INQA2023 Innsbruck, 6th - 8th November
Poster session

Poster ID	Title	Author	Institute/Organization	Country	Abstract
1	*A Genetic Quantum Annealing Algorithm*	Nutricati, Luca Armando	University College London	United Kingdom	A genetic algorithm (GA) is a search-based optimization technique based on the principles of Genetics and Natural Selection. We present an algorithm which enhances the classical GA with input from quantum annealers. As in a classical GA, the algorithm works by breeding a population of possible solutions based on their fitness. However, the population of individuals is defined by the continuous couplings on the quantum annealer, which then give rise via quantum annealing to the set of corresponding phenotypes that represent attempted solutions. This introduces a form of directed mutation into the algorithm that can enhance its performance in various ways. Two crucial enhancements come from the continuous couplings having strengths that are inherited from the fitness of the parents (so-called nepotism) and from the annealer couplings allowing the entire population to be influenced by the fittest individuals (so-called quantum-polyandry). We find our algorithm to be significantly more powerful on several simple problems than a classical GA.
2	*A new approach of quantum linear optics to solve classification tasks*	Sakurai, Akitada	Okinawa Institute of Science and Technology	Japan	A photon is one of the famous elementary particles in physics, which is historically significant and known as a minimum carrier of quantum information. Although quantum linear optical circuits (QLOC) consisting of phase shifters and beam splitters are not universal for quantum computation, the non-interacting boson sampling problem has shown to be hard to simulate classically (#P-hard). Utilizing its complexity for practical problems, however, remains highly nontrivial. In this talk, we will introduce a new quantum neural network (QNN) model based on QLOC to compute practical problems such as image classification problems. In particular, we design QLOC models to solve the classification problem with the hand-written digit data set (MNIST). The best performance with these models achieves 96.6% accuracy rate for testing with 4 photons and 16 waveguides, which is within the reach of the current technology. This model does not require programming nor optimization of the QLOC used in the model, similar to the quantum extreme reservoir computation, which not only contributes to its high feasibility but also ensures its applicability to other computational tasks. In these models, we show the encoding of the classical information into the quantum state for QLOCs influences the overall performance of the computational model and also discuss the advantages of the QNN.
3	*A sequential optimization method using Ising machines for combinatorial optimization problems with many constraints*	Yamashita, Masashi	Keio University	Japan	Ising machines including quantum annealing machines are expected to be able to efficiently find better solutions to combinatorial optimization problems. When Ising machines are used naively to solve combinatorial optimization problems with multiple correlated constraints, the solution accuracy may not be high or a feasible solution may not be obtained. The Vehicle Routing Problem (VRP) is one such problem where the primary objective is to find the optimal routes for a fleet of vehicles departing from a depot to deliver goods or services to a set of customers. Due to the large number of correlated constraints, VRPs are difficult to solve with Ising machines. To overcome the above drawback, we propose a novel hybrid algorithm that combines problem partitioning and sequential optimization using an Ising machine. In this algorithm, we first generate an initial solution to a target problem. Next, we partition the problem into subproblems with fewer constraints and find a better solution to a particular subproblem using an Ising machine. We improve an initial solution based on the obtained solution. Finally, we find a better solution to the target problem by iterating these operations. We then evaluated the performance of the proposed algorithm.
4	*Adding extra longitudinal biases to improve the performance of quantum annealing*	Hattori, Tomohiro	Keio University	Japan	Although quantum annealers aim to find optimal solutions to combinatorial optimization problems, it is not always possible to find optimal solutions in practical time. Therefore, it is necessary to develop more efficient annealing methods that increase the probability of the ground state. Many methods have been proposed to improve the efficiency of quantum annealing. In general, the time-independent target Hamiltonian we want to find the ground state is used in quantum annealing. Here, based on the idea of solving relaxation problems during quantum annealing, we investigated the method that uses the time-dependent problem Hamiltonian by adding extra longitudinal biases. In this quantum annealing process, the instantaneous ground state of the time-dependent target Hamiltonian is different from the ground state of the original problem, but eventually the ground state is the same as the ground state of the original Hamiltonian. This improves the efficiency of quantum annealing. By numerically simulating the dynamics for small instances, the performance of this method was investigated.
5	*Anti-crossings occurrence as exponentially closing gaps in Quantum Annealing*	Braida, Arthur	ATOS / Universoté d'Orléans	France	This work explores the phenomenon of avoided level crossings in quantum annealing, a promising framework for quantum computing that may provide a quantum advantage for certain tasks. Quantum annealing involves letting a quantum system evolve according to the Schrödinger equation, with the goal of obtaining the optimal solution to an optimization problem through measurements of the final state. However, the continuous nature of quantum annealing makes analytical analysis challenging, particularly with regard to the instantaneous eigenenergies. The adiabatic theorem provides a theoretical result for the annealing time required to obtain the optimal solution with high probability, which is inversely proportional to the square of the minimum spectral gap. Avoided level crossings can create exponentially closing gaps, which can lead to exponentially long running times for optimization problems. In this paper, we use a perturbative expansion to derive a condition for the occurrence of an avoided level crossing during the annealing process. We then apply this condition to the MaxCut problem on bipartite graphs. We show that no exponentially small gaps arise for regular bipartite graphs, implying that QA can efficiently solve MaxCut in that case. On the other hand, we show that irregularities in the vertex degrees can lead to the satisfaction of the avoided level crossing occurrence condition. We provide numerical evidence to support this theoretical development, and discuss the relation between the presence of exponentially closing gaps and the failure of quantum annealing.

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6	*Coherent Flux Qubits For Quantum Annealing*	Cozzolino, Luca	IFAE	Spain	The European consortium Annealing-Based Variational Quantum Processors (AVaQus) project has as its main goal to create a prototype for coherent quantum annealing. This poster displays the initial characterisation of multiple coherent flux qubits, all of which have been manufactured on a single silicon chip. The design includes variations in qubit shunt capacitance geometry and value. A total of six flux qubits are individually coupled to their respective readout resonators, all of which are connected to a common feedline. The poster presents spectroscopy and time domain measurements for each of these qubit designs. Based on the insights gathered from these results, we will motivate our flux qubit design that will be incorporated into the final AVaQuS prototype chip.
7	*Continuous-time quantum walks for MAX-CUT are hot*	Banks, Robert J	UCL	United Kingdom	By exploiting the link between time-independent Hamiltonians and thermalisation, heuristic predictions on the performance of continuous-time quantum walks for MAX-CUT can be made. These resulting predictions depend on the number of triangles in the underlying MAX-CUT graph. This demonstrates how thermalisation provides a novel way of understanding the role of unitary dynamics in tackling combinatorial optimisation problems with continuous-time quantum algorithms. We discuss how these results could be extended to time-dependent protocols. This talk is based on the recent arXiv preprint 2306.10365.
8	*Deep Unfolded Quantum-Inspired Annealing*	Arai, Shunta	Tokyo Institute of Technology	Japan	Quantum-Inspired Annealing (QIA) is a classical algorithm for solving combinatorial optimization algorithms [1]. The classical Hamiltonian in the QIA is based on the semi-classical approximation of the Quantum Hamiltonian. The algorithm of the QIA is composed of matrix multiplication and is inspired by the standard quantum annealing (QA). In the original QIA, the QA-like scheduling function is adapted. The learning of the scheduling function of QIA is a nontrivial problem. To learn the scheduling function of the OIA, we apply the deep unfolding (DU)[2]. The DU is the hyperparameter tuning method for iterative algorithms with gradient descent and was developed in the field of signal processing. In our talk, we show the benchmarking of the proposed algorithm for several combinatorial optimization problems. [1] J.Bowles et. al, Phys. Rev. Applied 18, 03401(2022) [2] S.Takabe, arXiv:2306.16264 (2023)
9	*Determining the Concentratable Entanglement of multipartite quantum states with projective measurements on an ensemble*	Foulds, Steph	University of Strathclyde	United Kingdom	Entanglement is a vital resource in quantum computation and information. In general, the amount of entanglement in a state determines its usefulness. The standard methods for detecting and characterising quantum entanglement are either resource intensive or require prior knowledge of the state in question. We extend the two-qubit pure state entanglement measure concurrence to the multipartite entanglement measure concentratable cntanglement (CE) and provide a more efficient method of experimentally estimating it, the Bell-basis test for entanglement, the output probabilities of which are related to the CE and purity of the input ensemble state. We show these results are robust to small variations in the input states and are therefore suitable for experimental estimation. The Bell-basis test can be achieved experimentally with current hardware with number of trials at maximum according to Hoeffding's inequality, and is particularly suited to larger (n>3) multipartite states. Unlike many other multipartite measures, concentratable cntanglement (CE) has a simple form, can be directly estimated from experiment, and can be used for mixed states; therefore, we present CE as a standard entanglement measure for multipartite states.
10	*Examples of early applications of quantum annealing in geophysics*	Dukalski, Marcin	Aramco Overseas Company	Netherlands, The	Many imaging disciplines rely on determining the properties of the medium under investigation from indirect measurements. Subsurface, and in particular seismic, imaging is probably one of the most computational demanding examples thereof. In this process we invert the scattered wave field measured at the surface for geological information below. This involves solving a number of very large optimization problems characterized by severely multimodal objective functions, and hence making it a top three high performance computing consumer globally. The reasons above would make subsurface imaging, and perhaps geophysics as a whole, an obvious candidate for quantum annealing use cases. A number of subtleties, however, make finding a practically viable use case a bit more challenging. We wish to present our perspective on geophysical application considering the limitations of currently available quantum annealers and showcase our progress on a typical problem encountered on land where geological anomalies such as underground rivers, caves or boulders locally misalign measured wavefronts. Correcting for these anomalies results in a higher resolution image and greater confidence in the faithful representation of the subsurface. Classical methods provide approximate solutions in cases where mean field approaches are sufficient. Classical global optimization techniques on the other hand can be susceptible to returning potentially far away in parameter space local optima which might give a false sense of certainty about the subsurface. Solving this problem has far reaching implications for civil engineering hydrology CO2 and H2 gas storage and hydrocarbon exploration. We show how to formulate this geophysical problem as a Potts model and how different variable encodings yield QUBOs which differ in their likelihood of returning a global optimum or a feasible solution at all. We explain these differences from both the problem formulation and the quantum annealer performance perspective focusing in particular on internal control errors. We also discuss how one could build a classical-quantum hybrid solver to address the aforementioned complications and suggest a number of other geophysical applications that could benefit from quantum annealing.
11	*Geometry of quantum states*	Střeleček, Jan	Charles University	Czech Republic	In this study, we aim to clarify the connection between Quantum Phase Transitions and the geometry of Ground State Manifolds. We use a specific parametrization of a Lipkin model and study ground states using the Hartree-Bose method. We show how quantum phase transitions are propagated into the geometry of states and discuss its meaning.

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12	*Impact of the form of weighted networks on the quantum extreme reservoir computation*	Hayashi, Aoi	SOKENDAI, OIST	Japan	The recent development of quantum devices raises expectations for utilizing them for practical applications, while still noisy. Driven by the expectation, quantum machine learning, considered robust to noise, is gathering much attention, and various models have been proposed. Among such models, the quantum extreme reservoir computing (QERC) [A. Sakurai, et al., Phys. Rev. Applied 17, 064044] has already shown the capability to achieve a high accuracy rate for an image classification task with the smallest number of qubits among previous works. This model utilizes a Hamiltonian quantum dynamics with a trainable classical neural network to solve tasks. As the performance of the model is dependent on the properties of the Hamiltonian quantum dynamics, there is still room to choose such fixed quantum dynamics; however, the relation between the properties of the quantum dynamics and the model performance remains unrevealed. In this talk, we focus on the relation between the properties of the quantum dynamics and the performance as the quantum machine learning model to understand how to design the quantum dynamics for this quantum machine learning model. To do so, we first introduce a method to characterize unitary matrices as networks. We then apply it to several unitary matrices, including random ones, and observe the characterization method captures their difference. Next, we benchmark the QERC performance with those unitary matrices. We will then find the relation between the weight distribution of networks associated with unitary matrices and the performance, especially generalization performance for image classification tasks. Lastly, we will show a Hamiltonian dynamics with a nearly optimal testing accuracy rate and the best generalization performance among our benchmarks.
13	*Learning Hamiltonian of black-box optimization problems with loosely coupled Ising model*	Seki, Yuya	Keio University	Japan	We developed a method to estimate a Hamiltonian for black-box optimization problems with loosely coupled Ising model. In a traditional optimization method by quantum annealing (QA) and simulated annealing (SA), an objective function for a target optimization problem must be derived analytically. However, it is impossible to derive an objective function for black-box optimization problems, because their cost functions are not given analytically. A promising approach for black-box optimization problems is surrogate-model based framework. This framework estimates a Hamiltonian, which is called surrogate model, that approximates an objective function of a black-box optimization problem. The optimal solution can be obtained by optimizing the surrogate model instead of the objective function of the black-box optimization problem. Accordingly, the surrogate model must be easier to optimize than the black-box function. Kitai et al. have proposed a surrogate model-based method for QA and SA called as Factorization Machine with Quantum Annealing (FMQA), and its application has been studied. In the study by Kitai et al., estimated Hamiltonian has fully connected interaction terms. Although the fully connected model has a high approximate accuracy for the target objective function, additional variables are required to find a low-energy solution of the fully connected model on actual annealing devices. To handle this issue, we develop an optimization method with loosely coupled Ising model as a surrogate model. In this presentation, we show the optimization performance of our approach obtained by numerical experiments, and approximate accuracy of the estimated model.
15	*Nonnegative/binary matrix factorization for image classification using quantum annealing*	Asaoka, Hinako	Ochanomizu University	Japan	With the development of quantum computing technology, many machine learning methods using quantum annealing have been proposed. However, since machine learning methods using classical computers, such as deep learning, have already been developed, it is important to show the advantages of introducing quantum technology to machine learning areas. In this work, we apply a matrix factorization method using quantum annealing to image classification and compare its performance with conventional machine learning methods. Nonnegative/Binary Matrix Factorization (NBMF) was originally introduced as a generative model. We propose its application as a multi-class classification model. In this work, we obtain features of handwritten digit images using NBMF and use them to solve the classification task. Our results showed that the accuracy of models trained by NBMF is higher than that of classical machine learning methods, such as neural networks, when the numbers of data, features, and epochs are small. We also found that the computation time is significantly reduced when we train models using a quantum annealing solver. Under specific conditions, there is an advantage in utilizing quantum annealing technology for machine learning methods.
16	*Physical Properties of Error Reduction Algorithms for Ising machines*	Hino, Kanta	Keio University	Japan	Ising machines are expected to be dedicated computers that efficiently search for good solutions to combinatorial optimization problems. When solving combinatorial optimization problems with an Ising machine, the objective function and constraints of the combinatorial optimization problem should be expressed using the Ising model or the form of Quadratic Unconstrained Binary Optimization (QUBO). Internal algorithms of Ising machines search for low-energy states of the Ising model and QUBO. Typical internal algorithms are Simulated Annealing (SA) and Quantum Annealing (QA). Both algorithms exhibit stochastic behavior, so the final solution may contain errors. Therefore, it is an essential issue in the field of Ising machines to mitigate errors as much as possible. An error reduction algorithm, Quantum Annealing Correction (QAC) model, for QA machines was proposed in the previous studies [1,2]. This algorithm reduces error by combining its geometric structure with a specific decoding method. Being inspired by the previous studies, we proposed another error reduction algorithm called stacked model. We investigated on the relationship between the penalty interaction and the success probability of the QAC model and the stacked model, for both QA and SA. The similarities and differences between the two models are discussed from a viewpoint of statistical mechanics. We also investigated on their physical properties against large-scale problems based on Markov chain Monte Carlo method for SA.

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17	*Quantum annealing with error mitigation*	Shingu, Yuta	National Institute of Advanced Industrial Science & Technology	Japan	Quantum annealing (QA) is one of the efficient methods to calculate the ground-state energy of a problem Hamiltonian. In the absence of noise, QA can accurately estimate the ground-state energy if the adiabatic condition is satisfied. However, in actual physical implementation, systems suffer from decoherence. On the other hand, much effort has been paid into the noisy intermediate-scale quantum (NISQ) computation research. For practical NISQ computation, many error mitigation (EM) methods have been devised to remove noise effects. In this talk, we propose a QA strategy combined with the EM method called dual-state purification to suppress the effects of decoherence. Our protocol consists of four parts; the conventional dynamics, single-qubit projective measurements, Hamiltonian dynamics corresponding to an inverse map of the first dynamics, and post-processing of measurement results. Importantly, our protocol works without two-qubit gates, and so our protocol is suitable for the devices designed for practical QA. We also provide numerical calculations to show that our protocol leads to a more accurate estimation of the ground energy than the conventional QA under decoherence.
18	*Quantum optimization for customer data science using penalty functions with linear terms*	Mirkarimi, Puya	Durham University	United Kingdom	Real-world combinatorial optimization problems often involve many constraints. In quantum annealing, constraints that are linear in the input variables are typically encoded in the problem's objective function by adding quadratic penalty functions that penalise infeasible solutions. The addition of these quadratic terms reduces the available dynamic range of qubit interactions and may increase the total number of qubit interactions that need to be implemented. We explore an alternative penalty method involving only linear terms, thereby avoiding some of the drawbacks of the quadratic penalty method. For our analysis, we consider an example problem from customer data science that has a structure which makes it particularly suitable for the linear method. We compare the performance of the two penalty methods on a D-Wave quantum annealer.
19	*Scalable embedding of parity constraints in quantum annealing hardware*	Cattelan, Michele	Volkswagen AG	Germany	Current state-of-the-art quantum annealing hardware based on superconducting qubits have rigid topological structures that limit qubits' connectivity. This limitation means that direct mappings of arbitrary combinatorial optimization problems are impossible. To mitigate this, it is necessary to use minor embedding techniques to match the problem topology to the hardware layout. Using such minor embedding algorithms is time-consuming and represents one of the major bottlenecks in using quantum annealers for practical purposes. In this work, we propose a scalable all-to-all embedding framework based on LHZ parity transformations that allows us to skip minor embedding for all combinatorial optimization problems. We do this by constructing regular structures of parity constraints which can be implemented directly on quantum hardware and add them to the problem Hamiltonian. To achieve this, we reformulate the parity constraints containing higher-order interactions as quadratic Ising Hamiltonians, and furthermore, study how this reformulation affects the spectral gap of the full Hamiltonian. We show how this framework can be used on any QPU that has a Pegasus topology as a subgraph, and use the multi-car paint shop problem as an example of a practical application of the developed techniques.
20	*Using the LHZ architecture to increase the success probability of quantum walks*	Bennett, Jemma Ellen	University of Innsbruck	Austria	When solving optimization problems using quantum walks, energy states other than the ground state are populated. In order to maximize success probability, multiple repeats are required. Encoding our optimization problem using the LHZ architecture, we introduce redundant partially correct energy states which are populated during the quantum walk. We show that by measuring spanning trees containing these partially correct states we are able to increase the quantum walk's success probability aside from using repeats.