Abstracts for the talks

Invited talk abstracts

1. Daniel Lidar (USC, USA; remote talk)
Title: Scaling Advantage in Approximate Optimization with Quantum Annealing

Abstract:
This talk will begin with a review of a decade of efforts to demonstrate a scaling advantage in optimization using quantum annealing. Exact optimization has proven to be an elusive target, but recent work has finally demonstrated a quantum scaling advantage in approximate optimization. Tailored quantum error suppression and correction methods play an important role in this demonstration. The advantage is achieved for a certain class of spin-glass problems, where, for sufficiently large optimality gaps, quantum annealing demonstrates a time-to-approximate solution that scales better than PT-ICM, the state-of-the-art classical method.

This is joint work with Humberto Munoz-Bauza, arXiv:2401.07184

2. Alexander Whiticar (D-Wave Systems Inc.)
Coherence advancements for next-generation quantum technologies

D-Wave Quantum continually works on developing next-generation superconducting quantum computing technologies. Recent results from a new quantum annealing prototype have brought into focus the importance of realizing and augmenting the role of coherent quantum dynamics during operation [1,2]. To that end, D-Wave Quantum has maintained an intensive in-house materials science program to reduce sources of noise in our quantum processors. In this talk I will discuss a broad range of methods to measure flux and charge noise

in flux-like qubits. It will be demonstrated how results from incoherent tunneling measurements and coherent driven dynamics offer complementary approaches to characterizing the noise spectral density [3]. I will also discuss how device design can be used to tune the relative coupling to charge versus flux noise. In particular, by increasing the inductance of our qubits, thus spanning the parametric range from flux qubit to fluxonium, we are able to obtain highly coherent qubits that can be used to probe the electromagnetic environment seen by our quantum processors.

[1] King, A. D., et al. "Coherent quantum annealing in a programmable 2,000 qubit Ising chain." Nat Phys 18.11 (2022): 1324-1328.

[2] King, A. D., et al. "Computational supremacy in quantum simulation." arXiv preprint arXiv:2403.00910 (2024).

[3] Whiticar, A. M., et al. "Probing flux and charge noise with macroscopic resonant tunneling." Physical Review B 107.7 (2023): 075412.

3. Natalie Pearson (PASQAL, France)
Rydberg Blockade Revisited

In Rydberg atom quantum computation, the well known blockade effect is a crucial phenomenon
where an atom in the Rydberg state prevents the excitation of any other nearby atom. Despite its
importance, analysis of this important mechanism is usually simplistic. We extend this analysis to better quantify the blockade phenomenon. Using these insights we explore ways of embedding graphs in Rydberg atom quantum computers by means of register arrangement and pulse sequence, to extend our capabilities for graph-based computation using this hardware.

4. Pol Forn-Díaz (IFAE, spain)
AVaQus project progress

The AVaQus (Annealing-Based Variational Quantum Processors) program is the largest-scale European effort to develop the technology and functionality to operate analog quantum processors as coherent quantum annealers and variational processors. The focus of the project is on both the hardware as well as the theoretical side, to yield a small-scale prototype representing the unit cell of a larger-scale processor that will succeed project AVaQus in the future.

In this talk, I will report on the current state of project AVAQus, focusing on the most recent developments as well as the upcoming challenges. In particular, I will describe the progress developing multi-qubit scalable platforms, the study of theoretical scenarios in search of quantum advantage, as well as the ongoing efforts to produce enabling technology necessary for superconducting qubit technology.

5. Sarah Muschinske (MIT, USA)
Quantum Simulation on a 3x3 Superconducting Qudit Lattice

Quantum simulation with superconducting circuits has largely focused on models of two-level systems such as the hard-core Bose-Hubbard model. However, this choice massively truncates the size of the available Hilbert space – preventing quantum information from being stored in the higher levels of the system and reducing the potential complexity of computation. In this paper, we will discuss the feasibility of performing multi-level analog quantum simulation of the Bose-Hubbard model using superconducting transmon qudits. This approach offers several advantages, including efficient emulation of time evolution (no Trotterization), reduced seepage into the computational subspace (non-Markovian dynamics), and a wider range of Hamiltonians that can be represented. However, with these improvements comes increased complexity in calibration, readout, and tomography protocols. We will give an overview of the design and control of transmon-based Bose-Hubbard emulators. We consider contributions to decoherence and decay of these higher excited states and discuss their impact on many-body behavior. Finally, we will give an outlook for future experiments as we move towards meaningful quantum advantage on noisy intermediate-scale quantum hardware.

6. Naoki Takeuchi (AIST, Japan)
Adiabatic Superconductor Logic: Recent Progress Toward Qubit Controllers

Superconducting digital circuits can operate with low power dissipation at cryogenic temperatures and are thus a promising building block for qubit controllers. Specifically, adiabatic quantum-flux-parametron (AQFP) circuits can operate with an extremely small power dissipation of ~10 pW per gate owing to adiabatic switching. In this study, we report recent progress of AQFP logic toward qubit controllers. We present two types of AQFP-based qubit controllers: microwave generator and flux-bias circuit. These circuits can generate qubit-control signals (microwave and dc magnetic flux) with a low power dissipation of ~100 pW per qubit. Proof-of-concept experiments of these circuits indicate the feasibility of energy-efficient, scalable qubit control using AQFP logic.

This study was supported by the JST FOREST (Grant No. JPMJFR212B) and JSPS KAKENHI (Grants No. JP19H05614 and No. JP19H05615). This study was partly based on results obtained from a project, JPNP16007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO), Japan.

Contributed Talk Abstracts

1. **Jack Raymond** : “Quantum error mitigation in quantum annealing ”

Quantum Error Mitigation (QEM) presents a promising near-term approach to reduce error when estimating expectation values in quantum computing. Here, we introduce QEM techniques tailored for quantum annealing, using Zero-Noise Extrapolation (ZNE). We implement ZNE through zero-temperature extrapolation as well as energy-time rescaling. We conduct experimental investigations into the quantum critical dynamics of a transverse-field Ising spin chain, demonstrating the successful mitigation of thermal noise through both of these techniques. Moreover, we show that energy-time rescaling effectively mitigates control errors in the coherent regime where the effect of thermal noise is minimal. Our ZNE results agree with exact calculations of the coherent evolution over a range of annealing times that exceeds the coherent annealing range by almost an order of magnitude.

arXiv:2311.01306

2. **Sebastian Leontica** : “Entanglement growth from squeezing on the MPS manifold ”

Finding suitable characterizations of quantum chaos is a major challenge in many-body physics, with a central difficulty posed by the linearity of the Schrödinger equation. A possible solution for recovering non-linearity is to project the dynamics onto some variational manifold. The classical chaos induced via this procedure may be used as a signature of quantum chaos in the full Hilbert space. Here, we demonstrate analytically a previously heuristic connection between the Lyapunov spectrum from projection onto the matrix product state (MPS) manifold and the growth of entanglement. This growth occurs by squeezing a localized distribution on the variational manifold. The process qualitatively resembles the Cardy-Calabrese picture [1], where local perturbations to a moving MPS reference are interpreted as bosonic quasi-particles. Taking careful account of the number of distinct channels for these processes recovers the connection to the Lyapunov spectrum. Our results rigorously establish the physical significance of the projected Lyapunov spectrum, suggesting it as an alternative method of characterizing chaos in quantum many- body systems, one that is manifestly connected to classical chaos.

[1] P. Calabrese and J. Cardy, Journal of Physics A: Mathematical and Theoretical 42, 504005 (2009).

3. **Roopayan Ghosh** : “n-local catalysts to speed up quantum annealing ”

The quantum speedup obtained to solve optimization problems via quantum annealing is largely bottlenecked by the closing of the energy gap in the changing potential landscape during the quantum anneal. Among several different methods studied to circumvent this hurdle, some of us previously showed the usage of XX catalyst during annealing increases the gap width[1], that is slows down the gap scaling with system size. In this work we extend the study to non-local catalysts, showing that for different instances of a generalized Maximum Weighted Independent Set (MWIS) problem, an informed choice of n-local (quantum gates involving n-qubits) catalysts can reduce and altogether prevent the closing of gaps during the anneal process. This leverages the symmetry and structure of the problem, but the price to pay is multi qubit quantum gates. The method can be looked upon as a quantum generalization of the multi-spin update process of cluster Monte Carlo algorithms. We discuss the effectiveness and efficacy of the approach under different settings, discussing whether for true quantum advantage one requires scalable multi qubit gates.

[1] Feinstein, N., Fry-Bouriaux, L., Bose, S., & Warburton, P. A. (2022). Effects of XX-catalysts on quantum annealing spectra with perturbative crossings. *arXiv preprint arXiv:2203.06779*.

4. **Anna Maria Dziubyna** : “Approximate tensor network contractions for large unit-cells quantum annealers ”

We develop a heuristic tensor-network-based algorithm aiming to reveal the low-energy spec- trum of certain low-dimensional spin-glass systems that encode optimization problems. Inspired by the present-day quantum annealers, we focus on Ising problems defined on quasi-2D lattices with a connectivity structure of the current QPU architectures. Our approach combines a branch and bound search strategy with the approximate calculation of marginals via tensor-network con- tractions. Application of the latter numerical techniques to lattices with large unit cells of up to 24 spins, relevant for the current quantum annealing processors, requires a dedicated approach that utilizes sparse structures appearing in tensor network representation, combined with GPU hardware acceleration. We benchmark our approach against D-Wave Advantage QPU and Sim- ulated Bifurcation algorithm for problems defined on Pegasus and Zephyr graphs with up to a few thousand spins. Apart from the quality of the best solution found, we examine the diversity of low-energy states sampled by all the solvers. We observe a good performance of quantum annealers in both these metrics for considered problem classes.

5. **Christopher Baldwin** : “Classical outperforms quantum reverse annealing in ferromagnetic mean-field models ”

Adiabatic reverse annealing, first introduced in Ref. [1], is a modification of conventional transverse-field annealing that uses an initial guess at the ground state to attempt to circum- vent problematic first-order phase transitions. Exact solutions for certain mean-field models (the ferromagnetic p-spin models) have confirmed that it can indeed avoid phase transitions altogether, thus providing extremely efficient annealing protocols to locate the desired ground state [2].

In this work [3], we identify the physics underlying the success of (adiabatic) reverse annealing and show that it motivates a corresponding classical reverse annealing algorithm that uses thermal rather than quantum fluctuations, which we term “simulated” reverse annealing (SRA) in contrast to the above “quantum” reverse annealing (QRA). Thus if QRA is to provide a significant advantage over classical algorithms, it must not only succeed in circumventing phase transitions but do so in parameter regimes where SRA fails. Accordingly, we analytically determine the phase diagrams for both QRA and SRA in a wide family of generalized mean-field models — a class sufficiently broad to include mean-field approximations to canonical optimization problems such as K-SAT and XOR-SAT — and unfortunately find no regime in which QRA succeeds while SRA fails (interestingly, we do find regimes in which SRA succeeds while QRA fails). Although discouraging, we also offer comments on why SRA may break down in more realistic problems with rugged energy landscapes, thus motivating future investigation.

In addition, we complement these results with exact calculations of the real-time dynamics under both QRA and SRA protocols, confirming that both indeed succeed in reaching the ground state in O(1) time. This adopts a slightly weaker (but still quite reasonable) definition of “success in O(1) time” — we require that states within arbitrarily small distance of the ground state be reached in O(1) time, but not necessarily the exact ground state itself. Such a definition is more amenable to the tools of statistical mechanics and allows us to perform analytic calculations directly in the thermodynamic limit, which may be of some independent interest.

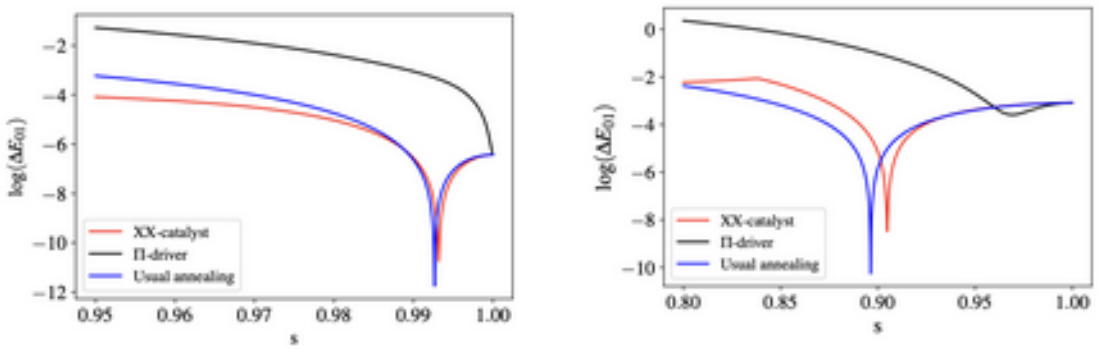
[1] A. Perdomo-Ortiz, S. E. Venegas-Andraca, and A. Aspuru-Guzik, “A study of heuristic guesses for adiabatic quantum computation,” Quantum Inf. Proc., vol. 10, p. 33, 2011.

[2] M. Ohkuwa, H. Nishimori, and D. A. Lidar, “Reverse annealing for the fully connected p-spin model,” Phys. Rev. A, vol. 98, p. 022314, 2018.

[3] C. L. Baldwin, “Classical outperforms quantum reverse annealing in ferromagnetic mean-field models,” In preparation.

6. **Luca Armando Nutricati** : “Using multiple XX-catalysts in quantum annealing to efficiently solve MWIS problems”

Whether a quantum annealer is capable of successfully finding the global solution or just a local minimum strongly depends on the intrinsic characteristics of the problem under study, such as its size, the structure of the energy landscape, the complexity class etc. Along with these specific properties, which are mostly related to the problem itself, other “external” aspects — which rely on how the problem is “prepared” to be solved — could play a crucial role, and include for example the choice of the embedding, the optimisation of the anneal schedule, the necessity of a reduction up to quadratic couplings etc. Among this variety of aspects, one of the bottlenecks in solving combinatorial optimisation problems using quantum annealers is the emergence of exponentially- closing energy gaps between the ground state and the first excited state during the annealing, which indicates that a first-order phase transition is taking place. As the adiabatic theorem dictates, the total evolution duration of the annealing must scale inversely with the square of the minimum energy gap. For certain problems a first-order phase transition may appear during the anneal, with the minimum energy gap scaling exponentially with the inverse of the system size, ultimately resulting in an exponentially large time required to ensure the adiabatic evolution. For this reason, it is useful to investigate techniques to avoid exponentially closing gaps, or, equivalently, first-order phase transitions. Here we will analyse the effect of using an alternative driver in various maximum weighted independent set (MWIS) problem instances. In Fig. 1 we show the advantage of using the new driver (called the Π-driver) for the bi-partite and the tri-partite cases reported in the figure. With the new



(a) Results for a bi-partite graph.

(b) Results for a tri-partite graph.

Figure 1: Avoided first-order phase transitions in the cases of (a) bi-partite and (b) tri-partite MWIS problem instances. In both cases the Π-driver (black) leads to a gap enhancement of two to three orders of magnitude by comparison with a usual X-driver (blue) and the use of an XX-catalyst (red).

driver the system does not undergo a first-order phase transition. Finally, an in-depth analysis will be conducted to examine the versatility and potential of the technique across various problem classes, shifting the emphasis away from the MWIS problem as the central theme.

7. **Sudeera Hasaranga Gunathilaka Mastiyage Don** : “Coherent Compressed Sensor for L0- Regularised Compressed Sensing ”

Increasingly, quantum-inspired Ising machines (QIIMs) have drawn significant attention because they have the potential to overcome the difficulties associated with solving large-scale combinatorial optimisation problems. Most of this interest has been directed towards implementing QIIMs and studying their behaviour, rather than practical applications.

To explore the practical applications of QIIMs, we focus on efficiently solving L0-norm compressed sensing (CS) problems with QIIMs. The CS method refers to the reconstruction of a high-dimensional signal or image using highly downscaled measurements. It has attracted significant interest from a wide range of fields and applications. Because L1-norm CS is a convex optimisation problem, many efficient algorithms have been developed that are widely used in real-world applications. The L0-norm CS, however, is believed to perform better than the L1-norm CS. However, optimisation of L0-norm CS is a challenging task since it involves combinatorial optimisation. In the case that L0-norm CS can be solved efficiently by a QIIM, this will pave the way for their practical applications.

In this research, we consider the coherent Ising machine (CIM), one of the most suitable machines for solving optimisation problems in L0-norm CS, since CIMs can construct a densely connected network. We share our proof-of-principle results about how accurately we can perform L0-norm CS on CIM (soft- spin-based machine) with and without a Zeeman term realisation technique. Using CIMs with chaotic amplitude control (CAC) feedback [3], we demonstrate that they can be used to solve L0-norm CS problems efficiently, outperforming both CIMs without CAC feedback and simulated annealing as well as other practical algorithms such as the Least Absolute Shrinkage and Selection Operator (LASSO) [1]. Furthermore, we show that the performance of CIM with CAC feedback approaches the theoretical limit of L0-norm CS compared to CIMs without CAC feedback [2]. For the real-world data, we have used 64×64 and 128×128 resized MRI images. Results have shown that reconstruction results with CIM with CAC feedback are relatively more accurate.

[1] MDSH Gunathilaka *et al.,* Sci Rep 13, 16140 (2023)
[2] Toru Aonishi *et al.,* Quantum Sci. Technol. 7 035013 (2022) [3] Yoshitaka Inui *et al.,* Commun Phys 5, 154 (2022)

8. **Natasha Feinstein** : “Escaping local optima in quantum annealing with XX-couplings ”

In quantum annealing, the time needed for a single annealing run to return the optimal solution with high fidelity is dependent on the instantaneous energy spectrum associated with the evolution. Reducing this run-time is of great interest with regards to both the efficiency of the algorithm and the demands on the coherence times of the hardware. A particular problem are the occurrence of perturbative crossings which form due to competing local optima of the problem. These perturbative crossings result in exponentially closing gaps in the annealing spectrum such that exponential anneal times are needed to remain in the ground state. One potential route to alleviating this problem is the introduction of an additional catalyst Hamiltonian containing non-stoquastic XX- couplings. In particular, one avenue being explored is the use of targeted catalysts that make use of accessible information about the problem in their construction. In our previous work, we have shown how XX-couplings can be chosen to target a local optimum responsible for a perturbative crossing to alleviate the associated exponential slowdown - either through gap enhancement or by introducing an additional gap minimum that allows the ground state to be reached through a diabatic path [1,2]. Here we show that this approach can be extended to settings where multiple local optima result in perturbative crossings. Using scalable graph structures we demonstrate that, by introducing non- stoquastic XX-couplings targeting each of the local optima responsible for a perturbative crossing, we can create a more efficient path to the ground state. Utilising the fact that polynomial run-times are likely to return precisely the local optima responsible for the perturbative crossings, we discuss the beginnings of a recursive algorithm in which the information needed to select each new coupling could be obtained form the previous annealing run.

[1] N. Feinstein *et al*, arXiv:2203.06779v2

[2] N. Feinstein *et al*, arXiv:2402.13811

9. **Dyon van Vreumingen** : “Gate-based counterdiabatic driving with complexity guarantees ”

Counterdiabatic driving (CD) has been proposed as an alternative to adiabatic quantum computing (AQC). In standard AQC, one carries out a time evolution under a gapped time-dependent hamiltonian $H(\lambda(t))$, whose parametrisation $\lambda(t)$ is a function of time such that $\lambda(0) = \lambda_i$ and $\lambda(T) = \lambda_f$ at some time T. The result of the driving at time T , when starting in an initial eigen- state $|n(\lambda_i)\rangle$ of $H(\lambda_i)$, is an approximation of a final eigenstate $|n(\lambda_f)\rangle$ of $H(\lambda_f)$. CD, then, is a method to actively suppress transitions into other eigenstates in such a pseudo-adiabatic evo- lution. The central object in CD is the adiabatic gauge potential (AGP) $A(\lambda)$, which is the generator of translations in λ space: $A(\lambda) = -i\partial$. When added to the hamiltonian to construct a λ˙ “counterdiabatic hamiltonian”, $H_{CD}(t) = H(\lambda(t))+\lambda(t)A(\lambda(t))$, transitionless driving is achieved. Finding the AGP, however, is highly nontrivial; hence most research so far has focussed on implementing approximate counterdiabatic driving through heuristics, such as in the work of Čepaitė et al. [1]. While these works show increased fidelity with the final eigenstate as a result of approximate CD, they leave one crucial question unaddressed: what is the added computational complexity of approximate CD as compared to standard AQC, and does the obtained increase in fidelity scale favourably with the added cost? We address this question by making a complexity comparison between a gate-based quantum simulation of standard AQC and a novel gate-based quantum algorithm for CD.

[1] Ieva Čepaitė, Anatoli Polkovnikov, Andrew J. Daley, and Cal- lum W. Duncan. Counterdiabatic optimized local driving. PRX Quantum, 4:010312, Jan 2023.

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[6] Nathan Wiebe, Dominic Berry, Peter Høyer, and Barry C Sanders. Higher order decompositions of ordered operator ex- ponentials. Journal of Physics A: Mathematical and Theoretical, 43(6):065203, jan 2010.

10. **Joseph Cunningham** : “Eigenpath traversal by Poisson-distributed phase randomisation ”

We present a new method for eigenpath traversal: given a path of Hamiltonians H(s), for $s \in [0, 1]$, and a state in an eigenstate of H(0), we want to prepare the corresponding eigenstate of H(1). This is the same basic goal as Adiabatic Quantum Computing (AQC) and thus it has many applications to the design of quantum algorithms.

Our method is a modification of the Randomisation Method (RM) of [1]. In the RM, the eigenstate is tracked by performing “phase randomisation” steps sufficiently often along the path. In order to perform one step of phase randomisation at some point s, the system is evolved under the Hamiltonian H(s) (as a time-independent Hamiltonian) for some random amount of time. If the right distribution of random times is chosen (this depends on the gap) and this step is performed often enough, then the ground state of H(1) can be prepared with arbitrarily small infidelity. One drawback of this method is that the state does not evolve smoothly in s: it jumps at the discrete points where phase randomisation is performed. This is very different from AQC, where the state evolves smoothly in s according to the differential equation $\frac{d\rho}{ds} = -iTH(t),\rho$. This equation can then be used to derive bounds on the time-complexity, see e.g. [2].
We propose to let the points at which phase randomisation is performed be chosen according to a Poisson process. Then the average state evolves smoothly in s and we show that its evolution is determined by $\frac{d\rho}{ds} = \lambda L(\rho)$ for some Lindbladian L. Here λ is the rate of the Poisson process. Thus increasing the rate
(i.e. increasing how often the phase randomisation step is performed) improves the fidelity of the final state, just like increasing T improves the fidelity in AQC. Based on the similarity between the two differential equations, we can adapt results derived for AQC to our setting.

It is well-known that the performance of AQC depends strongly on the minimal spectral gap $\Delta_m := \min_{s\in[0,1]} \Delta(s)$, where Δ(s) the difference between the lowest and the second lowest eigenvalue of the Hamiltonian H(s). For AQC it is known that the time complexity scales as $O(1/\Delta^{-1})$ if $\int_1^{R_1} 1\, ds = O(\Delta^{1-p})$ $m_0 \Delta p$ m holds for all p > 1, see [2]. We show that the same condition reproduces the scaling of $O(1/\Delta^{-1})$ using our m version of the RM. In particular, a direct application of our theorem to the Quantum Linear System Problem (QLSP) yields a time-complexity of O(κlog(1/ε)), where κ is the condition number and ε the error tolerance. This is asymptotically optimal and beats the previous state-of-the-art RM-based algorithm [3], whose stated time- complexity is O(κlog(κ/ε)). This time-complexity was previously obtained by an AQC-based algorithm [4]. The analysis of such AQC-based algorithms is complicated by the fact that quantum computers cannot easily simulate a continuously changing Hamiltonian, so some discretisation error is incurred. In order to deal with this, the algorithm in [4] uses the discrete adiabatic theorem, which is arguably more complicated than the usual adiabatic theorem. Our version of the RM side-steps this issue because it is based on the probabilistic execution of a discrete process, which means that there is no discretisation cost.

[1] Sergio Boixo, Emanuel Knill, and Rolando Somma. “Eigenpath traversal by phase randomization”. In: Quantum Information and Computation 9.9&10 (Sept. 2009), pp. 833–855. doi: 10.26421/QIC9.9- 10-7.

[2] Sabine Jansen, Mary-Beth Ruskai, and Ruedi Seiler. “Bounds for the adiabatic approximation with applications to quantum computation”. In: Journal of Mathematical Physics 48.10 (Oct. 2007). doi: 10.1063/1.2798382.

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[4] Pedro C.S. Costa et al. “Optimal Scaling Quantum Linear-Systems Solver via Discrete Adiabatic The- orem”. In: PRX Quantum 3 (4 Oct. 2022), p. 040303. doi: 10.1103/PRXQuantum.3.040303.

11. **Andrew King**: “Computational supremacy in quantum simulation ”

Quantum computers hold the promise of solving certain problems that lie beyond the reach of conventional computers. Establishing this capability, especially for impactful and meaningful problems, remains a central challenge. One such problem is the simulation of nonequilibrium dynamics of a magnetic spin system quenched through a quantum phase transition. State-of-the-art classi- cal simulations demand resources that grow exponentially with system size. Here we show that superconducting quantum annealing processors can rapidly generate samples in close agreement with solutions of the Schro¨dinger equation. We demonstrate area-law scaling of entanglement in the model quench in two-, three- and infinite-dimensional spin glasses, supporting the observed stretched-exponential scaling of effort for classical approaches. We assess approximate methods based on tensor networks and neural networks and conclude that no known approach can achieve the same accuracy as the quantum annealer within a reasonable timeframe. Thus quantum annealers can answer questions of practical importance that classical computers cannot.

12. **Ryoji Miyazaki** : “Three- and four-body switchable coupler for superconducting qubits to implement the parity encoding scheme ” [talk canceled]

How we encode interactions of logical qubits in a network of physical qubits is a fundamental issue for realizing quantum annealers. One promising candidate is the parity encoding scheme [1]. The physical-qubit network for this scheme has been proposed, which is called the parity architecture [2, 3]. The network is a planar one only with the nearest-neighbor interactions. The interactions, however, are three- and four-body ones. The scheme utilizes such multi-body interactions of physical qubits according to the problem instances to be embedded. In other words, one problem requires a four-body interaction of qubits, while another problem requires a three-body interaction for three of the same four qubits. Therefore, in order to implement this theoretical idea, we need a coupler which is not only of multi-body type but can also switch its order of interaction.

We theoretically propose such a coupler for superconducting qubits based on Josephson parametric oscillators. The proposed coupler is a part of four-qubit plaquette and works for three- and four-body interactions of the qubits. For the three-body interaction, we can select three of the four qubits to use. This is a generalization of a previously proposed coupler for the four-body interaction [4]. The previous circuit is generalized to the one for quarton [5], which is a specific setup of the circuit called SNAIL [6, 7]. This generalization allows switching from the four-body interaction to the three-body one by modulating the magnetic flux with a certain frequency, which threads the loop consisting of Josephson junctions in the coupler. We numerically demonstrate that the coupling constants for the three- and four-body interactions are comparable and can be increased with control nobs added by our generalization.

This presentation is based on results obtained from a project, JPNP16007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

[1] N. Sourlas, Phys. Rev. Lett. 94, 070601 (2005).
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13. **Takashi Imoto** : “Universal quantum computation using quantum annealing with the transverse-field Ising Hamiltonian ”

Quantum computation is a promising emerging technology, and by utilizing the principles of quantum mechanics, it is expected to achieve faster computations than classical computers for specific problems. There are two distinct architectures for quantum computation: gate-based quantum computers and quantum annealing. In gate-based quantum computation, we implement a sequence of quantum gates that manipulate qubits. This approach allows us to perform universal quantum computation, yet they pose significant experimental challenges for large-scale integration. On the other hand, with quantum annealing, the solution of the optimization problem can be obtained by preparing the ground state. Conventional quantum annealing devices with transverse-field Ising Hamiltonian, such as those manufactured by D-Wave Inc., achieving around 5000 qubits, are relatively more amenable to large-scale integration but are limited to specific computations. In this paper, we present a practical method for implementing universal quantum computation within the conventional quantum annealing architecture using the transverse-field Ising Hamiltonian. Our innovative approach relies on an adiabatic transformation of the Hamiltonian, changing from transverse fields to a ferromagnetic interaction regime, where the ground states become degenerate. Notably, our proposal is compatible with D-Wave devices, opening up possibilities for realizing large-scale gate-based quantum computers. This research bridges the gap between conventional quantum annealing and gate-based quantum computation, offering a promising path toward the development of scalable quantum computing platforms.

14. **Arthur Braida** : “Tight Lieb-Robinson Bound for approximation ratio in Quantum Annealing ”

Quantum annealing (QA) is one of the two promising frameworks for quantum computing that may end with a quantum advantage because it seems well-suited to solve combinatorial optimization problems. It stands for the analog part of the gate-based model (comparable to QAOA). The goal of quantum annealing is to let a quantum system evolve along a trajectory according to the Schrödinger equation. Comparing to QAOA, there exist few analytical results to attest the theoretical performance of QA. The main one is the adiabatic theorem which states that by allowing a runtime inversely proportional to the square of the minimum spectral gap, it ensures a constant probability of observing the optimal solution. The continuous part of QA makes the equations very difficult to manipulate.

A recent study from [1] suggests that QAOA, even in the NISQ era may bring a quantum advantage over classical algorithm for approximation in optimization problem. Several numerical studies like [2] suggests that QA performs well compared to QAOA however, numerical studies in QA are rarely convincing as the size of the instance is limited by the classical computational power to solve the Schrodinger equation or by the largest available quantum annealer. To tackle this comparison, some researchers tried to develop new mathematical tools to output an analytical value evaluating the performance of QA. As it has been widely used to benchmark metaheuristics, we choose to focus on the approximation ratio of MaxCut over cubic graph. With one layer, it is formally proven that QAOA achieves a ratio of 0.6925. In [3], the authors manage to formally prove that constant time QA achieves a ratio of 0.5933. This last result has been improved by Banks, Brown and Warburton to 0.6003. Above all, Hastings in [4] shows a simple classical local algorithm that outperforms QAOA with an approximation ratio of 0.6980. The difficulty in comparing QA to QAOA or other local algorithm is that QA is non-local by nature. However, we can still make a local analysis of it. In 1972, Lieb and Robinson showed the existence of an information speed limit inside quantum system. This means that, if the time of the evolution is short enough then two distant sites in the quantum system are correlated up to an exponentially small factor in term of the distance. This observation can be used to analyze QA as a local algorithm to foramlly compare approximation ratio value of other local algorithms.

In this work, we develop a new tighter Lieb-Robinson (LR) bound by using the commutativity graph from [5] over general regular graphs. This LR bound is adapted to QA applied to MaxCut. We also slightly modified the standard initial Hamiltonian with a free parameter in front of it. It appears that without changing the algorithm by itself, it helps to improve the tightness of the analysis. Eventually, we end up proving that a 1-local analysis of QA brings the approximation ratio above 0.7020. This value shows that constant time QA outperforms QAOA with one layer and the best known classical 1-local algorithm.

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15. **David López-núñez** : “Coherent Flux Qubits for Quantum Annealing ”

The main work presented in this talk is the initiation of an alternative path towards building coherent quantum annealers based on superconducting flux qubits. An uncoupled flux qubit device is designed to benchmark qubit coherence that will be used as the building block for future iterations of coherent quantum annealers. The Hamiltonian design of the flux qubits is focused on reducing the persistent current to reduce flux noise susceptibility. The processor is designed so that common coherence benchmarking experiments, such as T1 and T2 measurements, are performed. The physical design has been iterated to understand the role the qubit loop configurations and the qubit frequency have on the coherence times.

The flux qubits are measured inside a dilution refrigerator, where special focus is put on magnetic shielding. Spectroscopy measurements provide initial information on the qubit parameters and quality. Coherent control of flux qubits is achieved in the form of coherent Rabi oscillations, which are repeated for many flux operation points to understand the noise mechanisms. Decay times of 40us are shown, which are among the best results for flux qubits. However, the qubit coherence is low, leading to coherence times shorter than 20ns, probably because of flux noise. Moreover, due to device imperfections, the qubits could not be characterized at their optimal coherence conditions, which otherwise corresponds to the initial configuration for quantum annealing. In summary, the coherence results of the flux qubits measured represent an important benchmark in the development of a coherent quantum annealer and provide very valuable information on how to improve the flux qubits for future iterations of quantum annealing processors.

16. **Ana Palacios** : “A scalable 2-local architecture for quantum annealing of all-to-all Ising models ”

Quantum annealers are often used as application-specific devices intended to harness quantum effects to solve clas- sical optimisation tasks. This is due to the connection between the Ising model and QUBO (Quadratic Unconstrained Binary Optimisation) formulations, to which several problems of interest can be mapped. However, the hard-wiring of a fully connected graph, a general requirement for these applications, is not scalable due to crosstalk and packing issues within the chip. We present a scalable architecture to embed an all-to-all connected Ising model within another Ising model defined on a graph of degree d = 3 containing exclusively 2-local interactions. This essentially amounts to an efficient braiding of logical chains of qubits which can be derived from a description of the problem in terms of triangles, naturally linking to a family of equivalent formulations of an Ising instance [1].

In addition, we devise strategies to address the challenges of scalable architectures, such as the faster shrinking of the gap due to the larger physical Hilbert space and the scaling of penalty strengths [2, 3], in the specific context of our architecture. These strategies consist on selecting driver Hamiltonians that are more suited to the symmetries of the logical solution space, extending ideas from [4, 5]. In particular, we study the impact of ferromagnetic transverse-field Ising and ferromagnetic XYZ drivers by examining the scaling of the overlap of the ground state with the logical subspace, finding a feasible improvement of around an order of magnitude with respect to the standard transverse field driver, which relates to a mitigation of the penalty strengths required to find the logical ground state.

In summary, the hereby proposed architecture [6] opens an alternative route to scale up devices dedicated to classical optimization tasks within the quantum annealing paradigm.

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17. **Matthias Werner** : “Quantum simulation of 1D-fermionic systems with Ising Hamiltonians ”

In recent years, programmable, analogue quantum simulators have become capable of simulating quantum critical phenomena in many- body systems, including dynamical phase transitions. However, many of these quantum simulations are focussed on Ising-type Hamiltonians with transverse fields, as these are native to quantum hardware platforms like superconducting flux qubits or neutral atoms. The simulation of 1D-systems of spinless fermions, or quantum spin chains, poses a challenge to these platforms due to the lack of non-stoquastic couplings or limited control thereof.

We propose a method to simulate the time- evolution of certain spinless fermionic systems in 1D using simple Ising-type Hamiltonians with local transverse fields. Our method is based on domain-wall encoding [1], which is implemented via strong (anti-)ferromagnetic couplings |J|. We show that in the limit of strong |J|, the domain- walls behave like fermions in 1D. This approach makes the simulation of certain fermionic many- body systems accessible to contemporary analogue quantum hardware that natively implements Ising-type Hamiltonians with transverse fields. The Ising Hamiltonians are 1D chains of spins with nearest-neighbor and, optionally, next-nearest-neighbor interactions.

As a proof-of-concept, we perform numerical simulations of various fermionic systems, such as the Aubry-Andre model, using domain-wall evolution and accurately reproduce various properties, such as phase diagrams and dynamical phase transitions.

Ultimately, we discuss the feasibility of the approach to yield experimental results in the near future.

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18. **Seiya Miyamoto** : “Efficient sampling in a glassy phase using a machine-learning-assisted Markov Chain Monte Carlo Method ”

The Markov chain Monte Carlo (MCMC) method can in principle sample from arbitrary probability distributions. However, in practice, it often suffers from drastic slowing down in the dynamics and takes a very long time to obtain statistically independent samples. In physics, such situations emerge when the system is in the vicinity of a phase transition or in a glassy phase. The details of the dynamical rules in MCMC algorithms strongly control the dynamical slowing down, and, for some ferromagnetic models, highly efficient non-local algorithms can eliminate the slowing down at the critical points [1,2]. It is thus crucial to devise a better dynamical rule, even if it is ‘unphysical’, for efficient sampling.

For glassy systems with complex energy landscapes, it is challenging to find an efficient dynamical rule. While several non-local algorithms have been proposed for spin glass models [3,4], they are not efficient enough to access the equilibrium spin glass phase in large systems. Recent studies [5,6] have used machine-learning techniques to find non-local Monte Carlo moves, with promising and encouraging results. However, in computationally hard, glassy systems with a random first-order transition, they fail to approximate the equilibrium distributions, resulting in even slower dynamics than naive local algorithms [7,8].

Here, we test a machine-learning-assisted algorithm [5–7] on a mean-field model with a full-step replica-symmetry breaking transition, another class of glass transitions. We adapt the antiferromagnetic Ising model in a magnetic field on an Erd˝os–R´enyi random graph, with its ground state mapped onto the maximum independent set of the graph. We find that the algorithm accelerates decorrelation in the spin glass phase, providing a speedup of $\sim 10^4$. Our results suggest that, for the class of glassy systems, the machine-learning-assisted algorithm can efficiently approximate the global optimum. We will further discuss how the performance of the algorithm depends on the learning protocol of the machine-learning model.

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19. **Joseph Vovorsh** : “Amorphous quantum magnets in a two- dimensional Rydberg atom array ”

Amorphous solids, i.e., systems which feature well-defined short-range properties but lack long-range order, constitute an important research topic in condensed matter. While their microscopic structure is known to differ from their crystalline counterpart, there are still many open questions concerning the emergent collective behavior in amorphous materials. This is particularly the case in the quantum regime, where the numerical simulations are extremely challenging. In this talk, we instead propose to explore amorphous quantum magnets with an analog quantum simulator. To this end, we first present an algorithm to generate amorphous quantum magnets, suitable for Rydberg simulators of the Ising model. Subsequently, we use semiclassical approaches to get a preliminary insight of the physics of the model. In particular, we calculate mean-field phase diagrams, and use the linear-spin-wave theory to study localization properties and dynamical structure factors of the excitations. Finally, we outline an experimental proposal based on Rydberg atoms in programmable tweezer arrays, thus opening the road towards the study of amorphous quantum magnets in regimes difficult to simulate classically.

20. **Jonathan Pritchard** : “Demonstration of weighted graph optimisation on a Rydberg atom array using local light-shifts ”

Neutral atoms have emerged as a powerful and scalable platform for quantum computing, offering the ability to generate large numbers of identical and high quality qubits in reconfigurable arrays. By coupling atoms to highly excited Rydberg states with strong, long-range dipole-dipole interactions this system can natively implement graph problems [1] including finding the maximum independent set (MIS) on a unit disk graph [2], providing a route to performing analogue optimisation of real problems however with large systems required to reach a regime competitive against current classical optimisation protocols. To extend this approach to explore optimisation of a wider class of problems including weighted graphs and quadratic unconstrained binary optimisation (QuBO), it is necessary to introduce locally addressed light-shifts to enable weighting of nodes during the optimisation process, enabling problems to be encoded with at worst a quadratic resource overheads [3].

In this talk we present work to develop a large-scale system for quantum computing and annealing, and show preliminary results highlighting our ability to implement small-scale demonstrations of weighted graph optimisation using programmable local light-shifts across an atom array [4]. We introduce a hybrid annealing process combining global addressing with ramped light shifts, and outline prospects for scaling this approach to larger graph problems as a potential pathway to quantum utility.

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21. **Tomohiro Yamaji** : “Parametric dependence of effective local fields of Kerr parametric oscillators ”

Kerr parametric oscillators (KPOs), whose Kerr nonlinearities are larger than their photon loss rates, are interesting from the viewpoint of quantum optics and potential applications in quantum computing [1]. We are developing Josephson parametric oscillators (JPOs) operating in the KPO regime for application to quantum annealing [2]. The JPOs have two self-oscillating states with a relative phase of 0 or p, which can be utilized as a qubit. The oscillation probabilities of the two states can be controlled *in situ* by applying an input signal to the JPOs with the same frequency as the oscillation frequency (phase locking). The phase-locking signal corresponds to the local magnetic fields of an Ising Hamiltonian.

In the classical regime, where the photon loss rate is larger than the Kerr nonlinearity, a JPO can be phase-locked perfectly by applying a weak signal such that the mean photon number in the resonator is about unity [3]. While in the KPO regime, the phase locking of the JPO requires a signal stronger than the oscillation output [2]. We study parametric dependence of the phase locking in the KPO regime using an impedance-matched Josephson parametric amplifier [4]. The measured parametric dependence is consistent with the numerical calculation (Fig. 2) and can be understood by considering the steady state of JPO under phase-locking signals. We also discuss the optimization of the phase locking and quantum annealing using KPOs.

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22. **Kunal Prakash Vyas** : “Investigating scaling properties for quantum annealing to solve the Fermi-Hubbard model using the kinetic energy part as the driving Hamiltonian ”

Quantum annealing can help in finding the ground state of Hamiltonians describing many body systems. One such Hamiltonian is the Fermi-Hubbard Hamiltonian. We investigate the scaling complexity for the quantum annealing process carried out using the kinetic energy part of the Hubbard model as driving Hamiltonian for ground state calculations. The way we do this is by studying the gaps between the ground state and the 1st relevant excited state that participates in the diabatic evolution for a 1-dimensional system. The behavior of these gaps with increasing system size could hint at polynomial scaling of required annealing time for finding the ground state of the Hubbard Hamiltonian. We also try to extend this idea to a Hubbard model ladder to learn more about the scaling behavior of gaps relevant to adiabatic evolution. Further, we discuss about initial state preparation for the quantum annealing strategy under study. Information on the complexity coupled with an efficient way of preparing the initial state could bolster our hopes for using adiabatic quantum computation for solving correlated many-body Hamiltonians.

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23. **Robert Banks** : “Motivating continuous-time quantum optimisation without recourse to the adiabatic theorem ”

Continuous-time quantum algorithms for combinatorial optimisation problems have previously been motivated by the adiabatic principle. A number of continuous-time approaches have moved towards exploiting dynamics, no longer physically motivated by the adiabatic principle. In this presentation we take Planck's principle as the underlying physical motivation for these approaches. Planck's principle states that the energy of an isolated system cannot decrease as the result of a cyclic process. By applying this principle to multi-stage quantum walks, we show that the approximation ratio can only improve with each stage, motivating monotonic schedules in quantum annealing far from adiabaticity. We also show that the approximation ratio decreases in reverse quantum annealing.

24. **Nick Chancellor** : “A thermodynamic approach to optimization in complex quantum systems ”

We start by reviewing our recent published work in [1], which considers the problem of finding the energy minimum of a complex quantum Hamiltonian by employing a non-Markovian bath prepared in a low energy state. The energy minimization problem is thus turned into a thermodynamic cooling protocol in which we repeatedly put the system of interest in contact with a colder auxiliary system. By tuning the internal parameters of the bath, we show that the optimal cooling is obtained in a regime where the bath exhibits a quantum phase transition in the thermodynamic limit. This result highlights the importance of collective effects in thermodynamic devices.

We present this work as part of larger picture of optimisation far from the adiabatic limit, where transfering energy from the component of the Hamilto- nian which represents the optimisation problem of interest, as originally studied in [3]. This picture is extended by coupling to an additional system. We further present recent unpublished work which examines what happens when a bath is also annealed . Specificially we demonstrate a configuration where, in the adiabatic limit, the system can be returned to it’s ground state adiabatically even when initialised. We further argue that even far from the adibatic limit, the system can be made compatible with the energy redistribution arguments of [3]. Based on these arguments it is likely that fine tuning is not needed to im- prove algorithmic performance. Furthermore, we show that all the requirements we have here are realistic to implement in an experimental setting, specifically focusing on a superconducting flux-qubit annealer as an example.

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25. **Gregor Humar** : “Implementing a cooling protocol on a programmable quantum annealer ”

Finding low energy states is an important problem for quantum computers not only for preparing states for quantum simulations [1] but also solving optimization problems [2]. These can be mapped to spin models with the ground state representing the solution [3]. We present an implementation of a cooling protocol based on the theoretical proposal [4] on a D-Wave quantum annealer. The process is similar to how cooling is achieved in magnetic refrigeration, where a material in contact with a heat bath in a strong external magnetic field is first decoupled from the bath before removing the field which cools the material below the original temperature. The protocol consists of coupling qubits representing the problem we want to solve to ancillary qubits representing a spin bath. Starting in the fully polarized state, these bath qubits are subjected to an external field, which is ramped down during a cycle of the protocol. Each cycle is ended by a measurement of the system and bath qubits and only the system state is kept for the next cycle, removing the energy that the bath extracted from the system. The protocol is implemented by using annealing offsets to realize different values of fields in the system and in the bath qubits. Reverse annealing is used to set the initial state of the system at the beginning of each cycle. By transferring energy from one subset of qubits to another on the quantum annealing processor, this protocol has the potential to prepare better low energy states than other procedures, which are limited by a finite temperature of the processor. Results of the implementation are presented for the transverse field Ising model system implemented on the D-Wave device and compared to quantum annealing.

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26. **Shuta Kikuchi** : “Evaluation and analysis of hybrid method using quantum annealing machine and non-quantum type Ising machine ”

Quantum annealing (QA) machines are expected as fast and precision solvers for combinatorial optimization problems. To improve the performance of QA machines, a hybrid optimization method combined with a QA machine and a simulated-annealing-based Ising machine (non-quantum type Ising machine) was proposed [1]. The hybrid method is implemented in the following steps. First, the multiple solutions are obtained by non-quantum type Ising machine. Next, the problem variables that consistently have the same value across multiple solutions are fixed. Then, a QA machine solves the problem-size-reduced sub-Ising model by fixing variables. The steps are iterated until the solution is stable. In the previous study, the hybrid method outperformed the QA machine alone [1].

In this study, we evaluated the performance of the hybrid method for large-scale problems that cannot be input into the QA machine. Simulations were conducted using simulated annealing (SA) implemented by the Markov chain Monte Carlo method as a non- quantum type Ising machine, and a D-Wave Advantage as a QA machine. Sub-Ising models were reduced to the size that can be input into the QA machine. The results revealed that, even for large-scale problems, the hybrid method indicates higher solution accuracy than the preprocessing SA alone. Furthermore, it was found that the performance of the hybrid method is dependent on the sub-Ising model size.

Therefore, to investigate the reason for sub-Ising model size dependency, we analyzed through simulations using SA and QA, which were implemented by the master equation and the Schrödinger equation, respectively. The results suggested that the sub-Ising model size dependency is attributed to both the sub-Ising model creation method and the solution accuracy of the QA machines.

[1] Shuta Kikuchi, Nozomu Togawa, and Shu Tanaka, "Hybrid Optimization Method Using Simulated-Annealing-Based Ising Machine and Quantum Annealer," Journal of the Physical Society of Japan, vol. 92, 12 (2023): 124002.

27. **Asa Hopkins** : “Finding Spin Glass Ground States Using Multi- stage Quantum Walks ”

Previous work [1] has shown the advantages of quantum walks compared to other methods for finding spin glass ground states. In principal, such walks can be implemented on currently existing annealing hardware. In this work, multiple quantum walks are chained together without measurement to produce a multi-stage quantum walk, which paired with a heuristic for choosing parameters shows improved scaling compared to single stage walks. Additionally, the scaling exponent appears to scale as a polynomial in the number of stages, leading to an overall algorithm that has polynomial running time.

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28. **Lasse Gerblich** : “Advantage of multi-stage quantum walks over QAOA as approximations of quantum annealing ”

Methods to find the solution state for optimization problems encoded into Ising Hamiltonians are a very active area of current research. We compare the quantum approximate optimization algorithm (QAOA) with multi-stage quantum walks (MSQW). Both are types of variational quantum algorithms, where the control parameters usually need to be optimized classically.

Control theory has been used to show that QAOA corresponds to an optimal protocol for solving optimization problems although they are still outperformed by quantum annealing. Indeed, their effectiveness in solving such problems is derived from the fact that they approximate the annealing schedule.

We employ a similar argument to show that a multistage quantum walk also corresponds to an optimal protocol for optimization problems. Furthermore, we show analytically that we would expect MSQW to outperform QAOA with a large number of stages and an optimal choice of the control parameters for both protocols by comparing how well they approximate a given annealing schedule.

We also show numerically for random-spin glass ground state problems, which are a good toy model for realistic optimization problems, that we would expect MSQW to outperform QAOA already for a small number of stages. Furthermore, we show that the success probability of finding the ground state with a QAOA protocol is very sensitive to the choice of control parameters. This will quickly make them impractical as we increase the number of stages, since more parameters need to be determined more precisely to ensure the effectiveness of QAOA.

Quantum walks on the other hand do not suffer from this problem. The dependence on the control parameters is a lot smoother. Therefore, choosing “pretty good” heuristic values for them will already provide decent results. Furthermore, energetic considerations can also guide us to choose sensible parameters during the evolution, thus further decreasing the need for powerful classical optimization.

29. **Yusuke Sugita** : “Parameter-range setting of annealing optimization based on local optimal solutions ”

To realize high-speed and energy-efficient calculations for solving combinatorial optimization problems, the physics-inspired optimization hardware and algorithms have been actively studied. The Ising machine is a dedicated system for efficiently solving the ground-state search problem of the Ising model [1]. As the operation mechanism of the Ising machine, a typical one is the annealing method such as simulated annealing (SA) [2] and simulated quantum annealing (SQA) [3]. In the method, the annealing parameters control disturbances for variable updates in the optimization process. The appropriate annealing parameters depend on the problems to be solved and thus an efficient estimation method of the parameters is highly desired for the rapid application of the Ising machine to various real problems.

Here we investigate a method to estimate the appropriate annealing-parameter range from the probability distribution functions that variables follow. In the method, first, local optimal solutions are obtained by a local search [Figure (a)]. Second, the maximum and minimum values of the annealing parameters are estimated so that the variables move from the local optimum solutions at the maximum value and stay in the local optimum solutions at the minimum value [Figure (b)]. In the estimation, the standard deviation of the probability distribution function is referred to as an indicator of the movement for each variable. Finally, the main annealing optimization is performed with the determined parameters [Figure (c)]. Due to the second procedure, the appropriate annealing-parameter range is automatically adjusted according to the model coefficients of the target Ising model. In the presentation, we will show the benchmark results of the method for SA, SQA, and an extended SA method using continuous relaxation for variables [4].

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30. **Takuya Okuyama** : “Relaxed Momentum Annealing Theory and Applications ”

The effort to solve NP-hard problems spans various fields, including social network analysis, circuit design, and ma- chine learning, challenging the quest for accurate and efficient solutions [1–3]. The complexity of these problems often surpasses the capabilities of conventional computational strategies. Within this context, the Ising model emerges as a promising approach for combinatorial optimization. It describes systems of binary spins $s_i \in \{-1, 1\}$ interconnected through couplings J_{ij} and influenced by local fields h_i.

It has been proven that determining the ground state of Ising models is equivalent to solving combinatorial optimization problems [4]. This method has promoted the use of quantum annealing and other algorithms to overcome traditional algorithmic barriers in nonconvex optimization tasks [5–9]. We have introduced CMOS Annealing as an optimization technique that leverages extensive parallel computations in digital circuits [7]. A vital implementation of this technique, Momentum Annealing (MA), enables the simultaneous and independent update of all spins in a fully connected Ising model. MA is capable of approximating the ground state of Ising models with up to 100,000 variables and achieves a speedup of 250 times compared to conventional simulated annealing [10].

The challenge of integrating both binary and continuous variables into optimization methods, such as annealing methods, is substantial. In our presentation, we introduce an annealing approach designed to tackle a specific minimization problem, which includes finding the ground state of the Ising model as a special case:

$$\min H(s). \ (2) \ s_i \in D_i$$

Here, D_i defines the domain for each variable, which could be either $\{-1,1\}$ for binary variables or $[-1,1]$ for continuous ones. To enable simultaneous spin updates in the fully connected model facilitated by MA, we incorporate auxiliary vectors x and y. The solution to the initial problem is derived from the average of the solutions for x and y. This novel formulation avoids direct interactions between x components, allowing for probabilistic and independent element updates. The same principle is applied to y. Consequently, regardless of the sparsity of J, this new problem structure permits probabilistic updates of all variables in two phases, reflecting the MA method. In this presentation, we will further discuss the practical application outcomes of this algorithm, termed relaxed MA.

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31. **Tatsuhiko Shirai** : “Compressed space engineering for constrained combinatorial optimization ”

Combinatorial optimization has attracted much attention as a promising candidate to achieve quantum speedup. Constraints of a combinatorial optimization problem separate the solution space into feasible solution space with low energies and infeasible solution space with high energies. Recent studies have demonstrated the effectiveness of tailoring mixer terms for exploring lower-energy solutions within the feasible solution space [1]. However, finding appropriate mixer terms is generally challenging except for a specific class of constraints such as one-hot constraint. To address the issue of restricted applicability, we develop a method to engineer a compressed space. The compressed space expresses the feasible solution space with a smaller number of qubits than the original solution space. Since the portion of feasible solutions in the compressed space is large, searching for lower-energy solutions is easier. We develop a scalable variational method to determine the unitary transformation between the compressed space and the original solution space on gate-based quantum computers. Then we propose compressed Quantum Approximate Optimization Algorithm (compressed QAOA) that searches for the (near)-optimal solutions of a combinatorial optimization problem within the engineered compressed space. The figure below shows the simulation result of applying compressed QAOA to quadratic knapsack problems (QKP) with an inequality constraint. Compressed QAOA outperforms conventional QAOA. This work provides a new framework to solve various types of constrained combinatorial optimization problems.

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32. **Mayumi Nakano** : “Building a Model Learning Method by Reducing the Number of Training Data for Factorization Machine with Annealing ”

Ising machines are a promising method for searching for good solutions to combinational optimization problems. When solving a combinational optimization problem with an Ising machine, the objective function and the constraints must be expressed by the Ising model or, equivalently, by the Unconstrained Binary Optimization (QUBO). However, some combinatorial optimization problems, including black-box optimization problems, cannot be expressed in the QUBO form.

Factorization Machine with Annealing (FMA) has been proposed as a black-box optimization method, which uses machine learning and an Ising machine iteratively [1]. The process of FMA is divided into two parts: learning and optimization. In the learning process, a machine learning model called Factorization Machine (FM) learns the input-output relationship of an objective function and expresses the objective function in the QUBO form. In the optimization process, an Ising machine searches for a minimum point of the QUBO constructed in the learning process. The searched pairs of the minimum point and the value of the objective function for the point are added to the training dataset used in the learning process. These two processes are iterated, and the best minimum point is returned as a solution to the black-box optimization problem.

When solving constrained black-box optimization problems with FMA, it becomes difficult to generate feasible solutions, which satisfy the constraints. To generate feasible solutions more frequently, we proposed a new model learning method for FM. In our method, the training dataset used in the learning process is always filled with a certain number of the latest training data. That means that, as the FMA iterations proceed, the old training data are removed from the training dataset. In our study, we chose the traveling salesman problem as the target black-box optimization problem. We showed that by selecting the appropriate number of the latest training data, the proposed model learning method can generate feasible solutions more frequently than the conventional FMA.

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33. **Mārtiņš Kālis** : “A hybrid quantum-classical approach for inference on restricted Boltzmann machines ”

Boltzmann machine is a powerful machine learning model with many real-world applications, for example by constructing deep belief networks. Statistical inference on a Boltzmann machine can be carried out by sam- pling from its posterior distribution. However, uniform sampling from such a model is not trivial due to an extremely multi-modal distribution. Quantum computers have the promise of solving some non-trivial prob- lems in an efficient manner. We explored the application of a D-Wave quantum annealer to generate samples from a restricted Boltzmann ma- chine. The samples are further improved by Markov chains in a hybrid quantum-classical setup. We demonstrated that quantum annealer sam- ples can improve the performance of Gibbs sampling compared to random initialization. The hybrid setup is considerably more efficient than a pure classical sampling. We also investigated the impact of annealing parame- ters (temperature) to improve the quality of samples. By increasing the amount of classical processing (Gibbs updates) the benefit of quantum annealing vanishes, which may be justified by the limited performance of today’s quantum computers compared to classical.

34. **Renichiro Haba** : “Diverse solutions via quantum annealing leads to the discovery of diverse material compositions ”

Finding optimal solutions among a vast number of choices is a critical frontier in disciplines from materials science to computational science. Recently, quantum annealing (QA) has emerged as a promising metaheuristic optimization technique, leveraging quantum mechanics’ unique properties since D-Wave Systems debuted the first commercial device in 2011. A common use of quantum annealing is to solve combinatorial optimization problems, aiming to identify states that minimize a specific objective function. Nonetheless, recent research has revealed another benefit of QA: its superior ability in diverse sampling [1]. Materials exploration is one of the areas where quantum annealing is expected to be applied. In the material industry, in order to develop high performance materials, it is necessary to find the optimal composition from enormous candidates consisting of a wide variety of ingredient combinations. Although data science technologies like machine learning offer high-quality predictions of physical properties on uncharted material candidates, finding optimal compositions based on these predictions and certain constraints remains a daunting task in material informatics.

In this study, we introduce a method to identify components with ideal predictive properties using black-box optimization combined with QA machine [2]. Our experimental results indi- cate that the proposed method outperforms random sampling in search efficiency as shown in Fig. 1a. Moreover, we observed that the D-Wave QA machine yielded the highest number of composite solutions as illustrated in Fig. 1b. We found that the diversity of samples produced by QA in each step of black-box optimization surpasses that of traditional computational meth- ods, such as simulated annealing or exact optimization and this diversity positively influences the enumeration of solutions. Our research uncovers new potential uses of QA in materials chemistry and marks the first instance where sampling diversity is applied practically.

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35. **Dario De Santis** : “Optimized QUBO formulation methods for quantum computing ”

In recent years, many efforts have been devoted to understand to what extent modern noisy intermediate-scale quantum (NISQ) devices can help to solve optimization problems of any sort. Particular attention has been paid to their potential to solve NP- hard and NP-complete problems, which most of the times can be formulated as quadratic unconstrained binary optimizations (QUBO). For instance, all famous NP Karp’s problems [1] can be casted in this form [2]. The possibility to solve QUBO problems with quantum annealers has been explored widely. Although this technology is not expected to solve NP problems efficiently, namely providing exponential speed-ups compared to classical strategies, possible polynomial in-time advantages attract great interest. Indeed, given the importance of the real-world applications involved with the solutions of these hard combinatorial problems, any achievable improvement is well-received. Some examples of these scenarios come from finance, logistics and drug discovery.

Consider the situation where we aim to solve a generic constrained optimization problem with a QUBO solver. The first essential step is to reformulate it in this quadratic unconstrained form. We call *logical variables* those defining the initial problem. The constraints attached to the original problem can be enforced in a QUBO form by employing additional *slack variables*. The larger is the total number of variables, logical and slack, considered in a QUBO problem, the harder is to solve it.

Whereas the well-established procedures to translate optimization problems as QUBOs [3] can be efficient in several scenarios, their implementation can be extremely inefficient at times. We say that a method to obtain these formulations is inefficient for a problem whenever it requires too many slack variables, namely their number is comparable with that of logical variables. In these cases, the practical usefulness of QUBO solvers can be highly limited. For instance, if we have a maximum size for the problems that our solver can receive, any reduction of slack variables allows to increase the total number of logical variables associated to the initial problem, namely larger problems can be tackled. Moreover, the more slack variables we implement, the higher is the connectivity that we require in our QUBO and therefore in the QUBO solver that we aim to use. This consequence can be a very limiting factor for the performances of modern NISQ devices.

The main motivation of this work is to unlock the possibility to solve certain classes of optimization problems with quantum annealing. For this purpose, we introduce the iterative quadratic polynomial and master-satellite methods. Whereas the goal of both methods is to provide QUBO forms requiring a minimal employment of slack variables, the former consists in a new paradigm to translate problem constraints into corresponding quadratic penalty forms and the latter allows the simultaneous enforcement of different constraints sharing the same restricted set of binary variables. Noteworthy, non-linear equality and inequality constraints can be treated using the same techniques, without the need to employ slack variables solely to obtain corresponding linearizations. Hence, the same computational effort is required both for linear and non-linear constraints, where no approximate enforcing of the constraints is required.

We follow by approaching an NP-hard problem coming from finance, namely the Max-Profit Balance Settlement prob- lem [4], and we show how to apply our techniques for this optimization problem. In particular, we obtain a drastic reduction of the slack variable necessary to enforce the corresponding inequality constraint. We generate several instances of this problem reflecting some main features of realistic datasets and we show that our methods provide the corresponding QUBO forms by employing around 90% less slack variables, if compared with the QUBO forms obtainable with a standard procedure.

We solve several instances of this optimization problem with two different quantum annealers manufactured by D-Wave Systems, Inc., namely the D-wave Advantage_system4.1 and Advantage2_prototype1.1, which are designed specifically to solve QUBO problems. The annealer Advantage2_prototype1.1, being a prototype of the next-generation D-wave annealers, has a reduced number of qubits but is characterized by higher connectivity and lower noise. Hence, not only do we compare the outputs obtained when the QUBO problems are generated with different approaches, but we also provide a comparison between the performances of these annealers. We show that, while by using the standard approach the solution quality drops quite fast with the input size, our methods unlock the possibility to consider much larger instances. Indeed, the number of successes that we obtain when the QUBO reformulations are generated with our methods are always significantly more: the multiplicative factor between the successes obtainable with the two methods ranges from 7 (smallest instances with Advantage_system4.1) to 184 (largest instances with Advantage2_prototype1.1).

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36. **Omer Rathore** : “Load balancing for high performance computing using quantum annealing ”

With the advent of exascale computing, effective load balancing in massively parallel software applications is critically important for leveraging the full potential of high performance computing systems. Load balancing is the distribution of computational work between available processors. Here, we present findings from our recent work [1] on the application of quantum annealing to load balance two paradigmatic algorithms in high performance computing. Namely, adaptive mesh refinement (AMR) and smoothed particle hydrodynamics (SPH) are chosen as quintessential examples of grid and off-grid based algorithms for computational fluid dynamics.

AMR dynamically adjusts the computational grid to enhance resolution precisely where needed in real time, optimizing the allocation of grid resources for complex simulations. SPH, on the other hand, eschews the traditional grid framework altogether, instead simulating fluid dynamics through the interactions of particles that move according to the governing conservation laws. These methodologies underscore the versatility of algorithms used in fluid dynamics sim- ulations, each boasting unique advantages. However, due to differences in the underlying data structures, they also present distinct challenges when evenly distributing computational tasks between processors to maximize global efficiency.

Furthermore, our selection of applications is motivated by an appreciation of the evolving high performance computing landscape, particularly the shift towards heterogeneous computing architectures. This paradigm integrates diverse computing resources, including both classical and quantum processors, to tackle computational challenges more efficiently. We discuss how the strategic importance of applications like load balancing becomes evident in this context, as they stand to greatly benefit from such synergistic systems.

While the methodology for obtaining real simulation data to partition is application specific, the proposed balancing protocol itself remains completely general. In a grid based context, quantum annealing is found to outperform classical methods such as the round robin protocol and can potentially remain competitive with more advanced methods such as steepest descent or simulated annealing. For the more complex particle formulation, approached as a multi-objective optimization, quantum annealing solutions are demonstrably Pareto dominant to state of the art classical methods across both objectives. This signals a noteworthy advancement in solution quality which can have a large impact on effective CPU usage.

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37. **Puya Mirkarimi** : “Quantum optimization with linear Ising penalties for customer data science ”

Combinatorial optimization problems that arise in industry are often highly constrained. The standard approach to encoding constraints in quantum optimization is the quadratic penalty method. Quadratic penalties introduce additional couplings and energy scales to a problem’s objective function, which can be detrimental to the performance of a quantum optimizer, especially on near-term quantum devices with sparse interaction graphs. We explore an alternative penalty method involving only linear Ising terms, thereby avoiding some of the drawbacks of the quadratic penalty method, and we apply it to a problem in customer data science. In experiments performed on a D-Wave advantage quantum annealer, we find indications that the linear Ising penalty method can result in improved performance compared to the quadratic method. This is complemented by promising results obtained in simulations of quantum annealing and the quantum approximate optimization algorithm with closed-system dynamics. The presented work is based on Refs. [1, 2].

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38. **Narendra Hegade** : “Digitized Counterdiabatic Quantum Computing ”

I will introduce digitized counterdiabatic quantum computing (DCQC) as a novel paradigm for compressing digital quantum algorithms. It consists of a suitable digitization of the accelerated counterdiabatic dynamics of an adiabatic quantum computation, which encodes the chosen industry use case [1]. I will exemplify DCQC to the class of optimization problems: digitized counterdiabatic quantum optimization (DCQO) [2, 3]. In particular, I will present an advanced method called bias-field digitized counterdiabatic quantum optimization (bf-DCQO) for tackling combinatorial optimization problems on a digital quantum computer.

Along with the selected counterdiabatic (CD) terms in the adiabatic Hamiltonian, we introduce additional bias terms obtained either through classical methods, quantum annealers, or with iterations of DCQO itself. This combination of CD protocols and bias fields offers a way to address large-scale combinatorial optimization problems on current quantum computers with limited coherence time. By examining an all-to-all connected general Ising spin-glass problem, we observe a polynomial scaling enhancement in the time to solution compared to both DCQO and finite-time adiabatic quantum optimization. Moreover, the proposed method is purely quantum, eliminating the need for any classical optimization schemes. In this manner, we overcome the trainability drawbacks faced by variational quantum optimization algorithms.

Additionally, bf-DCQO significantly outperforms the quantum approximate optimization algorithm (QAOA) in terms of success probability and approximation ratio. Finally, I will present the experimental results of the proposed method on a trapped-ion quantum computer, tackling a fully connected spin-glass problem with 33 qubits and a maximum weighted independent set problem with 36 qubits. This represents the realization of the largest quantum computing problem of this nature, solved on a gate-based quantum computer by using a pure quantum algorithmic approach.

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