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T01

Multi-objective QUBO Solver: Bi-objective Quadratic Assignment Problem

Mayowa Ayodele[1], **Richard Allmendinger**[2], **Manuel López-Ibáñez** [2] **and Matthieu Parizy**[3]

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In recent years, there has been significant research interest in solving Quadratic Unconstrained Binary Optimisation (QUBO) problems. Physics-inspired optimisation algorithms such as quantum annealing or adaptations of simulated annealing have been proposed for solving QUBOs. These methods are particularly attractive within the context of using specialised hardware such as quantum computers, application specific CMOS and other high performance computing resources for solving optimisation problems. These hardware-based solution approaches can solve QUBOs effectively and efficiently. To take advantage of QUBO solvers such as the Digital Annealer or Quantum Annealer, combinatorial optimisation problems are converted to QUBOs to make the solvers applicable to those problems. Quantum and quantum-inspired optimisation algorithms are relatively newer approaches of solving combinatorial optimisation problem. They have shown promising performance when applied to academic benchmarks such as travelling salesman [1, 2], knapsack, quadratic assignment[3, 2] and graph partitioning problems . They have also been successfully applied to real-world problems such as the allocation of tasks to workers [5] and other problems in logistics and finance. In this work, we extend the applicability of the Digital Annealer by proposing modifications which allow it to solve problems with multiple objectives more efficiently.

This work addresses the challenges of optimising multiple objectives by exploring better scalarisation approaches. We also explore algorithmic changes that improve the performance of the Digital annealer algorithm on problems with multiple objectives. We asses performance of the proposed methods on time to solution and solution quality. We show that the proposed approaches achieve better solution quality in a shorter time when compared to existing methods.

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T02

Using Copies to Improve Precision in Continuous-time Quantum Computing

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In the quantum optimisation setting, we build on a scheme introduced by Young et al [1], where physical qubits in multiple copies of a problem encoded into an Ising spin Hamiltonian are linked together to increase the logical system's robustness to error. We introduce several innovations that improve this scheme significantly. First, we note that only one copy needs to be correct by the end of the computation, since solution quality can be checked efficiently. Second, we find that ferromagnetic links do not generally help in this "one correct copy" setting, but anti-ferromagnetic links do help on average, by suppressing the chance of the same error being present on all of the copies. Third, we find that minimum-strength anti-ferromagnetic links perform best, by counteracting the spin-flips induced by the errors. We have numerically tested our innovations on small instances of spin glasses from Callison et al [2] and we find improved error tolerance for three copies in configurations that include frustration. Interpreted as an effective precision increase, we obtain several extra bits of precision for three copies connected in a triangle. This provides proof-of-concept of a method for scaling quantum annealing beyond the precision limits of hardware. The paper is expected to be on ArXiv by Monday.

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[2] Callison A., Chancellor N., Mintert F., Kendon V., J. NJP **21**, 123022 (2019).

T03

Towards a quantum annealing approach to solving the phase problem in macromolecular crystallography

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Determining the structure of crystallised molecules is an important task in many areas of science and industry, including in biological and medical research, and in the pharmaceutical industry. A common experimental approach to studying such structure is via X-ray diffraction. Unfortunately, the diffraction pattern produced contains information only on the amplitudes of reflections, while reconstructing the molecule structure also requires the phase information. This is known as the "phase problem", and rapidly becomes computationally difficult for classical approaches as the size of the molecule grows. In this work, a quantum annealing approach to solving the phase problem is proposed via a quadratic unconstrained binary optimization (QUBO) formulation that encodes approximate relationship between the phases of specific triplets of reflections. By examining low-energy solutions to the QUBO created from real-world data, we show that quantum annealing outputs can be used to reconstruct the structure of target molecules.

T04

Digitized-Counterdiabatic Quantum Algorithms

Shortcuts to adiabaticity (STAs) are well-known methods for controlling the quantum dynamics beyond the adiabatic criteria, where counter-diabatic (CD) driving provides a promising means to speed up quantum many-body systems. In this talk, we show the applicability of CD driving to enhance the digitized adiabatic quantum computing paradigm in terms of fidelity and total simulation time. Firstly, we apply this technique in the preparation of Bell and GHZ states with high fidelity using a shallow quantum circuit. Secondly, we focus on quantum approximate optimization algorithm (QAOA) from solving combinatorial optimization problems to finding the ground state of many-body quantum systems. To this end, we propose a digitized version of QAOA enhanced via the use of STA. Specifically, we use a CD driving term to design a better ansatz, along with the Hamiltonian and mixing terms, enhancing the global performance for Ising models, and P-spin model. Finally, our talk will end up with different applications in quantum factorization, portfolio optimization, and other combinatorial optimization problems. It is concluded that the polynomial enhancement of digitized-counterdiabatic quantum optimization (DCQO) is accomplished by CD terms, severing as non-stoquastic catalyst.

T05

Dissipative Landau Zener tunneling: crossover from weak to strong environment coupling

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The Landau-Zener problem for a two-level system is a suitable toy problem for studying quantum tunnelling in an annealer. Coupling to the environment can influence the tunnelling probability and theoretical understanding is only available for specific coupling limits or noise models. We present experimental results on Landau-Zener measurements on a capacitively-shunted flux qubit. The result shows crossover from weak to strong coupling to the environment. Our results in the weak and strong coupling limits are consistent with previous theoretical and numerical studies and our result in the intermediate regime is novel. The result gives insight into the scaling of tunnelling probability in a large-scale quantum annealer.

T06

Effective Prime Factorization via Quantum Annealing by Modular Locally-structured Embedding

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Quantum annealing has shown the feasibility for prime factorization through reducing high-degree cost functions to quadratic either by using Groebner bases [1] or by using equivalent quadratic models produced by adding ancillary variables [2]. To date, the largest factorization problem mapped to D-Wave 2000Q is 376,289; and all bi-primes up to 200,000 have been solved by D-Wave 2X processors [1, 2].

In this paper, we propose a novel approach which is based on locally-structured embedding of a Satisfiability problem [3] to encode (prime) integer factorization problems into Ising models which are directly compliant with QA Pegasus topology [4], and solve them with D-Wave's Advantage systems. Our contributions are twofold.

Encoding. First, we present a novel modular encoding of a bitwise multiplier circuit into QA Pegasus topologies. The key contribution is a compact encoding of a *controlled full-adder* into an 8-qubit module in the Pegasus topology, which we synthesized offline by means of Optimization Modulo Theories [5]. The multiplier circuit is built by exploiting our idea of *qubit sharing* between neighboring adder modules. Qubit sharing allows us to save qubits which can be used as ancillary variables instead. This allows us to encode up to a 21×12-bit multiplier into the Pegasus 5760-qubit topology of current annealers, so that a faulty-free annealer can be fed an integer factorization problem up to $8,587,833,345 = 2,097,151 \times 4,095$.

Solving. Second, we have run an experimental evaluation of prime factoring problems on a D-Wave Advantage 4.1 QA. Due to faulty qubits and qubit couplings of the QA hardware we have access to, it was possible to feed to it at most a 17×8-bit multiplier, corresponding to at most a $33,423,105 = 131,071 \times 255$ factorization. In the experiments we adopted performance enhancement techniques like pausing [6] and reverse annealing [7] to compensate confined effective annealing time. From the results, through naively tuning the annealing process, $1,480,867 = 8,273 \times 179$ was the highest prime product which was factorized with non-zero energy and $378,227 = 2,113 \times 179$ the highest one with zero energy.

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[2] Shuxian Jiang, Keith A. Britt, Alexander J. McCaskey, Travis S. Humble, and Sabre Kais. Quantum annealing for prime factorization. *Scientific Reports*, 8:17667, 2018.

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[5] Roberto Sebastiani, Patrick Trentin. OptiMathSAT: A Tool for Optimization Modulo Theories Journal of Automated Reasoning, 3, 2020. Springer.

[6] Jeffrey Marshall, Davide Venturelli, Itay Hen, and Eleanor G. Rieffel. Power of pausing: Advancing understanding of thermalization in experimental quantum annealers. *Phys. Rev. Applied*, 11:044083, 2019.

[7] Reverse Annealing for Local Refinement of Solutions. D-Wave White Paper Series, no. 14-1018A-A. 2017. `https://www.dwavesys.com/resources/publications`.

T07

Parity Quantum Optimization: Encoding Constraints

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Hard constraints make it more challenging to solve hard optimization problems on quantum devices because they are typically implemented with large energy penalties and additional qubit overhead. Recent works [3, 4, 5] point out different alternatives to the penalty terms in quantum annealing, but only for hard constraints, which are pure sums over single logical qubits. The parity mapping, which has been introduced as an alternative to the spin encoding[1, 2], translates the problem to a representation using only parity variables that encodes products of spin variables into a single parity variable. In combining exchange interaction and single spin flip terms in the parity representation, constraints on sums, products of arbitrary k-body terms and sums over these products can be implemented without the usage of penalty terms in two-dimensional quantum systems. This gives us the opportunity to solve optimization problems with hard constraints using a new adiabatic quantum computing protocol.

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[5] T. Vyskocil, H. Djidjev, Algorithms **12**, 77 (2019).

T08

Effects of XX-catalysts on quantum annealing spectra with perturbative crossings

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The efficiency of Adiabatic Quantum Annealing is limited by the scaling with system size of the minimum gap that appears between the ground and first excited state in the annealing energy spectrum. In general the algorithm is unable to find the solution to an optimisation problem in polynomial time due to the presence of avoided level crossings at which the gap size closes exponentially with system size. One promising avenue being explored to produce more favourable gap scaling is the introduction of non-stoquastic XX-couplings in the form of a catalyst - of particular interest are catalysts which utilise accessible information about the optimisation problem in their construction. Here we present extreme sensitivity of the effect of an XX-catalyst to subtle changes in the encoding of the optimisation problem. In particular, we find that a targeted catalyst containing a single coupling at constant strength can significantly reduce the gap closing with system size at an avoided level crossing. For slightly different encodings of the same problems however, these same catalysts result in closing gaps in the annealing spectrum. To understand the origin of these closing gaps, we study how the evolution of the ground state vector is altered by the presence of the catalyst and find that the negative components of the ground state vector are key to understanding the response of the gap spectrum. These closing gaps show potential for exploitation in diabatic annealing protocols.

T09

Benchmarking Various Types of Ising Machines

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An Ising machine has been studied as a new efficient architecture for solving combinatorial optimization problems, which can efficiently obtain quasi-optimal solutions to some combinatorial optimization problems. In recent years, various Ising machines implemented on hardware and/or software have been studied. In this presentation, we evaluate the recent Ising machines including the third generation Digital Annealer on various combinatorial problems.

T10

Nonnegative binary matrix factorization by continuous relaxation and reverse annealing

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Nonnegative/binary matrix factorization (NBMF) is one of the methods for unsupervised machine learning [1]. For a given nonnegative matrix V as the original data, we approximate V as a product of two small matrices, W and H, where W is a nonnegative matrix, and H is a matrix with binary elements. NBMF is presented as a variant of nonnegative matrix factorization (NMF) and is experimentally known to behave differently from NMF in learning results. One of the approaches for NBMF is alternately reducing the difference between V and WH by solving optimization problems with fixed W or H. However, the optimizations with binary constraints require heavy computational tasks to find optimal solutions as the problems contain the subset-sum problem, famous for its NP-hardness. The problems are expressed as quadratic unconstrained binary optimization (QUBO) problems, which let us employ various general-purpose algorithms.

Quantum annealing is a heuristic algorithm to solve QUBO problems by driving binary variables through quantum fluctuations. Quantum annealing is broadly divided into forward and reverse methods. While forward annealing performs a global search starting in a superposition of all possible weights, reverse annealing is specialized in the local refinement of a given initial state. For some kinds of problems, the effectiveness of reverse annealing utilizing initial states obtained by forward annealing or classical algorithms has been elucidated [2].

Reverse annealing has been employed for NBMF as well and its efficient search by initial states obtained by a previous iteration or forward annealing contributes to improved learning performance compared to using forward annealing alone [3]. However, these methods still lack precision and have slower convergence than finding optimal solutions always. Therefore, we are interested in improving the performance of reverse annealing utilizing initial states obtained by fast classical algorithms.

In this study, we exploit the relaxation strategy to replace the discrete variables with continuous variables. The relaxed problems are convex and quite easier to solve than the original discrete problems and the rounded solutions provide good approximations for initial states. We evaluated our methods in the experiment of learning the features from facial images and their comparable performance to exact optimization was achieved. This improvement in reverse annealing was associated with the closeness of initial states to optimality. We revealed that the initial solutions obtained by the relaxation had a shorter Hamming distance than forward annealing. Furthermore, we investigated the dependency of the approximation accuracy on problem structures. For synthetic data, we found the deteriorating approximation performance of the rounded solutions by the relaxation as the greater part of the continuous solutions did not locate in the vicinity of 0 or 1. This research will extend the potential ability of quantum annealing applied to other problems through hybrid methods with reverse annealing and relaxation strategy.

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[2] Venturelli, D. & Kondratyev, A. *Quantum Mach. Intell.* **1**, 17–30 (2019).
[3] Golden, J. & O'Malley, D. *PLOS ONE* **16**, e0244026 (2021).

T11

Lower bounds for performance of shortcuts to adiabaticity

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Adiabatic time evolution is realized when parameters of a given system change slowly in time against energy gaps. As the result, the system conserves population of each instantaneous energy eigenstates. Recently, many quantum algorithms using adiabatic time evolution have been proposed. Among them, adiabatic quantum computation has been paid much attention. Typically, in adiabatic quantum computation, a trivial initial state is adiabatically transferred to a nontrivial target state. By measuring certain observables of the target state, we can obtain a solution of a given problem.

Performance of quantum algorithms using adiabatic time evolution is restricted by the adiabatic condition. Namely, long run-time is required to keep adiabaticity. Shortcuts to adiabaticity have been proposed and developed to overcome this drawback. They provide us with nonadiabatic routes to final destinations of adiabatic time evolution.

Finding exact shortcuts for many-body systems is not realistic, and thus we usually adopt approximate shortcuts. In this talk, we propose a method for evaluating quality of approximate shortcuts, i.e., we discuss how close we can results in final destinations of adiabatic time evolution via approximate shortcuts.

[1] T. Hatomura and K. Takahashi, Phys. Rev. A **103**, 012220 (2021).
[2] T. Hatomura, arXiv:2112.07253.

T12

Performance comparison among various methods of fixing spins in quantum annealing

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Quantum annealing was proposed as a computational method that uses quantum dynamics to find the ground states of Ising models which represent combinatorial optimization problems [1]. The number of qubits in quantum annealing machines is still small compared to the number of spins in Ising models which represent combinatorial optimization problems to be solved. To use such a quantum annealing machine, we should reduce the number of spins to be able to input them into the quantum annealing machine. Research on the effects of fixing spins to take advantage of quantum annealing machine is still in progress. One of the methods of fixing spins, called "HQA (Hybrid quantum annealing)", is proposed by H. Irie et al.[2] In HQA, we fix spins using a classical method and the size of problem is reduced so that we can input into the quantum annealing machine. There are also various methods of fixing spins in HQA. In this study, we compare them from the perspective of final energy values and the minimum energy gap by simulating the time-dependent Schrödinger equation.

[1] T. Kadowaki and H. Nishimori, Physical Review E, **58**, 5355 (1998).
[2] H. Irie, et al., Scientific Reports, **11**, 8426 (2021).

T13

Problem-Size Independent Angles for a Grover-Driven Quantum Approximate Optimisation Algorithm

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The Quantum Approximate Optimisation Algorithm requires that optimal circuit parameters are found with costly outer-loop optimisation procedures and repeated calls to a quantum computer, or via analytical means, to determine high-quality solutions to combinatorial optimisation problems. In this work we demonstrate that if one knows the probability density function describing how the objective function of a problem is distributed, the calculation of the expectation of such a problem Hamiltonian under a Grover-driven QAOA-prepared state can be performed independently of system size. Such calculations can help deliver insights into the performance of and predictability of angles in QAOA in the limit of large problem sizes, in particular, for the Number Partitioning Problem.

T14

Coupling 3-Josephson junctions flux qubits for Non-stoquastic Adiabatic Quantum Computation

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Many platforms have been proposed to implement Adiabatic Quantum Computation, from superconducting circuits to trap ions. Nevertheless, it is still not clear how to obtain general and fully tunable multi-qubits dynamics in any of those platforms. General enough qubit-qubit interactions would allow, for instance, to reproduce the dynamics of non-stoquastic Hamiltonians, the ones for which classical Monte-Carlo methods fail, opening the way to Universal Adiabatic Quantum Computation.

In this talk, we analyse the coupling between two 3-Josephson junctions flux qubits and present the effective Hamiltonian that controls the dynamics of the system when the two qubits are coupled via a capacitor and/or via a Josephson junction [1]. We show that those two elements allow engineering a fairly large family of qubit Hamiltonians with XX, YY and ZZ, including fully non-stoquastic interactions and ultrastrong coupled ones. In addition, we discuss the capacitive coupling between a flux qubit and an LC-resonator [2] and show ultrastrong coupling in a direction perpendicular to that of the commonly studied inductive coupling, leaving the door open to the simulations of quantum optics models unexplored up to date.

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[2] M. Hita-Pérez, G. Jaumà, M. Pino, and J.J. García-Ripoll, Phys. Rev. Appl. **17**, 014028 (2022).

T15

Structure optimization method of truss by quantum annealing

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The topology optimization problem is a problem of finding a combination of components that can achieve high performance at low cost. When solving combinatorial optimization problems such as topology optimization problems, local solutions may occur during computation, and the computational cost becomes high if the computation is repeated to obtain the overall optimal solution[1]. Therefore, it is becoming more and more important to develop computational methods that will improve the accuracy of the solution.
Recently, quantum annealing, a method specialized for solving combinatorial optimization problems, has been attracting attention. Quantum annealing uses the tunneling effect caused by quantum fluctuations to find a solution. Initially, we prepare the ground state of the Hamiltonian with a strong quantum fluctuation as the initial state, and then the quantum fluctuation is gradually decreased to find the point where the potential is minimized[2]. For example, the previous researches on combinatorial optimization problems using quantum annealing treated applications to traffic volume management and nurse scheduling problems.
Focusing on the minimization of the energy, it is expected that quantum annealing can be used to efficiently obtain global optimal solutions for topology optimization problems as well. However, the confirmation of such a method has not progressed much in the current situation. In this study, we aim to develop a new method for structural topology optimization of solids using quantum annealing. As an example, we take the optimization problem of a truss structure. Specifically, in order to use quantum annealing, the energy of the truss structure is replaced by a Hamiltonian in quadratic unconstrained binary optimization (QUBO) form. The real displacements and cross-sectional areas of the elements need to be expressed in binary variables. Optimization calculations by a D-Wave Hybrid Solver are carried out using the Hamiltonian constructed in this way, and its performance is evaluated.

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T16

Next Generation Quantum Annealing Processor

Emile Hoskinson

D-Wave

Quantum annealing continues to show immense promise for solving hard optimization problems that occur across a wide range of business applications. D-Wave has developed and delivered five generations of successively more powerful, commercially available quantum annealing based quantum computers. Development of our next generation technology is well underway. Advantage 2 processors will have more qubits, higher connectivity, and higher coherence. Here we describe the roadmap from our current generation processors to our upcoming Advantage 2 products.

T17

Quantum annealing with twisted fields

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Quantum annealing is one of promising methods for solving combinational optimization problems and performing quantum chemical calculations. It is known that the majority of sources of errors in quantum annealing are the effects of decoherence and non-adiabatic transition[1]. We propose a method for suppressing both these effects using inhomogeneous twist operators corresponding to the twist angles of transverse fields applied to qubits[2]. Additionally, we use a variational method to find the optimal inhomogeneous twist operator for minimizing the energy of the state after quantum annealing. Our approach is useful for increasing the energy gap and/or making the quantum states robust against decoherence during quantum annealing. In summary, our results can pave the way to a new approach for realizing practical quantum annealing.

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T18

Augmented Lagrangian method in Ising machines

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When solving constrained combinatorial optimization problems with constraints using Ising machines, the solution accuracy depends on the hyperparameters, which are generally difficult to tune. If the hyperparameters are small, feasible solutions cannot be obtained, but conversely, if the hyperparameters are large, the constraints are satisfied but the solution accuracy is reduced. Therefore, it is important to tune hyperparameters appropriately. Recently, Tanahashi and Tanaka proposed a method to tune hyperparameters adaptively. They adopted the augmented Lagrangian method for quantum annealing, a typical internal algorithm of Ising machines [1]. The results suggest that the augmented Lagrangian method is superior to the penalty method for quantum annealing. The goal of this study is that we examine the performance of the augmented Lagrangian method for simulated annealing, another typical internal algorithm of Ising machines. As a result, for problems with a single constraint, the number of hyperparameters updates in augmented Lagrangian method was fewer than that in penalty method. Also, for problems with multiple constraints, the augmented Lagrangian method outperformed the penalty method in many cases. However, there were cases where the penalty method was superior to the augmented Lagrangian method. In these cases, the trajectory of hyperparameters in augmented Lagrangian method behaves unstable. Therefore, we introduced the momentum method to stabilize the update of hyperparameters. As a result, the number of cases where the augmented Lagrangian method outperformed the penalty method, increases. Our results suggest that the augmented Lagrangian method is superior in simulated annealing.

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T19

Lossy compression of matrices by black-box optimisation of mixed-integer non-linear programming

In edge computing, suppressing data size is a challenge for machine learning models that perform complex tasks such as autonomous driving, in which computational resources (speed, memory size and power) are limited. Efficient lossy compression of matrix data has been introduced by decomposing it into the product of an integer and real matrices. However, its optimisation is difficult as it requires simultaneous optimisation of an integer and real variables. In this paper, we improve this optimisation by utilising recently developed black-box optimisation (BBO) algorithms with an Ising solver for integer variables. In addition, the algorithm can be used to solve mixed-integer programming problems that are linear and non-linear in terms of real and integer variables, respectively. The differences between the choice of Ising solvers (simulated annealing (SA), quantum annealing (QA) and simulated quenching (SQ)) and the strategies of the BBO algorithms (BOCS, FMQA and their variations) are discussed for further development of the BBO techniques. https://arxiv.org/abs/2204.10579

T20

Domain Wall Encoding Behaviour on Ising Machine

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When expressing an optimization problem in Quadratic Unconstrained Binary Optimization (QUBO) format that can be solved by an ising machine, it is necessary to choose an encoding method. Domain wall encoding [1] is said to have the advantage of making it easier to reach a good solution on a quantum annealing machine (D-Wave 2000Q/Advantage) [2], but the usefulness in classical ising machines is yet to be shown. We investigated the behaviour of domain wall encoding with and without graph embedding using a classical ising machine running on a GPU (Fixstars Amplify Annealing Engine). An original traffic optimization problem considering crossings was used in the investigation. For comparison, a similar test was conducted using one-hot encoding, which is a common encoding method. The results show that domain wall encoding gives equally or better solutions when embedding exists, while the one-hot encoding gives equally or better solutions when there is no embedding. These results encourage the use of different encoding methods depending on the ising machine used to solve optimization problems.

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T21

Identifying phase transitions with and without quantum annealers

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Consider the task of identifying phase transitions in low temperature systems of qubits on a lattice described by a family of Hamiltonians $\{H_\lambda\}$. We attempt to answer the question "can bitstrings obtained from quantum annealers help in this task". We investigate approaches to solving this problem with and without quantum annealers. First, we describe how to solve this task if we could get a dataset of bitstrings measured from a low temperature state of the system at different values of parameters. This is accomplished by reducing the problem of estimating classical fidelity susceptibility to a binary classification problem. Then we discuss the challenges in obtaining such a dataset using the D-Wave Advantage device. Finally, we describe the performance of the classical algorithms in this task. While ultimately we are interested in harder problems where the locations of phase transitions are not known, throughout the talk we use the frustrated Ising ladder as a toy model.

T22

A Cost and Power Feasibility Analysis of Quantum Annealing for NextG Cellular Wireless Networks

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[3] *University College London*

In order to meet mobile cellular users' ever-increasing data demands, today's 4G and 5G networks are designed mainly with the goal of maximizing spectral efficiency. While they have made progress in this regard, controlling the carbon footprint and operational costs of such networks remains a long-standing problem among network designers. Our work takes a long view on this problem, envisioning a NextG scenario where the network leverages quantum annealing for cellular baseband processing. We gather and synthesize insights on power consumption, computational throughput and latency, spectral efficiency, operational cost, and feasibility timelines surrounding quantum technology. Armed with these data, we analyze and project the quantitative performance targets future quantum annealing hardware must meet in order to provide a computational and power advantage over CMOS hardware, while matching its whole-network spectral efficiency. Our quantitative analysis predicts that with quantum annealing hardware operating at a 102 μs problem latency and 3.1M qubits, quantum annealing will achieve a spectral efficiency equal to CMOS computation while reducing power consumption by 41 kW (45% lower) in a 5G base station scenario with 400 MHz bandwidth and 64 antennas, and an 8 kW power reduction (16% lower) using 1.5M qubits in a 200 MHz-bandwidth 5G scenario.

Our work [1] presents the first extensive analysis on power consumption and quantum annealing (QA) architecture to make the case for the future feasibility of quantum processing based centralized radio access networks (C-RANs). While recent successful point-solutions that apply QA to a variety of RAN applications [2, 3] serve as our motivation, previous work stops short of a holistic power and cost comparison between QA and CMOS. Despite QA's benefits demonstrated by these prior works in their respective point settings, a reasoning of how these results will factor into the overall computational performance and power requirements of the base station and C-RAN remains lacking. Therefore, here we investigate these issues head-on, to make an end-to-end case that QA will likely offer benefits over CMOS for handling baseband unit (BBU) processing in RANs, and to make time predictions on when this benefit will be realized. Specifically, we present informed answers to the following questions:

Question 1: How many qubits (quantum bits) are required to realize a BS or C-RAN BBU processing requirements?

Question 2: Relative to purely CMOS BBU processing, how much power and cost does one save with such amount of qubits, viewed over the entire RAN?

Question 3: At what year will these qubit numbers become feasible, based on recent prior trends in the industry?

Question 4: To what amount will QA processing latency be reduced in the future?

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T23

Quantum critical dynamics in a 5000-qubit spin glass

Experiments on disordered alloys suggested that spin glasses can be relaxed to low-energy states faster by annealing quantum fluctuations than with conventional thermal annealing---reproducing this speedup in a programmable system has remained a central challenge in the field of quantum optimization. Here we present a realization of quantum critical dynamics in programmable spin glasses, using a superconducting quantum annealer. We first demonstrate quantitative agreement between quantum annealing and time-evolution of the Schroedinger equation in small spin glasses. We then experimentally measure critical exponents characteristic of a quantum phase transition into a glassy phase in three spatial dimensions, clearly distinguishing quantum annealing from the slower dynamics of the analogous thermal phase transition. Accordingly, we observe a dynamical speedup in quantum annealing over classical Monte Carlo methods, including simulated annealing and path-integral simulated quantum annealing.

T24

Milestones on the Quantum Utility Highway

Pau Farré and Catherine McGeoch

D-Wave

Drawing on classical methodologies for evaluating heuristic optimization solvers, we focus on performance characterization, asking: *On what inputs, compared to what alternative solvers, does the quantum processor show superior performance?* The figure of merit is based on the best-quality sample of S solutions returned within a fixed time limit T. Drawing on standards for benchmarking heterogeneous computing platforms, we include system costs of computation: *Is the quantum solver fast enough to overcome the overhead costs of using it?*

We identify some milestones for demonstrating superior quantum performance, based on categories of overheads. Milestone 0 (pure anneal time, no overheads) has been demonstrated in previous works surveyed in the paper.

We report results of new tests comparing the Advantage 4.1 system to four classical solvers running on CPUs and GPUs, using 12 application-relevant input classes, for varying S and T. Milestone 1 (measuring QPU access time, including programming and readout; all solvers read identical inputs) is demonstrated in all of our tests. Milestone 2 (CPU solvers read pre-embedded inputs, QPU and GPU solvers reads post-embedded inputs) is demonstrated in some of our tests. Figure 1 shows example results for two input classes called NAT1 (native spin glasses) and 3DLAT (3D lattices).

We develop an empirical performance model to explain these results and characterize inputs that lie on the can/cannot boundary of Milestone 2. We argue that this analysis bodes well for demonstrations using ever-expanding sets of inputs, and for more challenging milestones, as future QPU generations continue to increase in size and in quality of solutions returned.

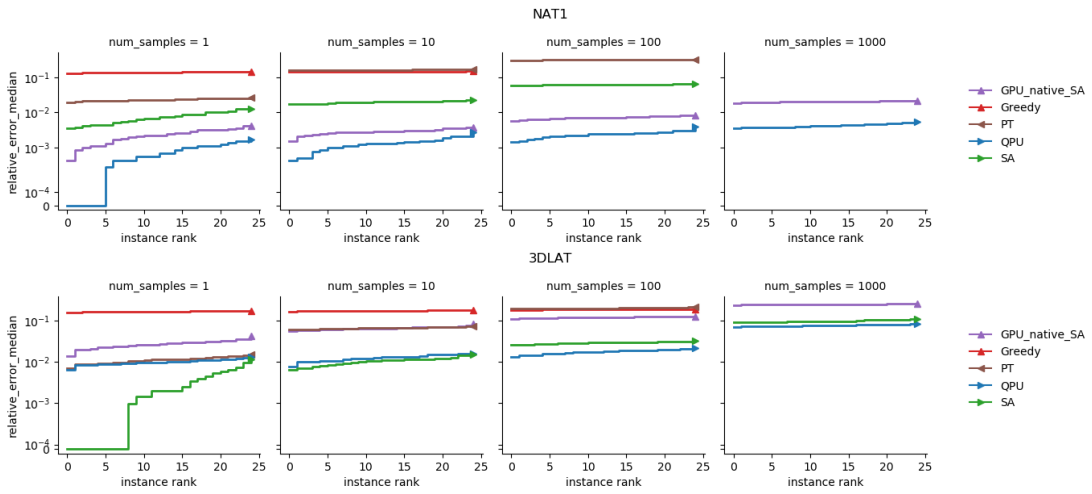

Figure 1: Median relative error (y-axis) in solution samples of size S (panels left to right), returned within $T = .5$ seconds, measuring QPU access time. PT, SA, and Greedy solvers read pre-embedded inputs; QPU and GPU_native_SA read post-embedded inputs. Each panel shows ranked outcomes for 25 instances from the input class (x-axis). The top row demonstrates Milestone 1, where QPU outperforms all other solvers in all tests. The bottom row demonstrates Milestone 2, where QPU outperforms all others when $S \geq 100$. Note that some classical solvers are missing from the rightmost panels, indicating a fundamental classical limitation: on large inputs $N > 2000$, these solvers cannot find 1000 independent solutions within .5 seconds.

T25

Comparing the Hardness of Max 2-SAT Problem Instances for Quantum and Classical Algorithms.

Puya Mirkarimi[1], **Adam Callison**[2], **Lewis Light**[1], **Nicholas Chancellor**[1], **and Viv Kendon**[1]

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Continuous-time quantum computing is a family of methods for solving computational problems through a continuous evolution of qubit states according to a Hamiltonian. Adiabatic quantum computing (AQC) and continuous-time quantum walks (QW) are both forms of continuous-time quantum computing that are well-suited for solving combinatorial optimization problems. We apply AQC and QW to the maximum 2-satisfiability problem (Max 2-SAT). Despite being NP-hard, modern classical algorithms for Max 2-SAT have been refined to the extent that they are very effective in practice. We analyse the relation between the hardness of Max 2-SAT instances for these quantum algorithms and for a particular classical algorithm, and we explore the viability of hybrid strategies that employ two of these algorithms in parallel. The nature of the correlations between hardness for quantum and classical algorithms is an indicator of the performance of different types of hybrid approaches, where a lower correlation for two algorithms indicates a better performance from running them in parallel, and this has important implications when identifying the types of approaches that are most suitable for quantum computing in practice.

T26

Semiclassical Approximate Optimization Algorithm

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A large class of NP-hard optimization problems enables Ising formulation such that an optimum corresponds to a ground state while the hardness is related to the spin-glass phase of an Ising Hamiltonian [1]. Recently, the Quantum Approximate Optimization Algorithm (QAOA) for solving this type of combinatorial problems was suggested [2] as a powerful diabatic alternative to the adiabatic quantum computation.

In this work, we develop a new semiclassical approximate optimization algorithm (SAOA) as a classical counterpart to QAQA. The new algorithm substitutes a quantum evolution of QAOA by the classical dynamics of spins. Within the Trotterization scheme of QAOA this dynamics can be found exactly for any number of layers p defining the algorithm. Employing a path integral description based on SU(2) spin-coherent states [3], we prove that for $p \gg 1$ the SAOA emerges as the mean-field approximation to QAOA which is justified for a large number of spins N and a large average degree Z of the graph. We test SAOA for the Sherrington-Kirkpatrick (SK) model and the number partition problem — it delivers an approximated optimum with accuracy of order $1/\sqrt{N}$ or higher in a polynomial time and outperforms QAOA.

To quantify quantum fluctuations around mean-field spin trajectories we solve an effective scattering problem in time. It describes a propagation of collective paramagnon modes above an instantaneous ground state of the adiabatic Hamiltonian $H(s)$ and is characterized by a spectrum of positive Lyapunov exponents which depend on a reduced time $s \in [0, 1]$. The largest Lyapunov exponents, $\lambda_0(s)$, shows a (number of) maximum(s) equal to $\lambda^{(i)}$ which are pinned to mini-gaps in the lowest part of a spectrum of $H(s)$. The case of all $\lambda^{(i)} \ll 1$ indicates for a simple instance where an optimimum can be found classically without invoking quantum computing. For hard instances a few maxima are large, $\lambda^{(j)} \gtrsim 1$, and SAOA typically fails.

The s-dependence of the largest Lyapunov exponent in the quantum SK model enables one to identify its instance specific critical point of the ergodic to many-body localization transition in the presence of transverse magnetic field [4]. We believe in the general applicability of SAOA for a large class of random optimization problems defined on strongly connected graphs.

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T27

Four-body interaction of superconducting qubits for quantum annealing

Graph structure of interconnected qubits is a fundamental issue for realizing quantum annealing in physical hardware. One promising candidate is the structure used in the so-called Lechner-Hauke-Zoller scheme [1]. In this scheme, two-body interactions between physical qubits are not needed, but rather physical qubits interact with neighboring qubits via a four-body interaction, which is not trivial to implement. One way to realize the scheme has been theoretically proposed, where superconducting circuits with Josephson parametric oscillators (JPOs) are investigated [2]. The proposed circuits for a four-qubit plaquette have four JPOs and a coupler for the four-body interaction. We revisit one of the circuits and theoretically find that precise tuning of parameters of the circuit is necessary to increase the four-body coupling constant. In order to achieve larger coupling constant, we propose a new coupler, which enables us to enhance the four-body interaction by tuning additional parameters. This work has been done in collaboration with Tsuyoshi Yamamoto and is based on results obtained from a project, JPNP16007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO). [1] W. Lechner, P. Hauke, and P. Zoller, Sci. Adv. 2015, e1500838. [2] S. Puri, C. K. Andersen, A. L. Grimsmo, and A. Blais, Nat. Commun. 8, 15785 (2017).

T28

Optimal control in many-body quantum machines

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Optimal control is essential for developing high-performing quantum machines. However, devising such control protocols can be highly non-trivial for many-body systems, owing to the exponentially diverging dimensions of the associated Hilbert spaces. I will talk about optimal control in many-body quantum critical batteries; I will discuss how one can use Kibble-Zurek mechanism to develop optimal control protocols for quantum batteries modeled with many-body quantum systems driven through quantum critical points [1].

[1] Ajinkya Werulkar, Victor Mukherjee and Sai Vinjanampathy, in preparation.

T29

High-quality Thermal Gibbs Sampling with Quantum Annealing Hardware

Quantum Annealing (QA) was originally intended for accelerating the solution of combinatorial optimization tasks that have natural encodings as Ising models. However, recent experiments on QA hardware platforms have demonstrated that, in the operating regime corresponding to weak interactions, the QA hardware behaves like a noisy Gibbs sampler at a hardware-specific effective temperature. This work builds on those insights and identifies a class of small hardware-native Ising models that are robust to noise effects and proposes a procedure for executing these models on QA hardware to maximize Gibbs sampling performance. Experimental results indicate that the proposed protocol results in high-quality Gibbs samples from a hardware-specific effective temperature. Furthermore, we show that this effective temperature can be adjusted by modulating the annealing time and energy scale. The procedure proposed in this work provides an approach to using QA hardware for Ising model sampling presenting potential new opportunities for applications in machine learning and physics simulation.

T30

Estimation of hyperparameters on Ising model with constraints

Quantum annealing is the technique for solving combinatorial optimization by mapping the problem to the Ising model which has no constraints. On the other hand, most of the practical problems of combinatorial optimization have constraints to be satisfied. Hence it is essential to consider the Ising model with equality (or inequality) constraints in order to use quantum annealer for practical use, which is in general difficult due to the necessity of fine-tuning process for hyperparameters. Here we address the problem by using the hybrid algorithms of the subgradient method and the augmented Lagrangian method. Our method does not need any fine-tuning process during the parameter estimation.

T31

A Quantum Annealing Algorithm For The Qubit Allocation Problem

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Qubit allocation is an important subproblem in the compilation process of gate-based quantum computing [1]. It consists on finding the optimal mapping of the algorithmic qubits present in the instruction set of a quantum program within a device with limited connectivity between physical qubits. More exhaustive overviews of this problem can be found in [2, 3]. The absence of a link between two qubits that need to interact requires the addition of extra gates that may end up increasing the circuit's depth greatly, which in turn translates to a greater exposure to noise. The standard way to achieve this previously non-existing link is by the inclusion of SWAP gates that exchange the allocation of two algorithmic qubits in their respective physical sites. Thus, in general the optimal solution of the qubit allocation problem implies a dynamical change in the algorithmic-to-physical qubit mapping as the circuit is executed. In addition, whenever two qubits that need to interact share a common neighbour, they may also be linked by means of a bridge gate, which allows to achieve the desired connectivity while preserving the current allocation of the algorithmic qubits.

Most previously existing algorithms for tackling this problem consist on (classical) heuristics that choose an initial allocation at the beginning of the quantum program and then sequentially select a set of transformations to achieve the required connectivity in every layer according to some greedy strategy. However, to our knowledge, up to date there are no proposals for approaching the truly optimal solution of this problem other than brute-force search. We provide an algorithm within the quantum annealing framework that provides access to this optimal solution by making explicit use of entanglement, in such a way that the cost of all possible sets of transformations is evaluated in parallel and the optimal solution is highlighted [4]. This is possible through the separation of the qubit register between a first subregister that keeps track of the circuit layers (i.e., time step of the quantum program) and a second subregister that encodes the allocation of the algorithmic qubits into the physical qubits, in a structure inspired by Kitaev's construction of the history state [5] and later used by Aharonov in her proof of universality of AQC [6]. The most straight-forward implementation of our algorithm provides the initial allocation corresponding to the optimal solution to the qubit allocation problem, which can already be used as a starting point for other sequential heuristic approaches. However, the algorithm also admits an iterative scheme that allows to extract algorithmic-to-physical qubit mappings corresponding to the optimal solution in between time steps of the quantum program.

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T32

Variational shortcuts-to-adiabaticity for Lindbladian dynamics

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Suppressing unwanted transitions out of the instantaneous ground state is a major challenge in adiabatic quantum computation (AQC). To counteract finite-time diabatic transitions, a modern approach consists in building counterdiabatic (CD) Hamiltonians using variational strategies. In this talk, I will discuss our recent proposal [1] of a variational approach for CD driving Lindbladian quantum evolutions, which can model open-system AQC—quantum annealing. In this case, our goal is the suppression of diabatic transitions between pairs of Jordan blocks of the Lindbladian superoperator. First, I will show that the variational equations derived in the Lindbladian framework are strikingly similar to the ones derived by Sels and Polkovnikov for unitary dynamics [2], and that unitary CD driving is recovered as a limiting case of our approach. More importantly, I will show that unitary counterdiabatic maps are successful for dissipative dynamics as well, in terms of both open-system adiabaticity and ground-state fidelity, allowing for easier experimental implementations compared to Lindbladian *ansätze* involving dissipation.

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T33

Diversity measure for discrete optimization: Sampling rare solutions via algorithmic quantum annealing

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[4] *Google, Mountain View, CA, USA*

Sampling a diverse set of high-quality solutions for hard optimization problems is of great practical relevance in many scientific disciplines and applications, such as artificial intelligence and operations research. One of the main open problems is the lack of ergodicity, or mode collapse, for typical stochastic solvers based on Monte Carlo techniques leading to poor generalization or lack of robustness to uncertainties. Currently, there is no universal metric to quantify such performance deficiencies across various solvers. Here, we introduce a new diversity measure for quantifying the number of independent approximate solutions for NP-hard optimization problems [1].

To test this metric, we compare the sampling power of various quantum annealing strategies, as applied to random frustrated 2D spin systems with local fields. Using Path-Integral Monte Carlo simulations, we show that the inhomogeneous quantum annealing schedules can redistribute and suppress the emergence of topological defects by controlling space-time separated critical fronts, leading to an advantage over standard quantum annealing schedules for finding rare solutions; quantified by Time-To-Diversity.

[1] M. Mohseni, M. M. Rams, S. V. Isakov, D. Eppens, S. Pielawa, J. Strumpfer, S. Boixo, H. Neven, arXiv:2110.10560 (2021).

T34

Unconstrained binary models of the Travelling Salesman Problem variants for quantum optimization

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The well-known Travelling Salesman Problem (TSP) and its variants have been investigated by many researchers in the literature. Among its variants, Travelling Salesman Problem with Time Windows (TSPTW) looks for a tour with the minimum cost where each city v is visited within the time interval $[e_v, l_v]$, where e_v is the earliest start time and l_v is the due time for city v. If the vehicle arrives at city v before e_v, the vehicle should wait. TSPTW aims to find a Hamiltonian cycle that minimizes the total cost and satisfies the time window constraints. It is proven that the TSPTW problem is NP-Hard, and even finding a feasible solution is proven to be NP-Complete.

The emerging technology of quantum computing opens up an alternative perspective for solving computationally hard problems. There have been promising attempts to solve optimization problems using quantum computing, Quantum Annealing (QA) being one of the most prominent ones. Quantum Annealing has attracted significant attention since it is realizable in the commercially available D-Wave machines. In order to solve a problem using QA, one can formulate the problem as a Quadratic Unconstrained Binary Optimization problem (QUBO) which is then easily recast into the problem Hamiltonian. Recently, Papalitsas et al. have proposed a QUBO formulation for the TSPTW problem [1]. However, the formulation is flawed as it omits the subtour conditions, the conditions required to ensure that the solution consists of a single closed tour. Furthermore, the authors assume that the earliest start time is equal to 0 for all cities, which limits the possible applications.

The contribution of the presented work is threefold. Firstly, we include an additional term in the Hamiltonian to remove disjoint tours from the set of feasible solutions. The additional term is included to ensure that the city left and entered at consecutive times is the same. We also extend the model presented in [1] by taking into account waiting time at each city by introducing additional variables. Secondly, we present an alternative Higher Order Binary Optimization (HOBO) formulation which is more space-efficient. We use an encoding through the nodes instead of the edges so that the binary variables represent the visited nodes at different time points. Finally, we present an alternative QUBO formulation based on the integer linear programming formulation given in [2].

All proposed models can be easily modified to obtain formulations for other variants of TSP like Makespan Problem with Time Windows, in which the total tour duration is minimized. To investigate the efficiency of the edge-based and ILP formulations, we provide experimental results obtained by running small instances of the problem on the D-Wave Advantage.

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T35

Fast forward adiabatic quantum dynamics of XY spin model on Kagome lattice

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We discussed a method to fast forward an adiabatic quantum dynamics of XY spin model. Accelerated scheme is constructed by adding the driving Hamiltonian to the original Hamiltonian [1] and speed it up with a large time-scaling factor and adiabatic parameter which realizes an adiabatic quantum dynamics on shortened time. Accelerated adiabatic dynamics starting by assuming the candidate of driving Hamiltonian consist of the pair-wise exchange interaction, and magnetic field [2,3]. The driving Hamiltonian terms multiplied by the velocity function together with the original Hamiltonian give the fast forward driving for adiabatic states. We apply our method to XY spin model [4,5] by considering 3 spin system on Kagome lattice. In this models, we obtained a nearest neighbors and next-nearest neighbors pair-wise exchange interaction as a driving interaction that should be added to accelerate the adiabatic motion. This pair-wise driving interaction in the fast-forward scheme guarantees the complete fidelity of accelerated states.

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T36

Decoding strategies to enhance Parity Quantum Approximate Optimization

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The LHZ architecture proposed in Ref. [1] aims at solving optimization problems on a planar quantum chip architecture using local interactions only, at the cost of redundant encoding in an enlarged Hilbert space. In this talk, I will discuss a novel procedure to make use of this redundant encoding for the quantum approximate optimization algorithm (QAOA). Instead of decoding physical qubits to logical qubits at the readout, the method uses the logical qubits during the quantum algorithm. Our results demonstrate that this method significantly improves the optimization results and shows quantitative error mitigation for QAOA in the presence of noise.

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T37

Localisation, Quantum Phase Transitions and Graph Theory for Adiabatic Quantum Computing

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In the context of adiabatic quantum computation (AQC), it has been argued that first order quantum phase transitions (QPTs) due to localisation phenomena will always cause AQC to fail by exponentially decreasing the minimal spectral gap of the Hamiltonian along the annealing path [1]. The vanishing spectral gap occurs due to localisation of the ground state in a local minimum, requiring the system to tunnel into the global minimum at a later stage of the annealing (see red arrows in Figure 1). However this notion has been subject to some debate in the community [2], since more recent findings suggest the existence of methods to avoid this by carefully designing the involved Hamiltonians. It remains a challenge to formulate a comprehensive theory on the effect of the various parameters and the conditions under which QPTs make the AQC algorithm fail. In this work [4] we investigate the conditions under which localisation causes first order QPTs using spectral graph theory, examine both analytically and numerically the role of the connectivity of the driver Hamiltonian H_d in the mitigation of such effects in different AQC algorithms and derive bounds on the location of the minimal spectral gap along the anneal path s_{min} (see Figures 2 and 3). Additionally, we show that in the limiting case of fully connected H_d as used in adiabatic Grover search [5], first order QPTs due to localisation are avoided entirely. Our analysis augments the tool box to design H_d such that first order QPTs are avoided and the runtime of AQC algorithms is improved.

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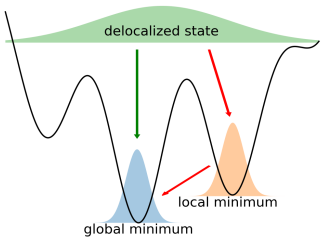

Figure 1: Ground state localisation with (red arrows) and without (green arrows) subsequent tunneling to the global minimum

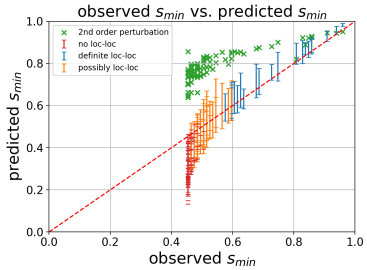

Figure 2: Predicted over observed s_{min} for a toy model with (blue bars) and (possibly) without (orange / red bars) tunneling, compared to method from [3] (green crosses)

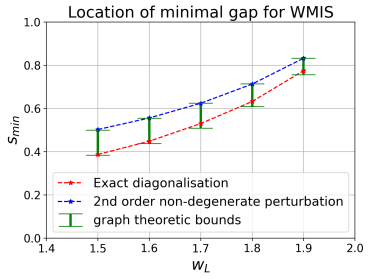

Figure 3: Predicted s_{min} for WMIS problem instances w_L from our method (green) and method from [3] (blue) compared to exact diagonalisation (red); compare to Fig. 4 (a) in [3]

T38

An analogue quantum variational embedding classifier

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Quantum machine learning could provide powerful algorithms for artificial intelligence. The pursuit of quantum advantage in quantum machine learning is an ongoing area of research. For current noisy, intermediate-scale quantum (NISQ) computers, various quantum-classical hybrid algorithms have been proposed. One such hybrid algorithm is a gate-based variational embedding classifier, which is composed of a classical neural-network and a gate-based quantum circuit [1]. We propose a quantum variational embedding classifier based on an analogue quantum computer, with a particular focus on a quantum annealer implementation. In our classifier, the nonlinear mapping of the classical data to a high-dimensional density matrix is realized in an analogue manner. The nonlinearity needed for a nonlinear classification problem is purely provided by the analogue quantum computer. We show the effectiveness of our algorithm for performing binary and multilabel classification on linearly inseparable datasets. Our algorithm performs much better than a classical linear classifier, e.g., comparing with a classical linear classifier, the error for a binary classification problem is reduced from >50% (a classical linear classifier) to <1% (our algorithm). We also characterized the performance of our algorithm in terms of the error scaling vs the number of qubits, etc. Our algorithm presents the possibility to use current quantum annealers for solving practical machine-learning problems and it could also be useful to explore quantum advantage in the quantum machine learning.

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T39

Signatures of Open Quantum System Dynamics in Single Qubit Annealing

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It has been shown that adding stochastic fluctuations to the longitudinal field of the transverse field Ising Hamiltonian can be a suitable effective model for reproducing full anneal output statistics that are observed on D-Wave's annealing hardware [1, 2]. However, the role of stochastic longitudinal field fluctuations in the dynamical process of quantum annealing remained unclear. In this work we use D-Wave's *h-gain-schedule* parameter to rapidly quench the system's dynamics, yielding interesting output statistics. By fitting these statistics to simulations of the weak-coupling adiabatic master equation [3] we identify key signatures of both longitudinal field noise and the system-bath coupling. We show that by including noise sources in the Hamiltonian which are not accounted for by the Ohmic bath, i.e. the fluctuating longitudinal field, it may adjust the system-bath coupling to values that are lower than in models that do not include these noise sources and it provides a better fit to observed output statistics from the annealing hardware. The proposed single-qubit protocol for data collection and model fitting provides a new scalable approach for characterizing key dynamic properties of qubits in quantum annealing hardware platforms.

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T40

Quantum Information Scrambling over Bipartitions

In recent years, the out-of-time-order correlator (OTOC) has emerged as a diagnostic tool for information scrambling in quantum many-body systems. In this talk, I will present exact analytical results for the OTOC for a typical pair of random local operators supported over two regions of a bipartition. Quite remarkably, we show that this “bipartite OTOC” is equal to the operator entanglement of the evolution. Furthermore, one can compute long-time averages of the OTOC and reveal their connection with eigenstate entanglement, the structure of the spectrum and elucidate how this affects the equilibration value of the OTOC. Finally, we provide operational significance to this bipartite OTOC by unraveling intimate connections with average entropy production and scrambling of information at the level of quantum channels.