encoded within the restrictions of finite precision and analog noise on these devices. Advantages and disadvantages of this simulational approach are discussed.

4. Pooya Ronagh, 1QBit

Reinforcement Learning Using Quantum Boltzmann Machines

The Boltzmann distribution of the energy function of a Boltzmann machine can be used to design machine learning algorithms. In this talk, instead of a classical energy function, we associate a transverse field Ising spin Hamiltonian with significant transverse field to the Boltzmann machine and propose a reinforcement learning algorithm based on this graphical model. We then discuss quantum Monte Carlo methods of approximating the partition function, the Gibbs free energy, and the expected values of the spins in the model along the measurement basis, and show that this richer Boltzmann machine can improve the convergence of the algorithm to an optimal policy for an autonomous agent seeking optimal control over its ambient environment.
Some of these results are disclosed in https://arxiv.org/abs/1612.05695.

5. Yuki Susa, Tokyo Institute of Technology

Relation between quantum fluctuations and the performance enhancement of quantum annealing in a non-stoquastic Hamiltonian

We study the relation between quantum fluctuations and the significant enhancement of the performance of quantum annealing in a non-stoquastic mean-field Hamiltonian. First-order quantum phase transitions were shown to be reduced to second-order by a non-stoquastic term in a mean-field-type many-body-interacting Ising spin system in a transverse field, which means an exponential speedup of quantum annealing by adiabatic quantum computation.
We investigate if and how quantum effects manifest themselves at around these first- and second-order phase transitions to understand if the non-stoquastic term appended to the conventional transverse-field Ising model induces notable quantum effects.
By measuring the proximity of the semi-classical spin-coherent state to the true ground state as well as the magnitude of the concurrence representing entanglement, we conclude that significant quantum fluctuations exist at around second-order transitions whereas quantum effects are much less prominent at first-order transitions.
This result suggests that the non-stoquastic term induces marked quantum effects, and it is likely to be related closely with the significant enhancement of the performance of quantum annealing.

6. Hamed Karimi, 1QBit

Effective optimization using sample persistence: a case study on quantum annealers, simulated annealing and simulated quantum annealing

We present and apply a general-purpose multi-start algorithm for improving the performance of low-energy samplers used for solving optimization problems. The algorithm iteratively fixes the value of a large portion of the variables to values that have a high probability of being optimal. The resulting problems are smaller and less connected, and samplers tend to give better low-energy samples for these problems. The algorithm is trivially parallelizable, since each start in the multi-start algorithm is independent, and could be applied to any heuristic solver which can be run multiple times to give a sample. We present results for several hard problem classes solved using simulated annealing (SA), path-integral quantum Monte Carlo (QMC) and a quantum annealer, and show that not only are success metrics improved substantially, but the scaling is as well. When combined with this algorithm, we observed that the quantum annealer outperformed SA and QMC on native Chimera problems. We also observed that with this algorithm the scaling of the time to solution of the quantum annealer is comparable to HFS on the weak-strong cluster problems.

7. **Manuel Pino Garcia, Insituto Física Fundamental, Calle de Serrano, 121, 28006 Madrid, CSIC, Spain**

Non-ergodic metallic and insulating phases of Josephson junction chains

A 1D array of Josephson junctions at high temperatures can exhibit a non-ergodic regime [1], which is similar to a glass. The glassiness occurs because the system is not able to reach all the many-body space. In fact, one can induce a transition to a fully many-body localized phase by heating up the system. In this talk, I will analyse the properties of the non-ergodic phase in the quantum and classical regime and compare with standard glasses.

[1] M. Pino, L. B. Ioffe, and B. L. Altshuler, Proceedings of the National Academy of Sciences (2015), 10.1073/pnas.1520033113.

8. **Jie Sun, Huazhong University of Science and Technology**

On the failure of the general models of adiabatic evolutions for quantum search

The general class of models of adiabatic evolution was proposed to further speed up the usual adiabatic evolution. But it can totally fail when the initial state is orthogonal to the final state in the quantum system. Here, we study a special form of these generalized adiabatic evolution and will find some interesting properties of it, which may further strengthen our thinking about these models and be helpful for designing adiabatic algorithms for practical problems.

9. **Hayato Goto, R&D Center, Toshiba Corporation**

Adiabatic quantum computation and Boltzmann sampling with a network of driven nonlinear oscillators

Last year, we proposed adiabatic quantum computation with a network of parametrically driven Kerr-nonlinear oscillators (KPO for short), where no dissipation was assumed [1]. Recently, we have investigated the network with dissipation by numerical simulation. Interestingly, the results suggest that the distribution of the outputs from the dissipative KPO network seems to become the Boltzmann distribution. This phenomenon can be explained by extending the theory of quantum heating in a single dissipative nonlinear oscillator to the network case. This result also provides a new application of the KPO network: Boltzmann sampling. This is useful for Boltzmann machine learning. [1] H.

Goto, Sci. Rep. 6, 21686 (2016).

10. Hitoshi Ishikawa, PEZY Computing, K.K.

A strategic scheme of quantum Monte Carlo implementation bringing out the potential in a supercomputer with many-core processors

Quantum annealing (QA) is a promising algorithm to solve combinatorial optimization problems with high efficiency [1,2]. Since the appearance of commercial quantum annealing processor, some hardware based on the Ising model to solve combinatorial optimization problems has been proposed and developed exhaustively. On the contrary, we considered a method to accelerate the parallel computation in quantum Monte Carlo (QMC) simulations. A QMC algorithm can treat QA in conventional classical computers toward the realization of high-performance computation of large-scale combinatorial optimization problems. We implemented a QMC algorithm on many-core processors, PEZY-SCs. PEZY-SC is a Multiple Instruction/Multiple Data (MIMD) processor with 1024 computing cores, in which eight threads run independently. In this architecture, by using the core-local memory and synchronization, the communications between the threads in a core are much faster than the global communications. Since QMC is implemented by using the Suzuki-Trotter decomposition [3,4], it can be regarded as a pseudo-parallelization calculation [5] in which the interactions in the imaginary-time direction exist. Thus, it is reasonable to assign the whole trotters of a spin (qubit) to the same core (i.e. eight threads). Furthermore, the MIMD feature of PEZY-SC is suited for an efficient calculation since the interactions between spins are inhomogeneous in combinatorial optimization problems. The communication between multiple processors is performed by Message Passing Interface (MPI), which can share the state of spins. To estimate the efficiency of the scaling of multiprocessors, we measured the performance of QMC on PEZY-SC depending on the problem size. Here, we assumed that the connections, i.e., the interactions between spins in the real space, are sparse as well as the Chimera graph that D-Wave Systems Inc. adopted. Our result suggests that when the number of spins is not so large, it is effective to retain all spins within a processor since the communications between processors require a certain amount of overhead for data exchange and synchronization. While when the number of spins grows, the advantage of multiple processors comes out.
This work was done in collaboration with Yuichiro Minato (mdr Inc. and Innovation Program, MIC), Ryo Tamura (NIMS), and Shu Tanaka (Waseda University).

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11. Steve Reinhardt, D-Wave Systems, Inc.

Graph Embedding by Filtering Pre-embeddings via a Distance-Aware Metric

Fast and space-efficient embedding of problem graphs to a given system is an important module for partitioning solvers like qbsolv. Recursive-bisection connectivity (RBC) as a metric describes the connectivity of a graph while incorporating a notion of distance within the graph. We describe a two-phase embedding approach that a) in advance creates numerous pre-embeddings of a given problem size and connectivity and b) at embedding time eliminates infeasible pre-embeddings quickly using RBC as a filter before graph matching is finally attempted. The algorithm and early results are described.

12. Gabriel M. Bianconi, QxBranch

Quantum-Assisted Learning for Convolutional Deep Belief Networks

The project aims to investigate whether adiabatic quantum computers can improve deep learning algorithms. Previous research focused on Boltzmann machines and related methods, but achieved little practical success due to limitations in existing quantum devices. We're developing a novel quantum-assisted (hybrid) learning algorithm for convolutional deep belief networks with the goal of overcoming some of these obstacles and enabling larger problems, particularly in vision, to be modeled.

13. Maxwell P. Henderson, QxBranch

Leveraging adiabatic quantum computation for election forecasting

Accurate, reliable sampling from fully-connected graphs with arbitrary correlations is an extremely difficult problem. Such sampling requires knowledge of the probabilities of observing every possible state of a graph. As graph size grows, the number of states becomes intractably large and efficient computation requires full sampling be replaced with heuristics and algorithms that are only approximations of full sampling. In this work we investigate what adiabatic quantum computation can contribute in lieu of some recent successes training various Boltzmann machines using a quantum device. In particular we investigate the potential use of quantum computation for predicting the 2016 Presidential election.

14. Yoichiro Hashizume, Tokyo University of Science

A construction method of initial Hamiltonian for singular value decomposition by quantum annealing

We investigated how the initial Hamiltonian affects the performance of quantum annealing (QA) for singular value decomposition. In the previous study, we introduced an implementation method of QA for singular value decomposition [1]. In the method, we have to find the eigenstate of the Gram matrix G generated by a target data matrix, where the eigenvalue of the eigenstate is the maximum value. In our scheme, the target Hamiltonian is defined as -G while the initial Hamiltonian H0 is prepared so that the ground state is a trivial eigenstate . After the preparation of Hamiltonians, QA realizes by changing the coefficients of both Hamiltonians. However, the previous studies [1,2] did not clarify the performance of QA depending on the initial Hamiltonian. To make it clear systematically, in the present study, we use hierarchical data matrices. We find that the performance of the above method depends on the initial gap between the ground state and the first excited state of H0. In addition, we find that when we set the initial gap is the same order as the trace or the Frobenius norm of G, QA is efficient for singular value decomposition. This work was done in collaboration with Ryo Tamura (MANA, NIMS and CMI2, NIMS) and Shu Tanaka (WIAS, Waseda University, JST, PRESTO, and MANA, NIMS).

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15. Songfeng Lu, Huazhong University of Science and Technology

Assisted driving Hamiltonian can be not unique in adiabat6ic evolution

If the overlap between the initial state and the final state of the quantum system is confined to some suitable ranges, even the assisted driving Hamiltonian is designed as the forms which are different from the usual one, the adiabatic evolution can still be successful for the quantum computation. This fact may tell us that, even in almost all of the occasions where assisted driving Hamiltonians could be used for the reducing the time complexity of the adiabatic evolution computing, in which the driving Hamiltonian has a relatively fixed form, however, there could still exist the freedoms of choosing other forms of extra assisted driving Hamiltonian for the adiabatic computation, if the overlap between the states of the system is supposed to be controlled appropriately at the same time.

16. Tomohiko Abe, Nextremer Co., Ltd.

Batch-learning self-organizing map with quadratic unconstrained binary optimization -- toward application to Ising machine --

Self-Organizing Map (SOM) is a kind of neural network trained by unsupervised learning [1]. In the framework of SOM, high-dimensional data is visualized by mapping of data on low-dimensional space. SOM has been used for many applications such as clustering [2]. Especially, batch-learning SOM is a practical application and has been studied exhaustively [3]. In algorithms of conventional batch-learning SOM, all data in a batch is used for updating weights in every epoch, on the other hand, selecting data in a batch can improve the quality of the obtained results.

In our study, we propose a new algorithm, batch-learning SOM with quadratic unconstrained binary optimization(QUBO). To optimize quantization error calculated by using selected data in a batch, we formulate the batch-learning SOM by using QUBO.

We apply this algorithm to some datasets and investigate the performance of this algorithm. This work was done in collaboration with Taichi Iki (Nextremer Co., Ltd.) and Shu Tanaka (Waseda University and JST, PRESTO).

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17. Yoshihiro Osakabe, Tohoku University

Comparison between Ising Hamiltonian and Neuro-inspired Hamiltonian for Quantum Associative Memory

In order to enlarge the applicable fields of quantum computing, it has been investigated the fusion of neural and quantum computing because neural computing has succeeded to provide conventional computers with an effective way to obtain new algorithms by learning [1]. Thus, some pioneers have investigated the quantum analog of neural networks, for example, Ventura et al. proposed a quantum associative memory (QuAM) by introducing quantum dynamics into neural associative memory [2]. They used quantum logic gates to memorize patterns and modified Grover's database search algorithm [3] to recall memorized patterns. Contrary to the previous study, we studied another approach to realize a QuAM in consideration of its hardware implementability. In this research, we propose a novel QuAM achieved with a qubit network by employing adiabatic Hamiltonian evolution [4]. To study the details of its dynamics in memorizing and retrieving procedure, we examine two types of Hamiltonians to memorize patterns; Ising Hamiltonian [5] which has diagonal elements and is similar to cost function of Hopfield network, and neuro-inspired Hamiltonian [6, 7] which has non-diagonal elements and is based on interactions of arbitrary two qubits. Numerical simulation results indicate that the proposed methods for memorizing and retrieving patterns work well with both types of Hamiltonians. The difference of the two Hamiltonians appears when we evaluate the probability of retrieving a target pattern with a one-bit flipped key input. When the number of memorized patterns M is small, the retrieving probability of the QuAM with an Ising Hamiltonian is larger than that with a neuro-inspired Hamiltonian. When M is getting larger, the difference of the retrieving probabilities is getting smaller. This dissimilarity is probably caused by the size difference of search space. On the other hand, the difference of the Hamiltonians doesn't influence the memory capacity M_{cap} of the QuAM which reaches 2^{N-1}, where N is a number of qubits. In fact, the average retrieving probability of the QuAM exceeds 70% for 4-qubit patterns no matter which Hamiltonian you choose. Therefore, we can conclude that the choice of which Hamiltonian to adopt depends on the hardware implementation feasibility. Because M_{cap} of a conventional neural network is limited to at most 0.14N [8], the large memory capacity of the QuAM would be a big advantage.

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18. Mutsuo Hidaka, National Institute of Advanced Industrial Science and Technology (AIST)

Fabrication Process and Device Structure for Nb-based Quantum Annealing Devices

We have been developing a Nb-based fabrication process for quantum annealing devices. Qubits and peripheral circuits for a control and readout circuits of the qubits are fabricated on different chips. The qubit chips consist of planarized three Nb layers with Nb/AlOx/Nb Josephson junctions which are fabricated directly on the substrate at the first step. In the qubit chip, possible noise sources of resistors and anodized oxide layers are eliminated. The peripheral circuit chips have planarized four Nb layers, a resistor layer and Nb/AlOx/Nb Josephson junctions whose critical current density is two orders of magnitude higher compared with that of the qubit chips. The qubit chips are settled on the peripheral chip as an interposer by using flip-chip bonding method. The peripheral circuit chips are placed on a package substrate and connected to wirings on the package substrate with through silicon vias (TSVs) in the peripheral circuit chips. The adjacent peripheral circuit chips are connected with a bridge interposer. We call this device structure QUIP (QUbit chips, Interposers and a Package) structure. QUIP structure is two-dimensionally scalable and promising to realize practical-scale quantum annealing machines.

This paper is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

19. Zhigang Zhang, Huazhong University of Science and Technology

Study the structure of local Hamiltonian on adiabatic quantum computation

The different encoding structures of initial Hamiltonian, final Hamiltonian and extra Hamiltonian can affect the efficiency of adiabatic quantum computation(AQC). As a matter of fact , all have done is to modify the structure
of local Hamiltonian,which is the time-dependent Hamiltonian during the adiabatic evolution. In this paper, we clarify the link between the structure of local Hamiltonian and the efficiency of AQC. On one hand, we analyze
the reason why an adiabatic algorithm can have a good or bad performance by using a conventional equivalent approximation, and find the structure of the local Hamiltonian must contain the flipping matrix to keep an efficient evolution in AQC. On the other hand, we discuss the relationship between the evolution time complexity and the structure of local Hamiltonian, and it shows the time complexity is depended on the relevant backdiagonal elements of the local Hamiltonian matrix. This may help us better understand the adiabatic analogue of resources required in adiabatic evolution model, just like the number of operations does for conventional quantum computing.

20. Gianni Mossi, SISSA
Many-body localization in quantum spin glasses

In this presentation I will compare glassiness and localization in their role as obstructions for (respectively) thermal annealing and quantum annealing by relating some recent results of my research. In particular, we studied the Ising spin glass model in a transverse field defined over a regular random graph as a test-case for a problem that exhibits both quantum glassiness and localization. Using the forward approximation we computed numerically the critical line where localization sets in (the "mobility edge") and found it to be distinct from the critical line of the glassy phase. Consequently, the glassy phase is split into a delocalized region where tunnelling amplitudes are expected to be nonzero in the thermodynamical limit, and a localized region where tunnelling is suppressed. This suggest that in the glassy, delocalized region quantum annealing will perform well while thermal annealing will fail.

21. Ryo Tamura, National Institute for Materials Science
Quantum annealing for clustering of artificial data set by quantum Monte Carlo methods

Quantum annealing (QA) is an efficient method to obtain the best solution for combinatorial optimization problems [1]. Combinatorial optimization problems are often mapped to the Ising model to perform QA, some of which succeeded to realize QA experimentally by using QA processors. However, to consider the performance of QA for systems with multi-valued variables is important to clarify the potential of QA [2,3,4,5], since it is convenient to use models with multi-valued variables (e.g., the Potts model and the clock model) for the representation of some problems in the information engineering field (i.e., clustering problem, coloring problem, and grey-scale or color image recovery problems). In addition, if a machine which can treat multi-valued variable as in Ref. [6] is developed, the motive would become more significant.

In this work, as an application of QA for the systems with multi-valued variables, we compare the performances for clustering of artificial data set by QA performed by quantum Monte Carlo methods and by the general algorithm. To investigate the efficiency systematically, we used the Gaussian mixture model. We clarify the potential of QA for solving the clustering problems.

This research is collaboration work with Shu Tanaka (WIAS, Waseda University, JST, PRESTO, and MANA, NIMS).

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22. Toshiyuki Ohki, Tokyo Institute of Technology

Verification of the performance of the quantum Boltzmann machine

We verify the numerical results of Amin et al (arXiv:1601.02036), in which they introduced a transverse field to the Ising model for Boltzmann machine learning. We investigated when and how the transverse field affect the performance of learning.

23. Masaki Ookuwa, Tokyo Institute of Technology

Application of the discrete WKB method to the ferromagnetic p-spin model with antiferromagnetic transverse interactions

We study the fully connected mean-field model with p-body ferromagnetic interactions and a transverse field. This model with p＞2 has a quantum phase transition of first order as a function of the strength of the transverse field at T=0 [1]. This first-order transition is known to be reduced to second order by an introduction of antiferromagnetic transverse interactions [2], which makes the Hamiltonian non-stoquastic [3]. Thus the computational complexity is drastically reduced from exponential to polynomial. In order to understand this phenomenon in more detail, we applied the discrete WKB method [4] to analytically derive the coefficient of the exponential decay of the energy gap, b in exp(-bN), at the first-order transition. The result shows that the coefficient b is almost constant along the line of first order transition between the paramagnetic and ferromagnetic phases but changes significantly along the line of first order transitions within the ferromagnetic phase.

This work was done in collaboration with Hidetoshi Nishimori.

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24. Nicholas Chancellor, Durham UIniversity

Modernizing Quantum Annealing (and beyond) using Local Search

I will discuss my recent work which examines how how to take advantage of protocols search the solution space locally by using hybrid algorithms. In doing this I will discuss the numerous advantages of doing this, and how such methods are compatible with many other cutting edge techniques which are currently being explored. I will also discuss, how such searches can be understood as `inference primitives' which encode not only a local state to search near, but also encode certainty values of bits or even clusters of bits. I will further discuss present and future work toward producing proof-of-principle results for such methods as well as the potential of extensions to other continuous time quantum computing methods such as closed system adiabatic quantum computation and quantum walk. This presentation is based mostly on work I have done on my own, but will also contain some work done in collaboration with Viv Kendon, James Morely and Suogato Bose.

25. Tomomitsu Motohashi, Recruit Life Style

Optimize Combination of Recommendation Items by Quantum Annealing Processor

Information recommendation is utilized on many websites, which provides useful information for users. In most information recommendation system, all items are scored independently, and items with a high score are selected, even when multiple items need to be recommended. Since the recommended items should influence each other actually, it seems that the information recommendation in consideration of affinity between items is more desirable for users. However, to find the optimal solution requires a large amount of computation, because the number of combination patterns of items explodes exponentially with the number of items. In our study, we investigated a method to achieve high optimality rapidly by quantum annealing [1,2]. Our problem is to find a combination of recommended items with a specified number so that the specified score function maximizes. The contribution of our study is as follows. First, we devised a framework of introducing constraint equations. Instead of just adding a penalty term representing the constraint of fixing recommendation number, we proposed a term giving a penalty for adopting a recommended item. In other words, a penalty term is introduced as long-ranged interactions in conventional methods, whereas in our proposed method, a penalty term is represented as external fields. Our framework brings out the performance of quantum annealing. Second, we performed the combinatorial optimization problem using quantum annealing hardware, D-Wave 2X. Here we used our framework as mentioned earlier. Using our framework corresponds to searching for penalty coefficients such that a specified number is selected. Thus, we succeeded to improve the combination optimality further and to reduce the required coefficient setting between qubits.

This work was done in collaboration with Shu Tanaka, Shinichi Takayanagi and Kotaro Tanahashi.

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26. Taichi Itoh, BrainPad Inc.
Quantum annealing for combinatorial optimization problems with multiple constraints

We study an application of quantum annealing to combinatorial optimization problems with multiple constraints. We propose a formulation of Ising spin Hamiltonian, including the case of capacitated vehicle routing problems (CVRP). We perform the quantum annealing to the Hamiltonian by quantum Monte Carlo methods. The performance of quantum annealing is compared with conventional methods.
This work was done in collaboration with Mitsuhisa Ohta (BrainPad Inc.) and Yuichi Yamasaki (BrainPad Inc.), and Shu Tanaka (Waseda University and JST, PRESTO).

27. Kohji Nishimura, Tokyo Institute of Technology
Inference of the ground state of spin-glass Hamiltonians using quantum fluctuations

We study the retrieval of the ground state of the spin-glass Hamiltonian by using data only from another Hamiltonian whose interactions are corrupted by noise. We show numerically that applying certain quantum fluctuation to a noisy Hamiltonian helps recover the ground state of the original noiseless Hamiltonian. This result implies that we may keep the transverse field finite at the end of quantum annealing to obtain more reliable data. An analytical approach by using mean-field approximation is also discussed. This work has been done in collaboration with Hidetoshi Nishimori.

28. Kadowaki, Tadashi
A design of annealer dynamics with quantum and thermal effects

We introduce a novel design of annealer dynamics which consists of quantum and thermal dynamics into optimization problems. The design space is not limited to the physically interpretable subspace. In this study, transverse field is utilized as a source of quantum effect, but any interaction can be applied. We use Sherrington-Kirkpatrick model to assess two annealer dynamics, a linear combination of von Neumann and Master equations, and a parallel dynamics of these equations with frequent intervention of both states to harmonize them. The parallel dynamics shows synergistic enhancement of performance on probability of finding ground state after averaged over randomness, while the linear combination dynamics does not. Performance improvements are observed in both conditions of shorter and longer annealing periods in which thermal dynamics is superior to quantum one and vice versa, respectively. The results suggest robust dynamics in a wide range of annealing period and its usefulness. Then, we investigate the two annealer dynamics with ferromagnetic and quantum signature models. In both models, the parallel dynamics seems to relax into a thermal equilibrium state of the quantum system with given amplitude of the quantum effect. This finding gives us an example of how we can design annealer dynamics.

29. Masaaki Maezawa, National Institute of Advanced Industrial Science and Technology

Thermal Annealing of Classical Bits

We propose a new annealing method of obtaining the minimum energy states of Ising models. The idea is based on a classical analog of D-Wave quantum annealing machine in which quantum noise leads the system to the minimum energy state during the change in qubit potential from monostable to bistable states by reducing the transvers field. By controlling the potential of the classical analog, we should find a similar annealing process with thermal noise at higher temperature instead of the quantum noise. The hypothesis was examined by circuit simulation of networks of quantum flux parametrons (QFPs) at 4 K which are basically the same circuits as D-Wave machine. We successfully observed the annealing operations in small systems consisting of a few bits. Possible annealing at room temperature is also discussed on the basis of the natural extension of the concept to semiconductor circuits with bistable states such as SRAM and Schmitt trigger.

Day 2: Tuesday, June 27

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30. Tobias Stollenwerk, German Aerospace Center

Quantum Annealing for Air Traffic Management

In addition to studying fundamental properties of quantum annealing, it is imperative to find possible real world application for this technology. We studied quantum annealing for the real-world planning problem of deconflicting wind-optimal trajectories from air traffic management (ATM) [1]. From real-world data, we extracted subproblems which we mapped to QUBO. We were able to embed small problem instances into the D-Wave quantum annealer's chimera architecture and solve them. We report on how the embeddability and solution quality depend on the temporal coarseness and configuration space restrictions used when mapping the ATM problem to QUBO, using both classical solvers and quantum annealing runs.

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31. Joaquin Ossorio-Castillo, ITMATI

Solving energy-related scheduling problems with column generation and an adiabatic quantum computer

We present an algorithm for solving an energy-related scheduling optimization problem with mixed binary variables. The main idea behind the algorithm is to divide the problem in two subproblems, one with the real variables and the other with the binary variables. Then, a column generation scheme is used, thus adding proposals iteratively for the real variables and the binary variables, while solving a master problem for pricing the subproblems. In order to add the binary proposals, a binary solver has to be used. We explain the advantages of using an adiabatic quantum computer such as D-Wave Two for this kind of problems and its integration with the rest of the scheme. This work is a collaboration with Francisco Pena from the University of Santiago de Compostela, Spain.

32. Kabuki Takada, Tokyo Institute of Technology

Behavior of Spin Systems with a First-Order Phase Transition under Dissipation

We study the properties of phase transitions of the spin system with p-body infinite-range ferromagnetic interactions in a transverse field coupled to the bosonic environment. In addition, we append transverse antiferromagnetic interactions, which exponentially enhance the efficiency of quantum annealing. Phase diagrams of this model reveal that interactions of the transverse components of the spins with the environment effectively produce transverse ferromagnetic interactions and are detrimental to quantum annealing. In contrast, interactions between the longitudinal components and the environment yield transverse antiferromagnetic interactions and improve the efficiency of quantum annealing. This work was done in collaboration with Hidetoshi Nishimori.

33. Chihiro H. Nakajima, Tohoku university

Minimal energy gap of adiabatic quantum computing of multi-state extended Simon's problem

A method to realize the oracle for Simon's problem by quantum adiabatic computation, which is discussed by Hen [1] is extended to the models with p states. With the model, how the minimal energy-gap is dependent on p is discussed. As the further extension of the p-dependence, the minimal energy-gap of the oracle of Shor's algorithm of factorization is discussed.

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34. Shunta Arai, Tohoku University

Detection of phase transition in transverse-field Ising model by neural network

We detect the quantum phase transition in the transverse-field Ising model on the one-dimensional chain by using a different way from the standard estimation of the order parameters. We employ a technique of the unsupervised machine learning. The used data for learning is generated by the quantum Monte-Carlo simulation by mapping the original transverse-field Ising model on the one-dimensional chain onto the two-dimensional classical Ising model via the Suzuki-Trotter decomposition.

We construct a simple feed-forward neural network which learns the feature of the ordered phase of the transeverse-field Ising model and the disordered one only from the spin configurations without any prior information of the detailed form of the Hamiltonian. In the previous study [1], the similar type of the neural network can detect the critical point of the classical Ising model on the square lattice from the fed data of the spin

configuration.
In the present study [2], following the previous study, we elucidate a new quantity corresponding to the order parameter via the procedure of the machine learning and it shows a fairly good estimation of the location of the critical point of the transeverse-field Ising model. The present study demonstrates the potential of the technique of the machine learning, which can predict nontrivial behavior of quantum spin systems.
This work is collaboration with Masayuki Ohzeki (Tohoku University).
[1] A. Tanaka and A. Tomiya: arxiv/1609.09087
[2] S. Arai and M. Ohzeki: to appear soon

35. Tomoyuki Obuchi, Tokyo Institute of Technology
Complex semiclassical analysis of the Loschmidt amplitude and dynamical quantum phase transitions

We propose a new computational method of the Loschmidt amplitude in a generic spin system on the basis of the complex semiclassical analysis on the spin-coherent state path integral. By applying this, dynamical transitions in the time evolution of the Loschmidt amplitude will be examined for the infinite-range transverse Ising model with a longitudinal field in a quantum quench setting. The corresponding dynamical phase diagrams will be shown. Possible examination in experiments or application of the present method to a performance analysis of quantum annealing will be discussed.

36. Steve Adachi, Lockheed Martin
Application of Quantum Annealing to Training of Deep Neural Networks

In Deep Learning, a well-known approach for training a Deep Neural Network starts by training a generative Deep Belief Network model, typically using Contrastive Divergence (CD), then fine-tuning the weights using backpropagation or other discriminative techniques. However, the generative training can be time-consuming due to the slow mixing of Gibbs sampling. We investigated an alternative approach that estimates model expectations of Restricted Boltzmann Machines using samples from a D-Wave quantum annealing machine. We tested this method on a coarse-grained version of the MNIST data set. In our tests we found that the quantum sampling-based training approach achieves comparable or better accuracy with significantly fewer iterations of generative training than conventional CD-based training. Further investigation is needed to determine whether similar improvements can be achieved for other data sets, and to what extent these improvements can be attributed to quantum effects.

37. Joseph S. Dulny, Booz Allen Hamilton
Quantum Annealing Enabled Cluster Analysis

Unsupervised machine learning applications are of critical importance in many fields given the lack of labeled training data. Clustering is a powerful unsupervised learning technique that involves dividing data points into groups that share “similar” characteristics. Many clustering algorithms aim to minimize a cost function: The sum of “within-the-cluster” distances between points. A straightforward approach which guarantees a global minimum involves examining all the possible assignments of points to each of the clusters. The number of possible assignments scales quickly with the number of data points and becomes computationally intractable even for very small datasets. In order to circumvent this issue, cost function minima are found using popular heuristic approaches such as k-means and hierarchical clustering. Due to their greedy nature, such techniques do not guarantee a global minimum will be found and can lead to sub-optimal clustering assignments. In this work, we describe how quantum annealing can be used to carry out clustering in an optimal manner. We map the problem to a quadratic binary optimization problem and discuss two clustering algorithms which are then implemented on commercially-available quantum annealing hardware. The first algorithm assigns N data points to K clusters, and the second is used to perform binary clustering in a hierarchical manner. We present our results in the form of benchmarks against well-known classical clustering methods and discuss the issues faced while implementing these algorithms on actual hardware.

38. Takuya Hatomura, University of Tokyo
Fast quantum annealing for the infinite-range Ising model by mean-field counterdiabatic driving

Finite-time adiabatic dynamics can be realized in the strategy of shortcuts to adiabaticity, for examples, the invariant-based inverse engineering and counterdiabatic driving. On the analogy of the invariant-based inverse engineering with the mean-field ansatz [1], we propose mean-field counterdiabatic driving for the infinite-range Ising model [2]. This method is demonstrated in the quantum annealing process.

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39. Yuya Seki, GSIS, Tohoku Univ.

Effect of State transition of multi level systems to Performance of Quantum Annealing

Yuya Seki, Shu Tanaka, Shun Kataoka, and Kazuyuki Tanaka

Hamiltonian design is an important factor for performance of quantum annealing (QA). It is known that selection of driver Hamiltonian which induces quantum effects into the system greatly influences the required running time of QA for certain problems: A non-stoquastic driver Hamiltonian including XX ferromagnetic interactions enables us to avoid problematic first-order phase transitions for the ferromagnetic p-spin model and the Hopfield model.

In the present work, we focus on the degree of freedom of quantum information unit. Although spin-1/2 system is usually used as the unit, we can use other system called qudit which has multi levels more than two. In this case, we have a choice of state transitions between the multi levels. We examine QA on multi level systems. First, we investigate the effect of the transitions, we study the Wajnflasz-Pick model which is considered as a simple extension of two level system. As a result, we found that we can control the degree of quantum phase transitions by changing the stat transitions between the multi levels. Second, we study the effect of state transitions of qudit for another multi level system, the Potts model. The first study is a joint work with Shu Tanaka, and the second study is with Shun Kataoka and Kazuyuki Tanaka.

40. Tatsuro Yuge, Shizuoka University

Appearance of a superposition of macroscopically distinct states in adiabatic quantum computation

We propose a new theoretical method of testing the quantum speedup of quantum adiabatic algorithms (QAAs). The method is based on a conjecture that if a QAA provides a quantum speedup then a superposition of macroscopically distinct states appears during the computation. We show the results in several QAAs, such as the adiabatic Grover algorithm, which support this conjecture.

41. Hikaru Wakaura, University of Tsukuba

Quantum Error Correction using spin-vortex induced loop currents as qubits

A theory for copper oxides (cuprates) high temperature superconductivity predicts the existence of spin-vortex-induced loop currents (SVILCs). The SVILCs are nano-sized persistent loop currents exists in the CuO2 plane of the cuprates. In this theory, holes lose their mobility since they form small polarons due to strong hole-lattice interaction at temperatures below the superconducting transition temperature. An exchange interaction exists between nearest neighbor copper dx2-y2 electrons, and in addition to it, a superexchange interaction occurs between copper dx2-y2 electrons across the small polaron holes. By these interaction, itinerant electrons move around holes with twisting their spins. As a consequence, spin-vortices are formed around each hole and circulating motion of itinerant electrons generates the SVILCs [1]. The goal of the present study is a physical realization of quantum computers using spin-vortex induced loop currents as qubits [2]. The single qubit is represented by a quantum state with a particular current pattern created by a single SVILC or a collection of SVILCs. Merits of the SVILC qubit are

1, By cooling each qubit from psudogap temperature, the state of each qubit drops to its bottom level[3].
2, By measuring magnetic field emerged by SVILCs themselves, the states of each qubit are easily identified.
3, By splitting the energy levels of each state by external static vertical magnetic field and irradiating laser equivalent to energy difference between two given states, rapid universal gate operation is affordable.
4, Each state of SVILCs is determined by topological winding number of χ on each spin-vortices. So, the states of SVILCs are certainly robust against environmental noise.
5, By allocating each qubit separately and coupling given neighboring qubits, the system with large number of qubits can be fabricated in microscale region.

Hence, the SVILC qubit is a very promising candidate for making practical quantum computers. In the present work, we will present the result of numerical simulations for bit-flip detections using a 3-qubit system of SVILCs, which 3 qubits are allocated in a row with keeping C2 symmetry on 100a × 10a sized CuO2 plane. Then, a=0.4nm is the lattice constant of CuO2 plane. And, all the states are split by parabolic vertical static magnetic field. In addition, dipole moments between two states are significant. Hence, gate operations are very swift. Coupling neighboring two qubits can be realized deliberately and selectively.

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42. Hiroyasu Koizumi, University of Tsukuba
Proposal for spin-vortex-induced loop current quantum computer

We propose a quantum computer that utilizes spin-vortex-induced loop current (SVILCs) as qubits. SVILCs are nano-sized loop currents predicted to exist in the cuprate high temperature superconductors. Although their existence is not experimentally confirmed, they have a number of properties that are suitable for qubits. We propose methods to detect the predicted SVILCs and also explain how they are used in quantum computers.

43. Zhaokai Li, University of Science and Technology of China
Experimental Adiabatic Quantum Factorization Based on a Single Spin System

I will report on our experimental realization of an adiabatic quantum algorithm on a single solid spin system under ambient conditions. All elements of adiabatic quantum computation, including initial state preparation, adiabatic evolution (simulated by optimal control), and final state readout, are realized experimentally. As an example, we found the ground state of the problem Hamiltonian SzIz on our adiabatic quantum processor, which can be mapped to the factorization of 35 into its prime factors 5 and 7. (Reference: Phys. Rev. Lett. 118, 130504). If time permits, I will also report an experimental realization of factorization of 291311 using 3 qubits. In this demonstration, we made use of the natural Hamiltonian of a realistic quantum system to mimic the Hamiltonian during the adiabatic passage.

44. Shuntaro Okada, DENSO CORPORATION
Reconsideration of adiabatic theorem toward efficient quantum annealing

In the standard understanding of quantum annealing, the ground state can be obtained with high probability when the quantum fluctuation slowly decreases enough with the warrant of the adiabatic theorem. Most of the preceding studies focused only

on the energy gap, which is contained in the denominator of the probability generating the excited states from the ground state in the formulation of the adiabatic theorem.
We considered the adiabatic theorem again toward efficient quantum annealing, and focused on the eigenvector of all excited states in the numerator of the characteristic quantity in the adiabatic theorem as a counterpart of the energy gap therein. We confirmed that the excitation from the ground state can occur even if the energy gap is large, because of the large value of the numerator. The result implies that both of the energy gap and eigenvector are significant for efficient quantum annealing.
Shuntaro Okada (DENSO CORPORATION, Tohoku University), Shu Tanaka (Waseda University), Masayuki Ohzeki (Tohoku University), Masayoshi Terabe (DENSO CORPORATION), Shinichiro Taguchi (DENSO CORPORATION)

45. Aniruddha A. Bapat, University of Maryland, College Park
Bang-Bang control of Classical and Quantum Optimization Algorithms

Authors: AB and Stephen Jordan (NIST, UMD College Park)
The problem of finding the global minimum of a given function over a large (but finite) search space—also known as combinatorial optimization—has been analyzed both in the classical and quantum setting. The so-called meta-heuristic approach seeks to find the best heuristic for minimizing the given function quickly but approximately. Classically, many meta-heuristic strategies exist, and some, such as simulated annealing, are motivated by natural processes. On the other hand, the quantum adiabatic algorithm has received much attention and has been shown to have exponential speedup over simulated annealing for certain problem instances. Here, we show that a different, "bang-bang" strategy solves one such problem classically in polynomial time. More generally, we argue that by using what is known as the Pontryagin Minimum Principle, one could potentially design optimal, bang-bang classical and quantum optimization algorithms.

46. Taro Yamashita, National Institute of Information and Communications Technology
Development of ferromagnetic Josephson junction based on niobium nitride

In recent years, novel physics emerged in superconductor/ferromagnet (S/F) hybrid structures have been studied actively and their device applications have been considered. Among various novel phenomena in SC/FM structures, "pi state" appearing in ferromagnetic Josephson junctions (S/F/S) is attractive as a phase shifter for several

superconducting devices based on macroscopic quantum effect [1]. In the present work, we have developed the ferromagnetic Josephson junction in order to realize a “quiet” superconducting flux quantum bit (qubit) with a pi junction [2,3]. The qubit with a pi junction can be operated without an external magnetic field which is a noise source, and thus good coherence characteristics is expected. Furthermore, zero magnetic field operation provides merits for realizing a highly-integrated system with many qubits. As the superconducting material of the junction, we adopted niobium nitride (NbN) with high superconducting critical temperature of ~16 K, which has a relatively smooth surface due to its epitaxial growth on a magnesium oxide substrate. We used copper nickel (CuNi) for the ferromagnetic barrier as a diluted weak ferromagnet, and fabricated the ferromagnetic Josephson junctions based on NbN electrodes with various junction sizes and CuNi thicknesses. We measured and analyzed the dependences of the Josephson critical current on the temperature and CuNi thickness.

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[2] T. Yamashita et al., Phys. Rev. Lett. 95, 097001 (2005).
[3] T. Yamashita et al., Appl. Phys. Lett. 88, 132501 (2006).

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47. Shoji Taime, The University of Tokyo

Quantum Simulation of Coherent Ising Machines with Positive-P Representation

Coherent Ising Machines (CIM) are novel computing schemes to solve combinational optimization problems with pulsed degenerate optical parametric oscillators(DOPO). In these machines, each DOPO is connected by approximate measurement and feedback. We propose a new quantum simulation method using positive-P representation in terms of off-diagonal coherent state expansion and analyze various quantum properties of the machines.

48. Ryoji Miyazaki, National Institute of Informatics

Application of coherent Ising machine to compressed sensing

There has been great interest in developing machines for solving combinatorial optimization problems that have lots of practical applications. The coherent Ising machine (CIM), based on network of optical parametric oscillators representing artificial spins, is a promising machine for such a purpose. The CIM searches for the ground state of the Ising Hamiltonian onto which our target optimization problem is mapped. Investigation of the CIM has demonstrated its efficiency for the Ising problems[1,2]. To further evaluate the ability of the CIM for practical optimization problems, here we numerically simulate the CIM for compressed sensing.

Compressed sensing is a technique for recovering signals from lower-dimensional compressed data[3]. We cannot reproduce them in general. Prior knowledge on sparsity of the original signals, however, makes it possible. Inference of the signals can be formulated as an optimization problem via LASSO[4]. We run numerical simulations of the CIM to solve the problem and compare resulting error rates with theoretical predictions for the possibility of reconstruction derived by an analytical method developed in statistical physics. We set a problem in which entries of signals are limited to be binary numbers. This problem is represented with an Ising Hamiltonian with the Zeeman term. Obtained results with the CIM are in good agreement with the theoretical prediction. We further tackle an extended problem in which the entries are general discrete numbers for using the CIM for compressed sensing of images. Simulation results of the CIM are consistent with prediction of the theory we derive also in this setting.

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[2] P. L. McMahon, et al., Science 354, 614 (2016).
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49. Meysam Namdari, Technische Universität Dresden

Ising machine using integrated photonics: Feasibility study for the realization of OPOs in silicon waveguides

Ising chains implemented using pulsed optical parametric oscillators (OPOs) have recently been demonstrated as a promising scalable simulated annealing platform. Current implementations of optical Ising machines use OPOs based on either Chi2 optical nonlinearity in LiNbO3 or Chi3 optical nonlinearity in optical fiber. In this paper, we will study the feasibility of the realizing OPOs and free carrier oscillators in a silicon waveguide for on-chip, spatially multiplexed optical Ising machines. Required parameters of a ring resonator to be used for an OPO or free carrier oscillator, e.g. optical power, dimensions, dispersion, and carrier life time are analyzed. This study can provide a scalable solution for the realization of commercial Ising machines.

Mircea Catuneanu (Technische Universität Dresden), Ryan Hamerly (National Institute of Informatics), Dodd Gray (Stanford University), Christopher Rogers (Stanford University), Hideo Mabuchi (Stanford University) and Kambiz Jamshidi (Technische Universität Dresden)

50. Neris I. Sombillo, University of the Philippines
Fixed-point quantum search as implemented in an Ising spin system

Authors: Neris I. Sombillo, Ronald S. Banzon and Cristine Villagonzalo
The fixed-point quantum search provides a solution to the oscillation problem in a quantum search algorithm through the variation of oracle and inversion phases at each iteration. We simulate the fixed-point algorithm in an Ising spin system with first- and second-nearest neighbor interactions. Since the oracle and the inversion operator acts on O(2), then the oracle qubit is required to be in a superposition of states at the start of the simulation. This provides a way to implement the rotation required in the variation of phases at each iteration. Results show that the probability of success calculated from the algorithm and obtained from the simulation gives a similar behavior which effectively damps the oscillation. We also investigate the effect of tolerance on the fidelity as we increase the number of iterations.

51. Denny Lane B. Sombillo, University of the Philippines
Tunneling time operator in quantum time of arrival formalism

Authors: Denny Lane B. Sombillo and Eric A. Galapon
Tunneling is an example of quantum phenomena with no classical counterpart. This means that the construction of a tunneling time operator cannot be done using the quantization of a classical observable. In this work we demonstrate how to construct a tunneling time operator using the quantum time of arrival formalism. This is done by taking the classical limit of the time of arrival operator with a square barrier potential. The dynamics of the tunneling time operator is explored by evolving its eigenfunctions. The result shows that the probability of finding the particle within the barrier region is a maximum at time equal to the operator's eigenvalue. We also calculate the resulting tunneling time distribution using a Gaussian incident wave function for different barrier height and barrier width. The peak of the distribution shifts toward lower values of tunneling time as the barrier height is increased and as the width is decreased.

52. Atsushi Yamamura, The University of Tokyo

Theoretical Analysis on the Measurement Feedback Coherent Ising Machine

The Coherent Ising Machine (CIM) is a degenerate optical parametric oscillator network to solve Ising-type combinatorial optimization problems. The CIM with measurement feedback system has been recently demonstrated at Stanford University and NTT independently. In these machines, the oscillators are coupled with the quantum measurement and feedback process. We formulated a quantum model with CPTP maps of the components, and numerically evaluated how much the quantum coherence of the “up spin” and the “down spin” exists during the optimization process.

53. Estelle Maeva Inack, ICTP/SISSA

Simulating quantum Ising models using the Diffusion Monte Carlo method

E. M. Inack, S. Pilati, G. E. Santoro and R. Fazio

In our previous work [1], we showed that on continuous-variable systems the Diffusion Monte Carlo (DMC) method can be used as a heuristic optimization tool that mimics the imaginary-time dynamics of the Schroedinger equation and is competitive compared with, e.g., path-integral Monte Carlo simulations. In this work, we present an implementation of the DMC algorithm to simulate the ground state of transverse-field Ising models. The accuracy of the method is verified on the one-dimensional spin chain. We also present some preliminary results of quantum annealing simulations based on the DMC algorithm.

[1] E. M. Inack, S. Pilati, PRE 92, 053304 (2015)

Authors: M. Inack, S. Pilati, G. E. Santoro and R. Fazio

54. Stefano Varotti, Dept of Information Engineering and Computer Science, University of Trento

New methods for encoding SAT for an adiabatic quantum computer

While quantum annealing (QA) offers the hope of solving hard discrete optimization and satisfaction problems faster than any classical algorithm, current implementations of QA are restricted to solving quadratic unconstrained boolean optimization problems (QUBOs) with a limited number of variables and sparse interactions. In this presentation we expand upon previous techniques and algorithms for encoding SAT effectively and efficiently into this restricted class of QUBOs that fit the QA hardware architecture. In particular, we present 1) a new technique for encoding small Boolean functions based on off-line usage of Satisfiability and Optimization Modulo Theories, in a way that identifies an optimal mapping of variables to qubits; and 2) a new method for decomposing SAT problems or boolean combinational circuits into minimal sets of efficiently encodable Boolean functions, based on classical technology mapping. Some preliminary empirical results using a D-Wave 2000Q system support the feasibility of this approach. This is joint work with Zhengbing Bian, Fabian Chudak, William Macready, Aidan Roy, and Roberto Sebastiani.

55. Matteo Michele Wauters, SISSA

Comparing simulated annealing with quantum annealing on a fully-connected Ising ferromagnet

We compare the performance of quantum annealing (QA, through Schrödinger dynamics) and simulated annealing (SA, through a classical master equation) on the p-spin infinite range ferro-magnetic Ising model, by slowly driving the system across its equilibrium, quantum or classical, phase transition. When the phase transition is second-order ($p = 2$, the familiar two-spin Ising interaction) SA shows a remarkable exponential speed-up over QA. For a first-order phase transition ($p \geq 3$, i.e., with multi-spin Ising interactions) instead, the classical annealing dynamics appears to remain stuck in the disordered phase, while we have evidences that QA shows a residual energy error which decreases towards 0 when the total annealing time τ increases, albeit in a rather slow (logarithmic) fashion. We also analyse the imaginary-time QA dynamics of the model, finding a $1/\tau$ 2 behaviour for all values of p, as predicted by the adiabatic theorem of quantum mechanics. Co-authors: Rosario Fazio, Hidetoshi NIshimori, Giuseppe E. Santoro

56. Richard Li, USC

Quantum annealing versus classical machine learning applied to a simplified computational biology problem

Transcription factors regulate gene expression, but how these proteins recognize and specifically bind to their DNA targets is still debated. Here we studied the ability of a quantum machine learning approach to predict binding specificity. Using simplified datasets of a small number of DNA sequences derived from actual binding affinity experiments, we compared the performance of a commercially available quantum annealer, D-Wave (DW), with several state-of-the-art classical techniques. Despite technological limitations, we find an advantage in classification performance and nearly equal ranking performance using the quantum annealer for fairly small training datasets. (Authors: Richard Li, Rosa Di Felice, Remo Rohs, Daniel Lidar)

57. Mario S. Könz, ETH Zurich

Comparing embedding penalties between minor-embedding, chimaera and the paqo-scheme (lhz-scheme) as well as to direct SQA

We briefly cover the minor embedding, the chimaera graph embedding and the recently introduced architecture based on parity constraints (paqo). Constraint scheduling optimization as well as corresponding decoding strategies will be presented. The main focus consists of the scaling-comparison between embeddings as well as a with direct SQA to determine the embedding penalty. The simulations are done with a high performance discrete-time metropolis-Monte Carlo SQA code, with embedded system sizes up to 2000-3000 spins. co-author: Dr. Wolfgang Lechner

58. Manaka Okuyama, Tokyo Institute of Technology

Quantum-Classical Correspondence of Shortcuts to Adiabaticity

We formulate the theory of shortcuts to adiabaticity in classical mechanics. For a reference Hamiltonian, the counterdiabatic term is constructed from the dispersionless Korteweg-de Vries (KdV) hierarchy. Then the adiabatic theorem holds exactly for an arbitrary choice of time-dependent parameters. We use the Hamilton-Jacobi theory to define the generalized action. The action is independent of the history of the parameters and is directly related to the adiabatic invariant. The dispersionless KdV hierarchy is obtained from the classical limit of the KdV hierarchy for the quantum shortcuts to adiabaticity. This correspondence suggests some relation between the quantum and classical adiabatic theorems.

59. Andriyan Bayu Suksmono, The School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Indonesia"

Finding a Hadamard matrix by simulated quantum annealing

We propose a simulated quantum annealing (QA)-based method to find a 4k order Hadamard matrix, where k is any positive integer. Using the analogy with the spins of the

Ising model, the binary spins are replaced by a binary vector called SH (Seminormalized Hadamard)-spin vectors; which are 4k length vectors with balanced number of +1 and -1. Connections among the SH spins-vectors are represented by a graph that reflects orthogonality relationship among the vectors. Optimization is conducted based on the PIMC (Path-Integral Monte-Carlo) QA of the SH-spin vector system, with an applied transverse magnetic field whose strength is decreased over time. In the numerical experiments, the proposed method is employed to find some low order H-matrices, including the ones that cannot be constructed trivially by the Sylvester method. We also compare the performance with the SA (Simulated Annealing) method by measuring residual energy after a sufficiently large number of iterations in finding a high-order H-matrix. With both of the QA and SA use linear annealing schedule, we found that the QA outperforms the SA.