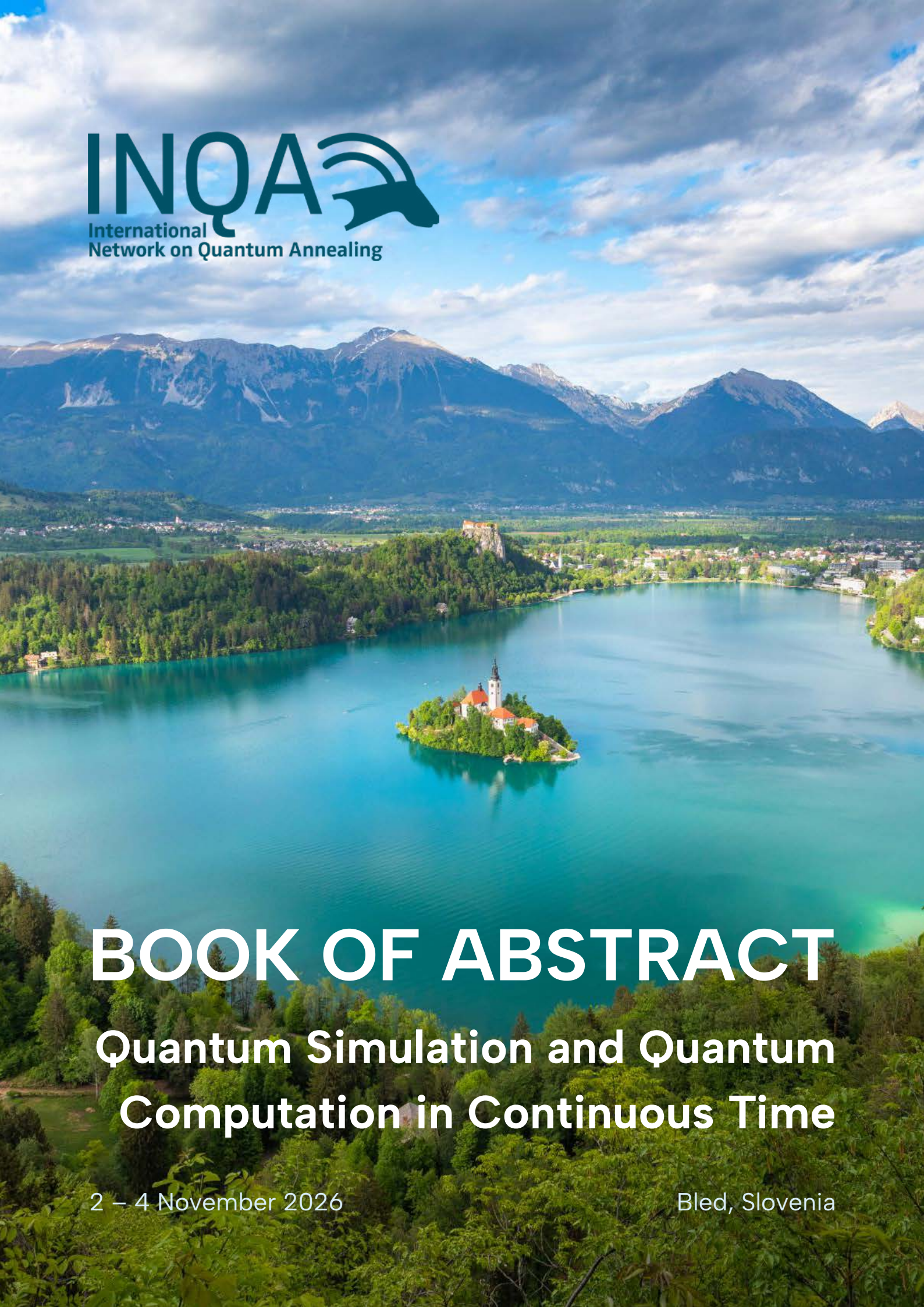




BOOK OF ABSTRACT

Quantum Simulation and Quantum Computation in Continuous Time

2 – 4 November 2026

Bled, Slovenia

BOOK OF ABSTRACTS

Quantum Simulation and Quantum Computation in Continuous Time

2 – 4 November 2026

Bled, Slovenia

Webpage: <https://inqa.ijs.si/>
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Content

Content.....	3
Program.....	4
Monday, 2 November	4
Tuesday, 3 November.....	5
Wednesday, 4 November.....	6
List of posters	7
Invited talks	9
Contributed talks.....	19
Posters	45
List of Participants	64

Program

Monday, 2 November

08:30–09:00	Registration and coffee		
09:00–09:15	Welcome and conference opening		
Annealing dynamics and nonequilibrium control			Session chair: Paul Warburton
09:15–10:00	<i>Madita Willsch</i>	INVITED TALK: Fast Coherent Evolution and Quasistatic Regimes: Benchmarking Quantum Annealing with Domain Wall Systems	10
10:00–10:25	<i>Takuya Hatomura</i>	Enhancing the performance of quantum annealing with weighted variational counterdiabatic driving	20
10:25–10:50	<i>Gregor Humar</i>	Resonant false vacuum decay in two dimensions on a 4000-qubit quantum annealer	21
10:50–11:15	Coffee break		
Hardware-aware control and annealing protocols			Session chair: Janez Povh
11:15–12:00	<i>Mikhail Feigel'man</i>	INVITED TALK: Hilbert space signatures of non-ergodic glassy dynamics	11
12:00–12:25	<i>Gonzalo Troncoso</i>	Adiabatic control of a fluxonium in a Landau-Zener experiment	22
12:25–12:50	<i>Matthias Werner</i>	Faster optimization and universal quantum computation by designing annealing schedules	23
12:50–14:10	Lunch		
D-Wave quantum simulation and interaction engineering			Session chair: Jaka Vodeb
14:10–14:35	<i>Ajmeri Amreen Chowdhury</i>	Using domain walls to benchmark fast quantum anneals	24
14:35–15:00	<i>Natasha Feinstein</i>	Effective XX-interactions for enhanced quantum annealing in the transverse-field Ising-model	25
15:00–15:25	Break		
15:25–16:10	<i>Rahul Deshpande</i>	The INQA D-Wave Lecture 2026 – Quantum Simulation on Quantum Annealers Beyond Quench Dynamics	12
16:10–16:35	<i>Daniil Teplitskiy</i>	Simulation of a Z2 lattice gauge theory on a D-Wave QPU	26
16:35–17:00	<i>Emanuele Mendicelli</i>	Towards Hadron Spectroscopy and Dynamics with Quantum Annealers	27
17:00–17:15	Break / workshop transition		
17:15–18:15	<i>Chris Rich</i>	Hands-on Workshop with D-Wave Quantum Computers – registration required; max. 50 participants	
Evening	Free evening / informal networking		

Tuesday, 3 November

Optimization formulations, constraints and hardware-aware design			
Session chair: Mikhail Feigel'man			
09:00–09:45	Tomohiro Hattori	INVITED TALK: Design Strategies toward Hardware-Friendly Quantum Optimization	13
09:45–10:10	Roman Kuzel	Encoding Matters More Than the Solver: Penalty Coefficients in QUBO Formulations for Quantum Annealing	28
10:10–10:35	Daniel Warkentin	Optimized cardinality constraints for quantum annealing	29
10:35–11:00	Coffee break		
Quantum resources, QAOA and the quantum-classical boundary			
Session chair: Alessandro Zenesini			
11:00–11:45	Gianluca Passarelli	Do Quantum Resources Matter for Quantum Optimization?	14
11:45–12:10	David Headley	Understanding the Role of Quantum Weirdness in Solving Hard Optimization Problems	30
12:10–12:35	Syed Muhammad Ali Hassan	Imaginary as a necessary resource for trainability in QAOA	31
12:35–15:00	Lunch + Poster Session — all posters presented simultaneously		
Benchmarking and applications of quantum optimization		Session chair: Madita Willsch	
15:00–15:45	Jakub Pawłowski	INVITED TALK: Closing the Quantum-Classical Scaling Gap in Approximate Optimization	15
15:45–16:10	Mátyás Koniorczyk	QUBO benchmarks from mixed Hamming packing problems	32
16:10–16:35	Taiga Hayashi	Improving Ising-Machine-Assisted Black-Box Optimization with Field-Weighted Surrogate Models	33
16:35–17:00	Break		
17:00–17:25	Robert Banks	Quantum Optimisation for Protein-Protein Interaction Network Alignment	34
17:25–17:50	Shuta Kikuchi	Effects of Variable Representation on Factorization Machine with Quadratic-Optimization Annealing for RNA Inverse Folding Problem	35
19:30–22:30	INQA Conference Dinner		

Wednesday, 4 November

Analogue quantum simulation and many-body dynamics			Session chair: Christopher Baldwin
09:00–09:45	<i>Alessandro Zenesini</i>	INVITED TALK: False and Hot Bubbles in Ferromagnetic Superfluids	16
09:45–10:10	<i>Andrea Babilio Rava</i>	Confinement Dynamics under Hardware-Induced Inhomogeneity in a Programmable Rydberg Atom Chain	36
10:10–10:35	<i>Andras Grabarits</i>	Universal dynamics of quantum phase transitions with fractional long-range interactions	37
10:35–11:00	Coffee break		
Hamiltonian methods and analogue quantum computation			Session chair: Gianluca Passarelli
11:00–11:45	<i>Jordi Riu Vicente</i>	INVITED TALK: Reshaping quantum annealing landscapes with diagonal catalysts	17
11:45–12:10	<i>Ana Palacios</i>	Closest Accessible Symmetry reduction: a tool for Hamiltonian interpolation analysis	38
12:10–12:35	<i>Arthur Braida</i>	Hamiltonian eigenvalue transformation with Local Gadget	39
12:35–14:15	Lunch		
Advanced annealing architectures, encodings and quantum applications			Session chair: Rahul Deshpande
14:15–15:00	<i>Christopher Baldwin</i>	INVITED TALK: The robustness of adiabatic reverse annealing	18
15:00–15:25	<i>Shunta Ide</i>	Effective XY Interactions and Ground-State Sampling in Penalty-Based Quantum Annealing	40
15:25–15:50	<i>Yuya Seki</i>	Adiabatic quantum computation in bosonic systems for combinatorial optimization via polyhedral domain partition	41
15:50–16:15	Coffee break		
16:15–16:40	<i>Boni Paul</i>	Applications of quantum annealing to magnetic dipole hyperfine structure constants: First results beyond energies for atoms	42
16:40–17:05	<i>Emanuele Costa</i>	Simulating DOCI Nuclear Hamiltonians with Ising Systems	43
17:05–17:15	Closing remarks		

List of posters

Tuesday, 3 November, 12:35–15:00

		Page
<i>Kehinde Ogundipe</i>	Toward a Qubit-Based Simulation of Continuous-Time Soliton Dynamics and Resonant Kink–Meson Scattering	46
<i>Hilbert Johan Kappen</i>	A Bayesian formulation of hybrid quantum–classical dynamics	47
<i>Konosuke Okisawa</i>	Exact Solution of Multi-Car Paint Shop Problem	48
<i>Eiji Kawase</i>	Effect of Integer-to-Binary Encoding on the Performance of Factorization Machine with Quadratic-Optimization Annealing for Constrained Engineering Optimization	49
<i>César Fernández Lamas</i>	Gadget Hamiltonians for an Implementation of Kitaev’s History-State Hamiltonian	50
<i>Takuma Yoshihara</i>	QUBO-Based Generation of LF Auxiliary Material Addition Candidates Using Transformer Prediction and Quantum Annealing	51
<i>Nicholas Chancellor</i>	Aircraft Loading Quantum Annealing Dataset	52
<i>Charles Zhou</i>	Quantum Evolution and Collaborative Self-Organizing Agents	53
<i>Kazuki Abe</i>	Correlation-Based Spin-Pair Merging for Quantum Annealing with Global Spin-Flip Symmetry	54
<i>Jemma Bennett</i>	A local-field belief propagation decoder for the LHZ parity embedding	55
<i>Yosuke Mukasa</i>	Robust Factorization-Machine Training for FMQA under Noisy Evaluations	56
<i>Beno Zupanc</i>	QBIQ: An Exact Hybrid Branch-and-Bound Solver for Binary Quadratic Optimization	57
<i>Duc-Truyen Le</i>	A Quantum Algorithm for the Quantum Mpemba Effect: Application to the Lattice Schwinger Model	58
<i>Haruya Kato</i>	Jaikumar Assignment Linearization with Interaction Terms for the CVRP with Loading Incompatibilities: A QUBO Formulation and Its Evaluation	59
<i>Pablo Pérez Fernández</i>	Topological edge states in a single flux qubit	60
<i>Hiroto Toyoshima</i>	Construction of an Outlier Removal Algorithm Using Black-Box Optimization with Quantum Annealing	61
<i>Gurpahul Singh</i>	Principles of Constrained Quantum Optimization	62

Invited talks

Fast Coherent Evolution and Quasistatic Regimes: Benchmarking Quantum Annealing with Domain Wall Systems

M. Willsch^{1,2}, G. C. Santra¹, D. Willsch^{1,3}, S. Morales¹, L. Mauth^{1,4},
V. Mehta¹, F. Jin¹, K. Michielsen^{1,2,4}

¹Jülich Supercomputing Centre, Forschungszentrum Jülich, 52425 Jülich, Germany

²AIDAS, 52425 Jülich, Germany

³FH Aachen University of Applied Sciences, 52066 Aachen, Germany

⁴Faculty of Mathematics and Natural Sciences, University of Cologne, 50923 Köln, Germany

We consider quantum annealing in two distinct models that both have ground states with a single domain wall.

The first system has linear connectivity and a degenerate ground state [1]. It allows for a clear distinction between a distribution obtained from coherent evolution and a quasistatic Boltzmann distribution.

The second system has almost all-to-all connectivity but the ground state can be proven to have a single domain wall [2]. Moreover, the model has a mean-field character with very unconventional oscillatory gap behavior, which defies standard scaling arguments in conventional quantum annealing. This feature makes this model particularly interesting for benchmarking as already small and medium-sized instances can have very small gaps and thus be difficult for quantum annealing.

Taking into account different noise sources and embedding consequences, we are able to relate experimental results from D-Wave QPUs in the fast quantum annealing regime with results from numerical simulations of coherent time evolution. In contrast, data from the slow quantum annealing regime is well compatible with a Boltzmann model including errors.

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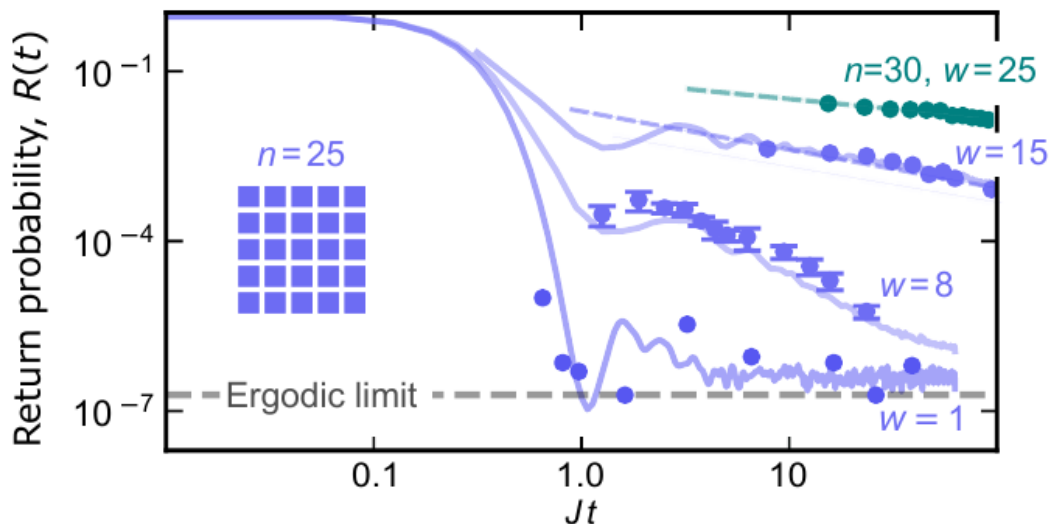
Hilbert space signatures of non-ergodic glassy dynamics

M. V. Feigel'man^{1,2}, Google Quantum AI and collaborators

¹CENN Nanocenter, Ljubljana, Slovenia

²Institute Jozef Stefan, Ljubljana, Slovenia

The dynamics of interacting quantum particles in disordered landscapes is a central problem in non-equilibrium physics. Theoretical and numerical approaches are severely limited by exponential Hilbert space scaling and the absence of translational symmetry. Here, we leverage the high data rates of a continuous-time superconducting quantum processor to efficiently sample Hilbert space configurations for 2D array of artificial spins $\frac{1}{2}$ with XY exchange and random fields along Z axis. Using a grid of up to 70 qubits, we measure the return probability $R(t)$ across a broad range of disorder strengths and for energies close to the middle of the band (infinite-temperature limit). At long times, $R(t)$ develops a heavy-tailed distribution, while its typical value follows a power-law scaling—both suggestive of non-ergodic glass-like dynamics. Furthermore, the probability distribution of z -configurations evolves from a Porter–Thomas form at low disorder to a power-law—spanning eight orders of magnitude—at higher disorder strengths. We cluster the wavefunctions on the basis of Hamming distance in Hilbert space, identifying three distinct regimes as a function of disorder strength. By directly probing Hilbert space dynamics, we provide a complementary perspective to the existing real-space picture of two-dimensional quantum systems, demonstrating the potential of current quantum processors to yield deeper insights into non-equilibrium physics [1]



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Quantum Simulation on Quantum Annealers Beyond Quench Dynamics

R. Deshpande¹

¹*D-Wave Quantum Inc.*

Quantum annealers have established themselves as platforms for quantum simulation with thousands of qubits, particularly in studies of quantum quench dynamics and critical phenomena. In this talk, I will show how an analog-digital mode of operation [1] extends these capabilities to a broader class of quantum dynamics. I will present experimental results demonstrating coherent and many-body effects, including quantum walks, localization in disordered systems and topological phenomena. These results position quantum annealers as a flexible, accessible, and large-scale platform for simulating nontrivial quantum dynamics.

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Design Strategies toward Hardware-Friendly Quantum Optimization

Tomohiro Hattori¹¹ Graduate School of Science and Technology, Keio University

Quantum optimization is a promising approach to solving combinatorial optimization problems by exploiting the dynamics of quantum systems. However, quantum optimization on physical hardware is subject to resource limitations and hardware constraints, such as limited numbers of qubits, restricted Hamiltonian controls, finite parameter ranges, control errors, and limited execution times. Effective use of these devices therefore requires algorithm design that explicitly accounts for available computational and physical resources. In this talk, I will present two directions for designing quantum optimization methods under such limitations.

The first concerns Hamiltonian design. I will discuss spin fixing as a strategy for reducing the number of variables required to represent an optimization problem, as well as quantum annealing correction based on redundant encoding. These approaches represent contrasting uses of quantum resources: reducing the number of spins when resources are scarce and introducing redundancy when additional spins can improve robustness and performance. Our results show that spin fixing can improve QA performance by increasing the minimum energy gap^{1,2}. In contrast, frustrated QAC can enhance performance by allowing the correct solution to be decoded not only from the ground state but also from excited states³. These approaches provide two guidelines for using qubits effectively through distinct physical mechanisms.

The second direction concerns schedule design. Control theory provides a systematic approach to schedule design. Although these methods are known to improve the performance, they often do not fully account for the computational cost of determining the schedule or the constraints on the controls available in quantum hardware. First, I discuss the control of quantum dynamics using optimal control theory for a first-order diagonal catalyst, which is relatively easy to implement on quantum hardware⁴. Second, I discuss quantum algorithms based on Lyapunov control and their corresponding classical counterparts⁵. For the former, we demonstrated improved performance on problems with small energy gaps even when only first-order diagonal catalyst terms were used, and further confirmed the transferability of the optimized schedule to similar problem instances. For the latter, our results suggest that quantum dynamics can find solutions not obtained by the corresponding classical dynamics, while classical dynamics can rapidly achieve, on average, solution quality comparable to that obtained by quantum dynamics.

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[5] T. Hattori and T. Hatomura, arXiv:2605.13082

Do Quantum Resources Matter for Quantum Optimization?

G. Passarelli¹

¹*Dipartimento di Fisica “E. Pancini”, Università di Napoli Federico II, Napoli, Italia*

Quantum annealing and related quantum optimization protocols rely on genuinely quantum dynamics to navigate complex optimization landscapes. Yet a fundamental question remains surprisingly open: *which quantum resources, if any, are actually responsible for their computational performance?* The presence of coherence, entanglement, or other forms of quantumness during an optimization process does not by itself establish that these resources provide a functional advantage, nor that generating more of them necessarily leads to better solutions.

In this talk, I will discuss this question focusing primarily on *entanglement* and *nonstabilizerness (magic)*. After briefly introducing these notions and their connection to classical simulability, I will review recent results suggesting that quantum optimization protocols can encounter characteristic resource barriers during their dynamics. In QAOA and quantum annealing, states may develop extensive bipartite entanglement on their way between comparatively simple initial and target states [1]. More refined measures reveal analogous barriers in genuine multipartite entanglement [2], while recent work has uncovered a similar phenomenology for nonstabilizerness [3]. Complementary studies of variational quantum algorithms have also shown that accurately reproducing the energy of a target state does not necessarily imply an equally accurate representation of its nonstabilizerness [4]. Together, these results highlight that optimization performance and the quantum-resource content of the underlying states need not be trivially related.

However, the existence of such barriers and correlations raises rather than settles the central question. Are these resources necessary ingredients of successful optimization, mere signatures of difficult dynamics, or quantities that can be actively controlled to improve performance? I will discuss how one may move beyond correlations between resource generation and optimization success toward controlled tests of their functional role, including comparisons between different resources, protocols, and dynamical regimes. This perspective motivates an ongoing research program aimed at identifying which genuinely quantum ingredients are useful for optimization and, ultimately, whether identifying the functional role of quantum resources can provide new principles for understanding and designing quantum optimization protocols.

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- [4] T. E. Spriggs et al., Mach. Learn.: Sci. Technol. 6, 015042 (2025).

Closing the Quantum-Classical Scaling Gap in Approximate Optimization

J. Pawłowski^{1,2*}, P. Tarasiuk², J. Tuziński^{2,3}, Ł. Paweła^{4,2}, B. Gardas⁴

¹*Institute of Theoretical Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland*

²*Quantumz.io Sp. z o.o., Warsaw, Poland*

³*Institute of Informatics, Faculty of Mathematics, Physics and Informatics, University of Gdańsk, Gdańsk, Poland*

⁴*Institute of Theoretical and Applied Informatics, Polish Academy of Sciences, Gliwice, Poland*

** Presenting author*

Establishing a credible quantum scaling advantage requires more than outperforming a single classical baseline at currently accessible system sizes. In this talk, I will discuss how the choice of baseline, finite-size effects, and runtime accounting shape claims of advantage in approximate Quadratic Unconstrained Binary Optimization. We revisit a recent quantum-annealing benchmark [1] using the Simulated Bifurcation Machine (SBM) [2], a quantum-inspired nonlinear dynamical solver utilizing chaotic Hamiltonian dynamics, instead of thermal fluctuations. SBM matches or surpasses the reported scaling of quantum annealing correction on the studied instances, showing that the apparent quantum-classical gap is an artifact of the choice of the classical solver. Extending the analysis to problems beyond the size accessible to present quantum annealers establishes a stronger classical baseline and exposes the danger of extrapolating asymptotic behavior from small systems. I will also highlight sparse problem classes for which quantum annealers are able to obtain high-quality solutions and where a genuine scaling advantage may become possible once hardware overheads are reduced. These results suggest practical criteria for designing future benchmarks that distinguish apparent performance gaps from durable quantum advantage.

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False and Hot Bubbles in Ferromagnetic Superfluids

A. Zenesini

¹CNR-INO TIFPA, and Università di Trento, Italy

False vacuum decay (FVD) represents a paradigmatic example of a beautiful and elegant theory that has fascinated generations of physicists but has waited decades for experimental confirmation. Recent advances in controlling and tailoring quantum systems allow to observe FVD in ultracold neutral atoms and quantum annealers, opening the way to novel investigations of quantum field theory in tabletop experiments.

In our experiments, we work with one-dimensional coherently coupled hyperfine mixtures of Bose-condensed sodium atoms. Owing to the specific combination of intra- and inter-state collisional properties, the mixture can be tuned into a ferromagnetic state, allowing us to study both first- and second-order phase transitions.

In particular, for the first time, we observe the formation of bubbles following the decay of a metastable state, an exemplary manifestation of FVD. More recently, we have investigated how temperature affects this decay process and extended our study to the dynamics and interactions of bubbles in flat potentials

Reshaping quantum annealing landscapes with diagonal catalysts

Jordi Riu

Qilimanjaro Quantum Tech, Barcelona, Spain

Quantum annealing performance depends on the landscape encountered during evolution. I will present a framework relating configuration energies to Hamming distance from the ground-state manifold, and use it to design two-body diagonal catalysts [1]. Built from the problem couplings using local patterns on open paths, these controls require no knowledge of the solution. Applied transiently, they deepen the average energy funnel and reduce the relative overlap between Hamming shells, leaving the final problem unchanged.

Simulations show increased probability near the ground-state manifold and in low-energy bands (Fig. 1). I will discuss the dependence on connectivity and catalyst construction, including comparisons with uniform reinforcement of the problem Hamiltonian. More broadly, the talk explores how landscape structure can inform diagonal controls and annealing schedules, connecting static geometric diagnostics with quantum dynamics and useful optimization protocols.

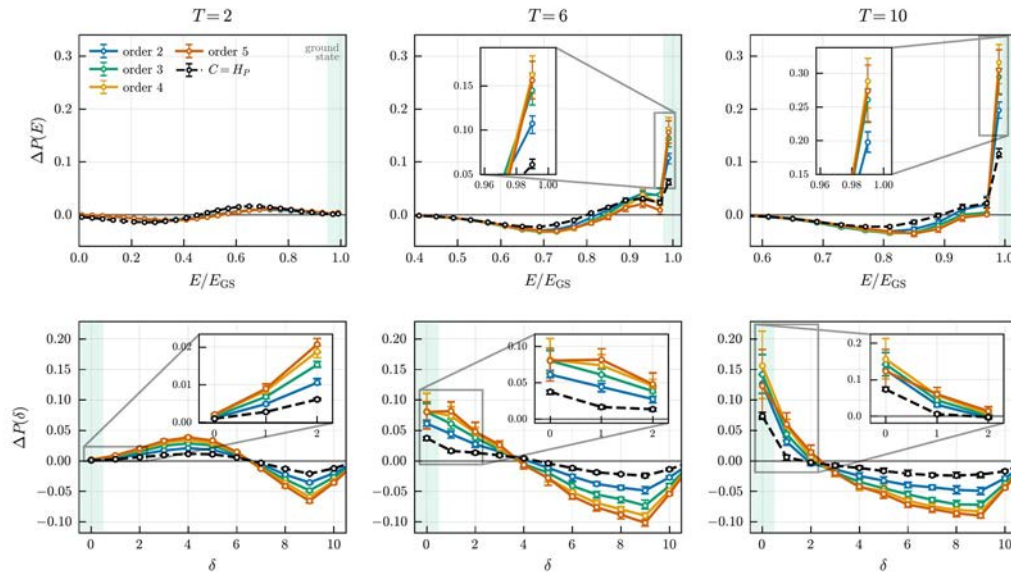


Figure 1: Probability changes relative to the uncatalyzed anneal on 200 random 3-regular, 20-spin instances, resolved by energy (top) and Hamming distance (bottom). From Ref. [1].

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The robustness of adiabatic reverse annealing

C. L. Baldwin¹

*¹Department of Physics & Astronomy, Michigan State University,
East Lansing, MI 48824, USA*

I summarize a series of recent works exploring “adiabatic reverse annealing” (ARA), a variant of conventional quantum annealing in which one uses a biased longitudinal field as a second control parameter to circumvent problematic phase transitions. In particular, I focus on whether and how ARA is resilient to a variety of algorithmic and experimental complications. I first discuss Ref. [1], in which we provide an interpretation of ARA in terms of its effects on the “free energy landscape” of the problem. This intuition shows that ARA does not require much fine-tuning to be successful, but it can also be used to develop competing classical algorithms, and we give a specific example termed “simulated reverse annealing”. I then discuss Ref. [2], in which we show that ARA can continue to work in the presence of — and even benefit dramatically from — a thermal environment, but that the performance depends sensitively on the environment’s temperature. Lastly, time permitting, I discuss ongoing work in which we assess the resilience of ARA to disorder in the problem Hamiltonian.

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Contributed talks

Enhancing the performance of quantum annealing with weighted variational counterdiabatic driving

Naruo Ohga^{1,2} and Takuya Hatomura^{2,3,*}

¹*Department of Physics, University of Tokyo, Tokyo, Japan*

²*Basic Research Laboratories, NTT, Inc., Kanagawa, Japan*

³*NTT Research Center for Theoretical Quantum Information, NTT, Inc., Kanagawa, Japan*

**Presenting author*

Quantum annealing has attracted considerable attention as a quantum algorithm for combinatorial optimization [1]. In quantum annealing, we search for a solution to a given problem by adiabatically tracking the ground state of a Hamiltonian. The performance of quantum annealing relies on maintaining adiabaticity, and thus a long operation time is required to obtain an optimal solution. This is one of the main drawbacks of quantum annealing.

Counterdiabatic driving is a method for improving adiabaticity [2,3]. In counterdiabatic driving, we introduce control fields and/or interactions that counteract diabatic transitions. In particular, variational counterdiabatic driving is a practical approach to approximating counterdiabatic driving [4]. However, its effectiveness remains limited when it is applied to quantum annealing [5].

We propose *weighted variational counterdiabatic driving* [6]. In this method, we assign weights to target states to tailor variational counterdiabatic driving for a specific control objective. In particular, we introduce a weight for ground-state control. We show that our method significantly enhances the performance of quantum annealing.

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Resonant false vacuum decay in two dimensions on a 4000-qubit quantum annealer

Gregor Humar^{1, 2} Jean-Yves Desaulles,³ Luka Pavešić,^{4, 5} Marko Ljubotina,^{6, 7} Zlatko Papić,⁸ Kristel Michielsen,^{9, 10} and Jaka Vodeb^{1, 11, 12}

¹*Department of Complex Matter, Jožef Stefan Institute, Ljubljana, Slovenia*

²*Department of Physics, Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia*

³*Institute of Science and Technology Austria (ISTA), Klosterneuburg, Austria*

⁴*Department of Physics and Astronomy “G. Galilei”, University of Padova, Padova, Italy*

⁵*National Institute for Nuclear Physics (INFN), Section of Padova, Padova, Italy*

⁶*Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany*

⁷*Munich Center for Quantum Science and Technology (MCQST), München, Germany*

⁸*School of Physics and Astronomy, University of Leeds, Leeds, UK*

⁹*Jülich Supercomputing Centre, Forschungszentrum Jülich, Jülich, Germany*

¹⁰*Department of Computer Science, University of Cologne, Cologne, Germany*

¹¹*CENN Nanocenter, Ljubljana, Slovenia*

¹²*Jülich Supercomputing Centre, Institute for Advanced Simulation, Forschungszentrum Jülich, Jülich, Germany*

False vacuum decay (FVD) is a fundamental non-perturbative phenomenon in quantum field theory and statistical mechanics, typically described as a two-stage process of semiclassical nucleation followed by expansion. However, its complexity and limited experimental accessibility make it challenging to study, leaving key questions about the nucleation, propagation, and interactions of true vacuum bubbles [1-3]. Building on studies of one-dimensional Ising chains [4], we investigate FVD in the two-dimensional quantum Ising model and identify a distinct dynamical regime in which nucleation and growth are intertwined through local resonance conditions [5]. Using a programmable quantum annealer with over 4000 qubits, we realize a metastable false vacuum where single-spin flips at the bubble interface become energy-conserving at a tunable resonance, enabling kinetically constrained, fractal-like growth. Combining experiments with tensor-network simulations and stochastic circuit modeling, we find robust ballistic propagation of the true-vacuum wavefront, persisting in the presence of dissipation and disorder. The interface simultaneously exhibits sub-ballistic broadening consistent with Kardar–Parisi–Zhang (KPZ) universality. Our results establish a resonance-driven, growth-dominated regime of FVD beyond the conventional separation between nucleation and expansion.

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Adiabatic control of a fluxonium in a Landau-Zener experiment

G. Troncoso¹, A. Navas^{1,2}, A. Pérez^{1,2}, V. Tozan¹, O. De Miguel¹, J. Riu¹, D. G. Atanasova¹,
A. Riera¹, B.L. Nájera¹, Y. Chen¹, M. Tena¹, O. Pihl¹, L. Scarpelli¹, T. Duty¹

¹ Qilimanjaro Quantum Tech, Barcelona, Spain

² Universidad de Barcelona, Barcelona, Spain

Quantum annealing using superconducting circuits has long been accomplished using traditional, large persistent-current flux qubits as an implementation of the transverse-field Ising model [1]. Recently, fluxoniums have emerged as a viable alternative to the traditional flux qubits. Due to a very small persistent current, it can exhibit significantly larger coherence times [2]. We aim to harness this important feature to achieve coherent quantum annealing.

Here we present experiments that illustrate Landau-Zener-Stuckleberg physics, which describe passage of a two-level system through an avoided crossing. The device consists of a tunable fluxonium qubit in which the small junction is replaced by a CJJ, or so-called, dc-SQUID, allowing an extended control over the system's potential landscape. Simulations were performed from the cQED Hamiltonian at each flux point along the transition ramp projected onto the computational basis. The measurements are in good agreement with numerical simulations. In figure 1 we can see the results for the three paths chosen for the Landau-Zener transition. This experiment shows a fundamental first step for Analog Quantum Computing, opening the door to multi-qubit annealing experiments [3] and exploring other annealing schedules [4].

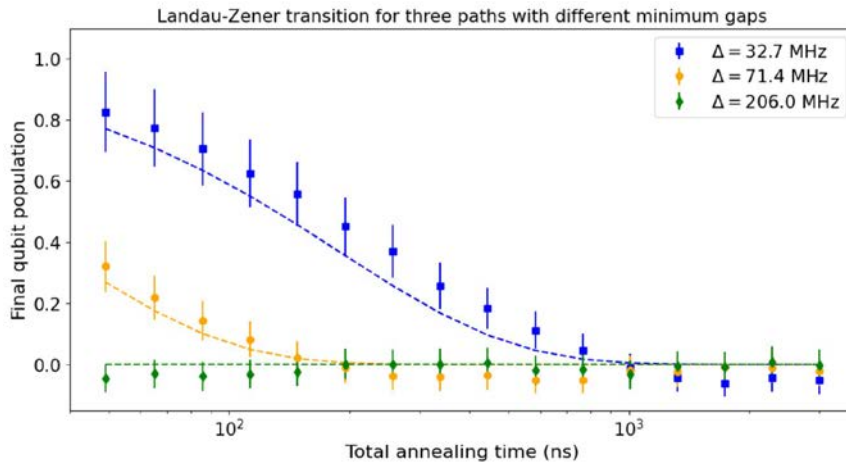


Figure 1: Main results for the Landau-Zener transition at different energy splitting. Markers are measurement and the dotted line the numerical simulation. Each curve minimum energy splitting is indicated in the legend.

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Faster optimization and universal quantum computation by designing annealing schedules

M. Werner^{1,2}

¹*Qilimanjaro Quantum Tech, Barcelona, Spain*

²*University of Barcelona, Barcelona, Spain*

We present our recent results on designing annealing schedules for the globally controlled transverse-field Ising model. First, we present an efficiently trainable variational ansatz for diabatic quantum annealing, which allows us to overcome exponentially closing spectral gaps under particular circumstances by populating the first excited state before the closing of the gap [1]. We show several examples of problem instances where this problem occurs and demonstrate that our proposed ansatz prepares the ground state of the target Hamiltonian significantly faster than linear ramp quantum annealing. We argue that coherence is the key resource that is exploited to obtain an exponential speed-up for some problem instances.

In a second work, we turn our attention to the question of what capabilities can theoretically be gained by controlling the schedule of a quantum annealer. It can be shown that sufficient control over the schedule allows us to simulate the circuit model of quantum computation using the globally controlled transverse-field Ising model at a polynomial overhead in terms of coupling strength, qubit number and time [2]. This establishes the equivalence between the transverse-field Ising model and the gate model of quantum computation. While the exponents we prove here are too large to make our construction operationally applicable to realistic hardware, our result resolves an open question in complexity theory about the computational capabilities of quantum annealing hardware. As a corollary, our result establishes that under common complexity theoretic assumptions, the transverse-field Ising model cannot, in general, be efficiently simulated classically.

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Using domain walls to benchmark fast quantum anneals

Shushmi Chowdhury¹, Asa Hopkins¹, Nicholas Chancellor², and Viv Kendon¹

¹ *Department of Physics, University of Strathclyde, Glasgow, G4 0NG, United Kingdom.*

² *School of Computing, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom.*

We consider the distribution of domain walls arising in ground states of frustrated 1-dimensional Ising spin chains with anti-parallel boundary spins. For an ideal chain, a sine-squared particle-in-a-box distribution of domain walls is expected in the quantum setting, and a uniform distribution expected classically. However, prior work [1] found that the distribution in a physical implementation corresponded to neither. Instead, the domain wall distribution forms a U-shaped profile arising from a classical model with random fields, where the combination of averaging over these fields and thermal averaging produces the characteristic U-shape. With D-Wave's newer fast anneal feature, we access anneal times shorter than the coherence time and observe the expected coherent quantum behavior in the form of a sine-squared distribution. In this fast anneal regime, the experimental probability distributions are reproduced by simulations of the closed system quantum dynamics, obtained by solving the Schrödinger equation under the annealing Hamiltonian, with additional static local fields modelling control errors. The disorder strength is extracted by minimizing the Kullback Leibler divergence between the simulated and experimental domain-wall probability distributions. At longer annealing times, a thermal admixture is incorporated to account for the observed flattening of the sine-squared distribution.

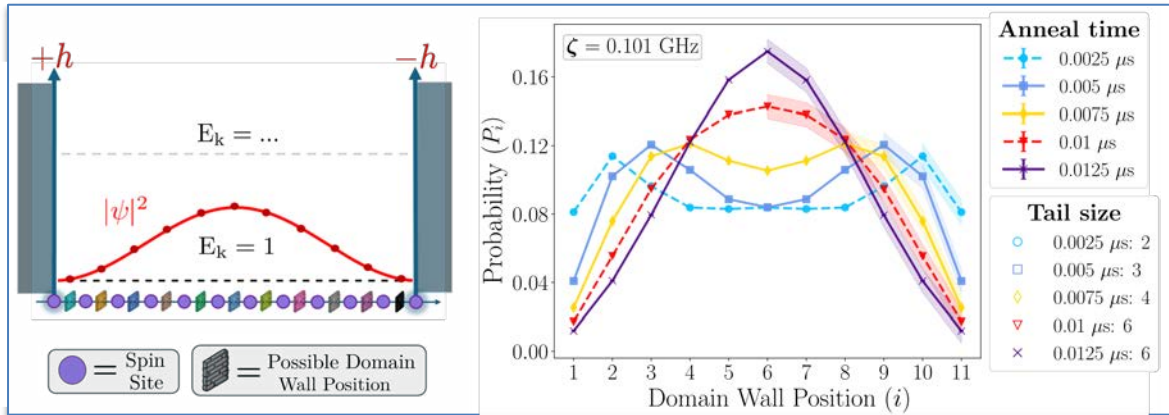


Figure: Particle-in-a-box ground-state $\sin^2$ probability density and corresponding spin chain (left). Simulated domain wall distributions (right) for different anneal times using the fitted disorder strength, $\sigma = 0.101 \pm 0.007$ GHz.

We introduce the extent of the domain wall distribution tail (see Figure), as a metric that captures signatures of both coherence time and noise levels. Using the D-Wave device as an initial benchmarking platform, we show that this measure depends only on the abstract model being implemented rather than device specific details. We therefore propose it as a portable benchmark for assessing the capabilities and robustness of analog quantum devices. As a next step, we will test the broader applicability by simulating Rydberg platforms. This also enables a direct comparison between two distinct analog quantum computing architectures [2].

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Effective XX-interactions for enhanced quantum annealing in the transverse-field Ising-model

N. Feinstein¹, R. J. Banks¹, R. Ghosh^{2,3}, S. Schulz⁴, K. Michielsen^{4,5}, S. Bose³, P. A. Warburton¹

¹*London Centre for Nanotechnology, UCL, London, United Kingdom*

²*School of Basic Sciences, Indian Institute of Technology, Bhubaneswar, India*

³*Department of Physics and Astronomy, UCL, London, United Kingdom*

⁴*Jülich Supercomputing Centre, Institute for Advanced Simulation, Forschungszentrum Jülich, Germany*

Quantum annealing, in its most standard form, is implemented with the transverse-field Ising-model [1]. Restricted to these interactions, however, the algorithm is plagued by the appearance of spectral gaps which close exponentially with the problem size, resulting in a corresponding exponential suppression to the final ground-state fidelity [2,3,4]. A number of works in the literature demonstrate the capacity of stoquastic two-body XX-couplings to enhance these spectral gaps [5,6,7,8,9]. Such interactions, however, are not currently supported by quantum annealing hardware. Here we introduce a parity-encoding based gadget that emulates such an XX-coupling using only the interactions present in the transverse-field Ising-model. The qubit overhead of the gadget is at worst polynomial in system size and if 3- and 4-body Z interactions are also available, only one additional qubit is required for every chain of XX-interactions introduced.

We report two different experimental benchmarks of the gadget. First, we establish that the gadget results in logical dynamics that are consistent with a genuine XX-interaction using a Trotterised gate-based implementation of the gadget on the IonQ Forte ion-trap quantum computer. Next, we demonstrate that the effective XX-interaction produced by the gadget can provide the same advantages as a native XX-coupling in a quantum annealing context. Here, we implement a toy-problem on the D-Wave Advantage2_system2 QPU for which a correctly placed XX-coupling is expected to enhance the final ground-state fidelity. We find that the effective XX-interaction facilitated by the gadget results in a three-order-of-magnitude enhancement over the gadget-free implementation.

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Simulation of a $\mathbb{Z}_2$ lattice gauge theory on a D-Wave QPU

D.Teplitskiy^{1,2,3}, D.Willsch^{2,4}, M.Willsch^{2,3}, A.Rava², G.Pederiva^{2,5}, K.Michielsen^{1,2,3}, J.Vodeb^{6,7}

¹*University of Cologne, Faculty of Mathematics and Natural Sciences, Cologne, Germany*

²*Jülich Supercomputing Centre, Forschungszentrum Jülich, 52425 Jülich, Germany*

³*AIDAS, 52425 Jülich, Germany*

⁴*FH Aachen University of Applied Sciences, 52066 Aachen, Germany*

⁵*Center for Advanced Simulation and Analytics (CASA), Forschungszentrum Jülich, 52425 Jülich, Germany*

⁶*Department of Complex Matter, Jožef Stefan Institute, Jamova 39, 1000, Ljubljana, Slovenia*

⁷*CENN Nanocenter, Jamova 39, 1000, Ljubljana, Slovenia*

Quantum chromodynamics fundamentally governs the strong interaction, yet central phenomena such as confinement and hadronization remain inherently non-perturbative and inaccessible via conventional perturbation theory. Lattice gauge theory emerged as a rigorous framework to formulate these strongly coupled regimes on a discretized spacetime. However, full non-Abelian lattice simulations remain computationally demanding, motivating the study of discrete gauge models such as $\mathbb{Z}_2$ gauge theory, which capture essential non-perturbative mechanisms, including confinement-deconfinement transitions and string tension, within a simplified setting.

In this work, we simulate a $\mathbb{Z}_2$ lattice gauge theory in $(2 + 1)$ dimensions on a D-Wave ‘Research’ Quantum Processing Unit (QPU) using multicolor annealing. To implement the model on hardware, we identify the Union-Jack lattice as the geometric dual of the QPU’s native square-octagonal connectivity graph. By formulating the gauge Hamiltonian on the Union-Jack lattice and applying an exact duality transformation [1], we map the constrained gauge theory directly to an unconstrained transverse-field Ising Hamiltonian on the square-octagonal graph. We use this mapped Hamiltonian to realize and study the real-time dynamics of the lattice gauge theory directly on quantum annealing hardware.

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Towards Hadron Spectroscopy and Dynamics with Quantum Annealers

E. Mendicelli^{1,2},

¹*University of Liverpool, Liverpool, United Kingdom*

²*Jozef Stefan Institute, Ljubljana, Slovenia*

Over the past two decades, experiments have uncovered dozens of candidate exotic hadrons, yet their binding mechanisms, spectra, lifetimes, and dynamics remain poorly understood [1-2]. Lattice QCD conventionally addresses these systems through the Lüscher formalism, but accessing excited states is challenging and real-time dynamics are not directly available. In this talk, we discuss how quantum computing can provide a complementary Hamiltonian approach to hadron spectroscopy and dynamics. We study a one-dimensional QCD model previously implemented on IBM quantum hardware [3] and realize it on a D-Wave quantum annealer. Using the Adaptive QAE algorithm developed in [4], we extract its low-lying hadron spectrum. We then move beyond static spectroscopy to real-time dynamics, using Kitaev–Feynman clock states [5], implemented on D-Wave in [4], to extract energy gaps from dynamical evolution. Together, these results provide a first step toward using quantum annealing to study both hadron spectroscopy and real-time dynamics. We conclude by discussing the scalability of the approach and its prospects for achieving quantum advantage in lattice gauge theory.

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Encoding Matters More Than the Solver: Penalty Coefficients in QUBO Formulations for Quantum Annealing

Roman Kužel¹, Máttyás Koniorczyk², Janez Povh¹

¹ *Rudolfovo – Science and Technology Centre Novo Mesto, Novo Mesto, Slovenia*

² *HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*

roman.kuzel@rudolfovo.eu

Encoding constrained combinatorial problems as Quadratic Unconstrained Binary Optimization (QUBO) instances requires choosing penalty coefficients that enforce feasibility. The standard practice of setting these penalties “large enough” is known to be problematic, yet the mechanism by which oversized penalties degrade solver performance — and the extent of the damage — has not been fully characterized.

We present a solver-independent analysis of the search-space distortion caused by large quadratic penalties in the QUBO encoding. For problems with a single cardinality constraint (prescribed Hamming weight of the solution vector), we derive tight analytical bounds on the linear and quadratic penalty coefficients, including a necessary and sufficient condition under which the quadratic penalty can be dropped entirely in favor of a purely linear term. We show that computing the optimal penalty is NP-hard, and we propose a problem-adapted Augmented Lagrangian Method (AL) that approximates the distortion-minimizing encoding using only a greedy warm-start.

Two complementary degradation mechanisms are identified. First, a landscape-roughening effect: the large quadratic penalty erects energy barriers of height η at every intermediate Hamming-weight state, exponentially suppressing the acceptance probability of swap moves in any single-flip dynamics — including the Metropolis process underlying simulated annealing. Second, a hardware-precision effect specific to quantum annealers: after the QUBO-to-Ising conversion and rescaling to the device’s dynamic range, a large η compresses the objective-carrying coupler differences below the QPU’s programming precision floor, effectively erasing the problem signal.

We validate the framework on the sparsest k -subgraph problem across 270 benchmark instances using a broad range of inner QUBO solvers, including D-Wave quantum annealer, simulated annealing, MQLib hyper-heuristic, simulated bifurcation, and the BiqBin exact solver. On the D-Wave QPU with a simple greedy steepest-descent post-processing, the AL loop achieves 83% optimality while the conventional “large enough” based penalties collapse to 2%. With classical heuristics the effect is equally stark: suboptimal encoding reduces optimality rates from 100% to single digits and inflates exact-solver runtimes by up to 1 000 $\times$. Crucially, the hardness is entirely encoding-induced: the same solvers that fail under large penalties reach full optimality when the AL loop keeps η small. The penalty strategy thus matters more than the choice of solver — a finding with direct implications for the practical use of quantum annealers.

Keywords: *QUBO, quantum annealing, Augmented Lagrangian Method, penalty coefficients, search-space distortion, sparsest k -subgraph*

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Optimized cardinality constraints for quantum annealing

D. Warkentin^{1,2}, M. Willsch^{1,3}, D. Willsch^{1,4}, P. van den Heuvel^{1,5}, C. Gawehn^{1,2}, K. Michielsen^{1,2}

¹*Jülich Supercomputing Centre, Forschungszentrum Jülich, 52425 Jülich, Germany*

²*Department of Computer Science, University of Cologne, 50931 Cologne, Germany*

³*AIDAS, 52425 Jülich, Germany*

⁴*Faculty of Medical Engineering and Technomathematics, University of Applied Sciences Aachen, 52428 Jülich, Germany*

⁵*RWTH Aachen University, 52056 Aachen, Germany*

Even small improvements to well-known optimization problems can have a huge impact and quantum annealing has the potential to accomplish that. A crucial part of many optimization problems are cardinality constraints. In the SAT literature encodings that implement such constraints are well-studied, and they can be adapted well for QUBO solvers like current quantum annealing devices, such as D-Wave. Still, this connection has only recently been investigated. In this paper we focus on the at-most-one encodings, but we show how this can theoretically be adapted for the exactly-one or the at-least-one case. On top of that we demonstrate how the case, when the required cardinality is one can be generalized to the case, when the required cardinality is any arbitrary integer k . We build a framework that combines these rather unexplored encodings from SAT and more established encodings in the quantum annealer literature into more complex encodings. We also introduce a connection to error correction. Current error suppression and correction for adiabatic quantum computation is more limited than in the circuit model and requires too high locality Hamiltonians that are not suited for current annealing devices. Here the concept of ‘quantum annealing correction’ was introduced that focuses especially on how to make current quantum annealers devices more resilient to noise. We introduce a new way of implementing concepts of error correction into quantum annealing that is specific for our cardinality constraints. In future work this can be generalized for other constraints. We benchmarked our encodings using the Advantage_system4 and Advantage2_system1 solvers from D-Wave. Then similar to previous benchmarking of cardinality constraints we calculate the percentage of how often the constraint is met. Our results reveal that the domain wall encoding that was previously used for the exactly-one case performs well as long as its variables are not too highly connected. Here some encodings from the SAT literature perform better than the domain wall. Both perform better than the standard quadratic penalty method as soon as the number of variables become moderate. Our framework demonstrates that the advantages of each encoding can be combined and hence it offers a good baseline to implement cardinality constraints on the quantum annealer, which is required for many optimization problems.

Understanding the Role of Quantum Weirdness in Solving Hard Optimization Problems

D. Headley¹, N. Chancellor¹, J. R. Hance¹

¹*School of Computing, Newcastle University, 1 Science Square, Newcastle upon Tyne, NE4 5TG, United Kingdom*

Quantum algorithms can achieve scaling advantages over classical algorithms on classes of optimization problems with frustrated, computationally hard landscapes. We investigate how gate-based and continuous-time quantum algorithms find high-quality solutions alongside their classical analogues---simulated annealing-based algorithms. By comparing classical probability flow with the flow of quasi-probability [1,2] through the same state space, we demonstrate how mechanisms of optimization used by the quantum and classical algorithms differ in nature. Quantum algorithms need not prepare states with monotonically improving quality at intermediate stages of an algorithm but can instead build relative phases that a final layer may exploit to transfer far more probability mass to high-quality configurations than a single iteration of simulated annealing.

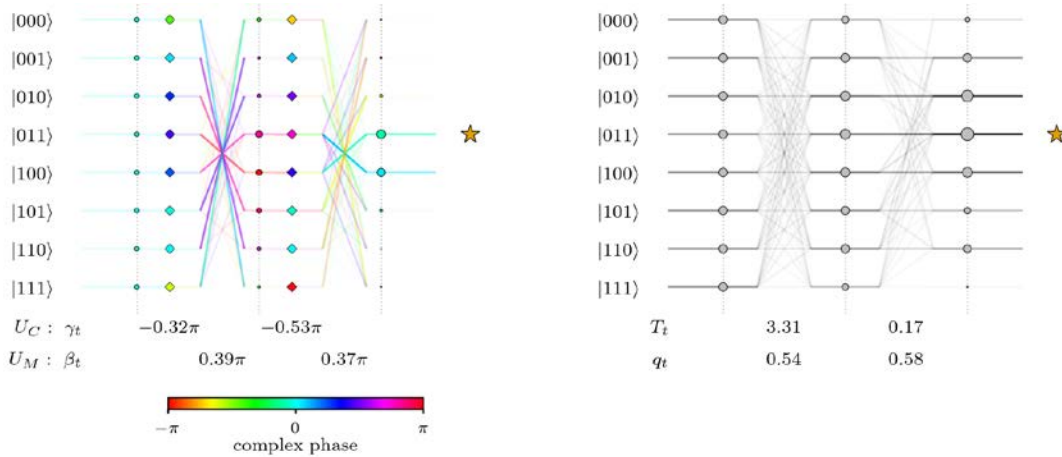


Figure 1: Left: flows of complex amplitude in a QAOA state space for an Ising problem. Right: Flows of probability mass for a simulated annealing algorithm on an identical problem.

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Imaginary as a necessary resource for trainability in QAOA

S. M. Ali Hassan¹, K. Blekos¹, S. Kühn², N. Kollas³, K. Jansen^{1,2}

¹*Computation-based Science and Technology Research Center, Nicosia, Cyprus*

²*Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany*

³*University of Patras, Patras, Greece*

The quantum approximate optimization algorithm (QAOA) searches for good solutions to combinatorial problems by alternating two tunable quantum operations: one encodes the objective function, and the other redistributes probability among candidate solutions [1]. A quantum device estimates the objective, and a classical optimizer uses these measurements to update the parameters. Training becomes difficult when parameter changes have little effect on the objective; in large systems, exponentially flat parameter regions are known as barren plateaus [2]. We ask when varying the parameter of the final mixing operation can provide a nonzero local training signal. When the objective is diagonal and the mixing operation is real in the basis that labels candidate solutions, the corresponding derivative depends only on imaginary coherences—phase-sensitive correlations—between candidates directly connected by that operation [3, 4]. A weighted sum of these coherences bounds the derivative, making these imaginary coherences necessary for a nonzero signal. This condition is not sufficient because different contributions can cancel. For the standard QAOA mixing operation, the relevant candidates differ by one bit. As a concrete example, we apply the result to Max-Cut, a graph-partitioning problem, where the bound is controlled by the maximum number of edges incident on any vertex. With noise applied after the circuit, the correct bound uses a noise-modified effective objective evaluated on the state before noise. The imaginarity remaining in the final noisy state does not generally determine this bound. Exact simulations on small random regular Max-Cut instances illustrate these relations under standard noise models.

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QUBO benchmarks from mixed Hamming packing problems

Mátyás Koniorczyk¹, Roman Kužel², Péter Naszvadi^{1,3}, Marcell Tukora¹

¹HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

²Rudolfovo – Science and Technology Centre Novo Mesto, Novo Mesto, Slovenia

³Faculty of Informatics, Eötvös Loránd University, Budapest, Hungary
koniorczyk.matyas@wigner.hun-ren.hu

Benchmarking NISQ quantum annealers needs problems that are of small size, yet preferably challenging for classical algorithms. Classical benchmarks [1] are typically not the best choice. Meanwhile there is an extensive literature of benchmarks designed to test certain features of actual quantum hardware, but these rarely model practically relevant optimization problems.

In a previous contribution [2] we analyzed a simple 0-1 linear programming (LP) formulation of the problem of mixed Hamming packings; a celebrated problem in coding theory. The problem itself is to find the maximum number of codewords that are farther from each other in Hamming distance than a given prescribed minimal distance, in a space of codewords whose letters come from alphabets of different cardinality. By adding extra constraints to the naive inefficient 0-1 LP model, it became useful for addressing smaller instances of the problem. We also defined a problem-specific decomposition method there. Notably, the linear formulation can be easily rewritten into QUBO form, providing small and challenging solver instances.

Here we present our results of evaluating the so-arising systematic set of QUBOs using a broad range of solvers. We position our benchmarks in the feature space defined in [1], finding that our instances penetrate domains less covered by other benchmarks. We use the 0-1 LP results as a baseline. We solve these problems with a classical exact QUBO solver (Gurobi), the MQLib collection of classical heuristics [1], a cloud implementation [3] of simulated bifurcation [4], and D-Wave quantum hardware.

We find that the problems challenging for 0-1 LP solvers are also challenging for QUBO solvers. It appears that even some classical heuristics perform better than the LP solver when the time to find the optimum (without proving optimality) is concerned, while the LP solver performs better than the exact QUBO solver when proving optimality, suggesting that a hybrid approach can be fruitful in this case. Simulated bifurcation, as a quantum-like classical heuristic, appears to be extremely efficient for our problems. On quantum hardware, our instances are at the borderline of what is addressable in the NISQ context, and it appears that embedding is the key challenge in the case of the considered problems.

Keywords: *QUBO, combinatorial optimization, benchmarking, quantum annealing, NISQ devices, simulated bifurcation, coding theory*

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Improving Ising-Machine-Assisted Black-Box Optimization with Field-Weighted Surrogate Models

Taiga Hayashi¹, Yuya Seki^{1,2}, Kotaro Terada³, Yosuke Mukasa^{1,3}, Shuta Kikuchi^{1,2}, Shu Tanaka^{1,2,4}

¹ Graduate School of Science and Technology, Keio University, Yokohama, Japan

² Keio University Sustainable Quantum Artificial Intelligence Center (KSQAIC), Keio University, Tokyo, Japan

³ Quanmatic Inc., Tokyo, Japan

⁴ Human Biology-Microbiome-Quantum Research Center (WPI-Bio2Q), Keio University, Tokyo, Japan

Abstract

Black-box optimization is important in engineering problems where objective-function evaluations are computationally or experimentally expensive. Factorization machine with quadratic-optimization annealing (FMQA) ^[1,2] reduces the number of such evaluations by training a factorization machine (FM) surrogate and expressing it as a quadratic unconstrained binary optimization (QUBO) model. An Ising machine, including a quantum annealer, can approximately solve the QUBO to propose the next candidate configuration. With one-hot encoding of categorical variables, the binary features representing each variable form a field. A conventional FM assigns one latent vector to each feature but has no separate trainable weight for each pair of fields. This omission may reduce sample efficiency under limited evaluation budgets.

We propose Field-Weighted FMQA (FwFMQA) by replacing the FM surrogate with a field-weighted factorization machine (FwFM) ^[3], which learns a weight for each pair of fields. Because the field weights only rescale pairwise coefficients, the trained FwFM remains quadratic and can be expressed directly as a QUBO. We evaluate FwFMQA on the Pest Control benchmark ^[4], which comprises 25 sequential stages, each treated as a field with five categorical choices. Its search space contains 5^{25} configurations under one-hot constraints.

Across 30 independent runs conducted under the same experimental settings, FwFMQA reduced the mean best-found objective value at the final evaluation budget by approximately 32.2% relative to the mean of the initial random samples, outperforming conventional FMQA by 5.1 percentage points. At one-third of the total evaluation budget, FwFMQA had already achieved a 31.0% reduction from the same baseline, compared with 18.7% for FMQA. These results indicate that FwFMQA accelerates convergence and improves sample efficiency on the Pest Control benchmark while retaining a QUBO formulation compatible with Ising machines, including quantum annealers.

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Quantum Optimisation for Protein-Protein Interaction Network Alignment

Merle Stahl^{1,*}, Robert J. Banks^{2,*,**}, Matthias Traube², Josua Unger³, Wolfgang Lechner^{2,3,4},
Jan Baumbach^{1,5} and Mhaned Oubounyt¹

¹ *Institute for Computational Systems Biomedicine, University of Hamburg, 22761 Hamburg, Germany*

² *Parity Quantum Computing Germany GmbH, 20095 Hamburg, Germany*

³ *Parity Quantum Computing GmbH, A-6020 Innsbruck, Austria*

⁴ *Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria*

⁵ *Department of Mathematics and Computer Science, University of Southern Denmark, 5230 Odense, Denmark*

** These authors contributed equally to this work. ** Presenting author.*

Protein-protein interaction (PPI) network alignment combines topological and sequence information to identify conserved modules across species, but global alignment remains challenging: heuristics sacrifice optimality, while exact methods lack scalability.

We model the alignment as a weighted maximum common induced subgraph problem and reformulate it through the modular product graph to a minimum-weight vertex cover on the graph complement, with node weights carrying sequence similarity. To solve this problem, we focus on the Quantum Approximate Optimisation Algorithm (QAOA). We investigate novel driver Hamiltonians for QAOA applied to this problem. Instead of just soft constraints enforced by penalties in the problem Hamiltonian or hard constraints enforced by constraining the dynamics through the driver Hamiltonian, we investigate the combination of both. This allows us to investigate the trade-off between constraining dynamics and the cost of circuit implementations. We compare our results to vanilla QAOA and a version which fully constrains the dynamics into the feasible subspace.

Inspired by adiabatic quantum optimisation, we show how the unitary associated with the driver Hamiltonians can be implemented without Trotter error. For single-round QAOA, we derive closed-form expressions for the expected cost for circulant driver Hamiltonians, enabling performance analysis without circuit simulation. As far as the authors are aware, this presents the first examination of QAOA at scale with constrained driving.

Applied to synthetic and real-world PPI networks reduced to KEGG pathways, the QAOA formulations achieve high topological conservation on the aligned core while at least maintaining biological conservation comparable to leading classical aligners, at the cost of reduced node coverage. Across selected KEGG pathways, the aligned subnetworks retain disease-associated genes, preserving biologically relevant information. To tackle larger problems, we combine the QAOA formulations with kernelization and branch-and-bound.

Together, these results highlight the potential of quantum optimization for PPI network alignment and the resource trade-offs that will shape its scalability as quantum hardware matures. The details of this work can be found in arXiv:2609.05238.

Effects of Variable Representation on Factorization Machine with Quadratic-Optimization Annealing for RNA Inverse Folding Problem

Shuta Kikuchi^{1,2} and Shu Tanaka^{1,2,3,4}

¹*Graduate School of Science and Technology, Keio University, Kanagawa, Japan*

²*Keio University Sustainable Quantum Artificial Intelligence Center (KSQAIC), Keio University, Tokyo, Japan*

³*Department of Applied Physics and Physico-Informatics, Keio University, Kanagawa, Japan*

⁴*Human Biology-Microbiome-Quantum Research Center (WPI-Bio2), Keio University, Tokyo, Japan*

RNA molecules exhibit diverse biological functions through their secondary structures. An RNA sequence is composed of four types of nucleotides, adenine (A), uracil (U), guanine (G), and cytosine (C), and a sequence of length L has 4^L possible combinations. Therefore, designing nucleotide sequences that stably fold into a desired secondary structure, known as the RNA inverse folding problem^[1], remains difficult to solve.

We apply a factorization machine with quadratic-optimization annealing (FMQA) to RNA inverse folding^[2]. FMQA is a discrete black-box optimization method that employs a factorization machine as a surrogate model and performs optimization using an Ising machine, including a quantum annealing machine^[3]. FMQA has attracted attention because it can efficiently search for better solutions with a limited number of objective-function evaluations. To apply FMQA to RNA inverse folding, categorical nucleotide variables are represented by binary variables. One approach is to assign the four nucleotides to integer values and then encode these integers into binary variables. However, both the nucleotide-to-integer assignment and the integer-binary encoding methods are non-unique. A previous study has shown that the choice of integer-binary encoding method can affect the performance of optimization problems involving integer variables^[4]. Nevertheless, how these representation choices influence FMQA, particularly for categorical optimization problems, remains unclear.

We investigated the effects of these representation choices by evaluating all 24 ($4!$) possible nucleotide-to-integer assignments in combination with four integer-binary encoding methods: one-hot, domain-wall, binary, and unary encodings. One-hot and domain-wall encodings achieved better RNA design performance than binary and unary encodings. Furthermore, domain-wall encoding exhibited a characteristic bias toward nucleotides assigned to the boundary integer values. These results demonstrate that variable representation is not merely an implementation detail in FMQA but can affect optimization performance and solution characteristics. Our findings highlight the importance of jointly designing category-to-integer assignments and integer-binary encoding methods, while also providing practical guidelines for applying FMQA to problems involving categorical variables.

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Confinement Dynamics under Hardware-Induced Inhomogeneity in a Programmable Rydberg Atom Chain

Andrea B. Rava¹, J. A. Montañez-Barrera¹, Kristel Michielsen^{1,2}, Jaka Vodeb^{3,4}

¹Jülich Supercomputing Centre, Forschungszentrum Jülich, D-52425 Jülich, Germany

²Department of Computer Science, University of Cologne, 50931 Cologne, Germany

³Department of Complex Matter, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

⁴CENN Nanocenter, Jamova 39, 1000, Ljubljana, Slovenia

Programmable Rydberg-atom arrays provide a direct route to real-time quantum simulation of spin dynamics, but their interpretation requires distinguishing coherent Hamiltonian mechanisms from hardware-induced inhomogeneity. Here we study correlation spreading in a one-dimensional Rydberg atom chain on QuEra's Aquila quantum processor. Starting from a polarized state in the ferromagnetic Ising frame, we monitor the time- and distance-resolved connected correlations after quenches to different longitudinal fields. Ideal coherent emulations with the Jülich Quantum Annealing Simulator (JUQAS) show the expected confinement of domain-wall excitations into meson-like bound states, visible as a progressive truncation of the ballistic correlation light cone. The experimental data exhibit finite-range correlation spreading already in the nominally deconfined regime, consistent with previously observed hardware-induced disorder effects in Rydberg atom simulations. By incorporating hardware-motivated imperfections into JUQAS, we reproduce the main experimental trends and find that local-detuning-pattern errors provide the largest contribution within the tested phenomenological noise model. The finite-longitudinal-field data are therefore interpreted as confinement dynamics observed on top of a device-induced finite correlation length. Our results provide a hardware-aware benchmark of confinement physics in a programmable Rydberg chain and clarify how local-detuning control can be used to probe mesonic dynamics in the presence of realistic device imperfections.

Universal dynamics of quantum phase transitions with fractional long-range interactions

Andr s Grabarits¹, Lincoln D. Carr^{2,3,4}, and Adolfo del Campo^{1,5}

¹*Department of Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg, Luxembourg*

²*Quantum Engineering Program, Colorado School of Mines, 1523 Illinois St., Golden, CO 80401, USA*

³*Department of Physics, Colorado School of Mines, 1523 Illinois St., Golden, CO 80401, USA*

⁴*Department of Applied Mathematics and Statistics, Colorado School of Mines, 1523 Illinois St., Golden, CO 80401, USA*

⁵*Donostia International Physics Center, E-20018 San Sebastian, Spain*

The complete statistical characterization of defects generated in a quantum phase transition has mostly been studied in exactly solvable models, and its properties remain little explored in nonintegrable systems such as long-range interacting spin chains. We provide the first characterization of the full defect counting statistics in a nonintegrable long-range spin chain, the fractional Ising model, by time-dependent variational-principle simulations within the matrix-product-state and matrix-product-operator formalism. While bare power-law couplings are usually manufactured artificially, fractional interactions capture emergent multiscale correlations and long-range effects in nature, governed by the order of the underlying fractional derivative. Such couplings are readily accessible to existing quantum simulation platforms, allowing for the experimental extraction of the full defect statistics. Driving the transverse field across the critical point along a linear annealing ramp, we find that the defect number statistics obey universal scaling laws with respect to the fractional order. At low fractional order, deep in the long-range regime, the mean defect number decays slower than what is predicted by the Kibble-Zurek mechanism (KZM), while at intermediate order the KZM holds with the numerically extracted critical exponents. At larger fractional order the dynamics is captured by an exactly solvable free-fermionic p -wave superconductor with fractional hoppings and pairings, which misses the many-body physics deep in the long-range regime but becomes progressively more accurate as the short-range limit is reached. Remarkably, regardless of the validity of the KZM or the mean-field approximations, the higher-order defect number cumulants remain proportional to the mean, while the full statistics approaches a Gaussian distribution up to high accuracy.

Closest Accessible Symmetry reduction: a tool for Hamiltonian interpolation analysis

A. Palacios^{1,2,3}, A. Garcia-Saez^{1,4}, A. Riera¹ and M. P. Estarellas¹

¹*Qilimanjaro Quantum Tech, Barcelona 08007, Spain*

²*Universitat de Barcelona, E-08028 Barcelona, Spain*

³*ICCUB, Universitat de Barcelona, E-08028 Barcelona, Spain.*

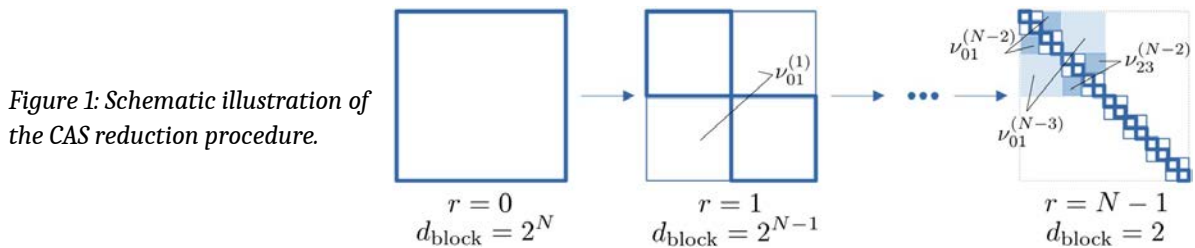
⁴*Barcelona Supercomputing Center, Barcelona 08034, Spain.*

We introduce a framework for analysing the spectrum of Hamiltonian interpolations without heavily relying on discretising the interpolation parameter. This analysis is particularly relevant in the context of adiabatic quantum computation.

The method is based on the concept of accessible symmetries: a problem-class-dependent family of certifiable reflections that induce bipartitions of Hilbert space. In a recursive manner, the interpolation Hamiltonian is projected onto the sectors of the accessible symmetry that is closest to being satisfied throughout (the Closest Accessible Symmetry, CAS for short), yielding a hierarchy of weakly coupled pseudo-eigenspaces together with explicit residual couplings between them (see Fig. 1). Moreover, a polynomial number of the associated pseudo-energies can be efficiently computed, allowing for the calculation of an approximation to the true low-energy landscape throughout the interpolation if the lowest-energy branches of the CAS recursion tree are identified. The error of this approximation remains known, since it is encoded in the aforementioned residual couplings, and, in addition, it provides an interpretation of the underlying true spectrum through its structure.

We explicitly develop the CAS set for the family of Hamiltonian interpolations between the transverse field and an arbitrary Ising Hamiltonian, which is of particular relevance to analogue quantum optimisation, and demonstrate its potential on a large instance ($N=101$) of the frustrated Ising ring. We show that the resulting representation captures qualitative signatures of quantum phase transitions, provides quantitative estimates of their location, and offers insight into their nature. The quality of the approximation is controlled by the compatibility between the accessible symmetry family and the structure of the problem instance.

Although motivated by adiabatic quantum computation, our approach applies more broadly to the study of Hamiltonian phase diagrams, providing a new perspective on the spectral reorganisation of many-body quantum systems.



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Hamiltonian Eigenvalue Transformation by Local Gadgets

Arthur Braida¹, Joseph Cunningham², Jérémie Roland³

¹Université Paris Cité, CNRS, IRIF, France

²Université de Bordeaux, CNRS, LaBRI, France

³Université Libre de Bruxelles, QuIC, Belgium

Continuous-time quantum algorithms are designed around operators no device can build. Analog search interpolates towards the rank-one projector $|m\rangle\langle m|$ on 2^n dimensions, as far from local as an operator can be [1], whereas hardware offers a local Hamiltonian whose ground state is the marked string, of which the projector is a steep polynomial. Can a prescribed polynomial of a local Hamiltonian be realised as the spectrum of another local one?

The primitive is a perturbative gadget [4] used in reverse: an open chain of $2m$ ancilla qubits with couplings alternating between the input and 1 and one boundary site detuned by $-\Delta$ (Fig. 1), a finite Su–Schrieffer–Heeger chain with a defect [5]. Replacing the scalar by a Hamiltonian H costs two in locality, κ -local input to $(\kappa+2)$ -local gadget. The chain carries one isolated eigenvalue, a high-order function of the input, since the excitation must cross the chain and return before it shifts the boundary energy, so the first $m-1$ even powers cancel identically. Different lengths give different leading orders, so the family is triangular and complete. Weighted sums of chains then reproduce any polynomial term by term, one parity per family, giving one time-independent Hamiltonian that carries the transformation exactly on an invariant subspace.

The analysis is exact rather than perturbative. The characteristic polynomial obeys the Chebyshev recurrence, which makes the branch unique and analytic on a disc of any radius $r < 1$, certified by one closed-form threshold $\Delta \geq \Delta_\star(r) \sim (1-r)^{-2}$ on the detuning. That radius is exactly the largest input norm for which adding chains drives the synthesis error to zero, geometrically at rate $\|H\|^2/r^2$. The trade-off against the circuit model is then explicit: quantum singular value transformation (QSVT) [2,3] pays degree d in depth, d sequential oracle calls on $O(1)$ ancillas, whereas degree d and accuracy ε here need $L = d/2 + O(\log 1/\varepsilon)$ chains, hence $O(L^2)$ ancillas and no sequencing at all. Time is traded for space, with Δ setting the energy scale $\|\Sigma\| \leq (\Delta+2)\Sigma_j|\alpha_j|$ at no cost in locality.

As an application we build a Chebyshev filter isolating the ground state of a local H_1 with spectrum in $\{0\} \cup [\delta, \sigma]$ [6], where the trade-off is locality against energy. One pass keeps the locality at $\kappa+2$ but inherits the coefficients of the degree- $2N$ filter, exponential in N , and with them the energy scale. The doubling identity $T_{2M} = 2T_M^2 - 1$ instead rewrites the filter as $\log_2 N$ compositions of a single quadratic, synthesised once and reused, so the largest weight stays Δ at every stage while the locality grows to $\kappa + 2\log_2 N + 2$, on $O(\log^2 N)$ gadgets and $O(\log^3 N)$ ancillas. The filter is one instance of a general primitive: a polynomial of a local Hamiltonian carried by the spectrum of a local Hamiltonian is the continuous-time counterpart of QSVT, a building block for ground state preparation, gap amplification and analog measurement-like operations.

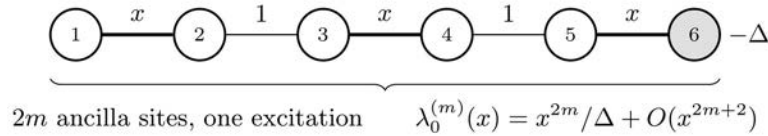


Figure 1: The even gadget for $m = 3$. Thick bonds carry the input and become the operator H .

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Effective XY Interactions and Ground-State Sampling in Penalty-Based Quantum Annealing

Shunta Ide¹ and Shu Tanaka^{1,2,3,4,5}

¹*Graduate School of Science and Technology, Keio University, Kanagawa, Japan*

²*Department of Applied Physics and Physico-Informatics, Keio University, Kanagawa, Japan*

³*Keio University Sustainable Quantum Artificial Intelligence Center, Keio University, Tokyo, Japan*

⁴*Human Biology-Microbiome-Quantum Research Center (WPI-Bio2Q), Keio University, Tokyo, Japan*

⁵*Green Computing Systems Research Organization, Waseda University, Tokyo, Japan*

Quantum annealing (QA) [1] is known to exhibit unfair sampling, where degenerate ground states are obtained with nonuniform probabilities even for long annealing times. In our previous work, we investigated the ground state sampling of penalty-based QA for the graph bipartitioning problem (GBP) and showed that increasing the penalty coefficient generally suppresses unfair sampling [2]. However, its mechanism and relation to alternative constraint-handling approaches remain unclear. In this work, we investigate the origin of this behavior by comparing penalty-based QA [3] with a transverse-field driver and constrained quantum annealing (CQA) [4] with an all-to-all XY driver.

To address this question, we numerically solve the time-dependent Schrödinger equation for 100 randomly generated GBP instances with at least four degenerate ground states for each system size $N = 6, 8, 10, 12$. We compare the sampling distributions over degenerate ground states obtained by penalty-based QA and CQA for different values of the QA penalty coefficient. The distributions are evaluated against both the uniform distribution and each other using Jensen–Shannon divergence (JSD).

As the penalty coefficient increases, the sampling distribution of penalty-based QA depends strongly on the annealing time: it approaches the uniform distribution at short times, whereas at longer times, as the ground-state probability approaches unity, it becomes increasingly similar to the CQA distribution. For $N = 12$, the mean JSD from the uniform distribution is nearly zero up to $T = 10^3$, whereas at $T = 10^4$, the mean JSD between the QA and CQA distributions decreases from 6.5×10^{-2} to 3×10^{-3} as the additional penalty coefficient increases from 0.01 to 10. Degenerate perturbation theory indicates that, in the large penalty regime, the transverse-field driver induces effective spin-exchange processes at second order, analogous to those generated by an XY driver. These effective exchange processes provide a physical interpretation of the observed similarity between the ground-state sampling distributions of penalty-based QA and CQA. This connection may guide the choice of penalty strengths and driver Hamiltonians for shaping ground-state sampling distributions in constrained optimization.

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Adiabatic quantum computation in bosonic systems for combinatorial optimization via polyhedral domain partition

Yuya Seki^{1,2} and Shu Tanaka^{1,2,3}

¹*Graduate School of Science and Technology, Keio University, Kanagawa, Japan*

²*Keio University Sustainable Quantum Artificial Intelligence Center (KSQAIC), Keio University,
Tokyo, Japan*

³*Human Biology-Microbiome-Quantum Research Center (WPI-Bio2Q), Keio University, Tokyo, Japan*

Adiabatic quantum computation (AQC) is one approach to solving combinatorial optimization problems [1]. While research on applying the fast search for solutions of AQC to application problems has been advancing, a long-standing difficulty inherent in conventional AQC has been widely discussed. This difficulty is the breakdown of quantum adiabaticity caused by the shrinking of the energy gap that appears during the quantum dynamics. In regions where the energy gap narrows, the quantum state is excited, reducing the probability of reaching the optimal solution. To address this issue, research has been carried out to improve the efficiency of AQC by engineering the driver Hamiltonian (see, e.g., Ref. [2]). Whereas conventional AQC drives the quantum state with a transverse field, it has been shown through theoretical analysis and simulation that the improved AQC can avoid the shrinking of the energy gap by introducing an XX interaction. However, such an XX interaction has not yet been implemented on a large scale using flux qubits.

In this talk, we introduce an AQC in which the driver Hamiltonian is easy to implement according to the structure of the target problem. The proposed method first converts a combinatorial optimization problem into an equivalent continuous-variable optimization problem. The resulting cost function has multiple, polyhedrally partitioned regions in space, one of which corresponds to the optimal solution of the original problem. We consider a method to search for this optimal region by means of AQC. By introducing momentum operators conjugate to the continuous variables representing position, the entire system is expressed as a bosonic system. The tunneling induced by the momentum (kinetic) term can be controlled through the inverse-mass matrix. In particular, we propose a method for estimating an appropriate inverse-mass matrix from the interaction matrix of the original problem, and we show that it improves the efficiency of AQC in the bosonic system. In addition, we discuss how to implement the proposed method in a photonic system.

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Applications of quantum annealing to magnetic dipole hyperfine structure constants: First results beyond energies for atoms

Boni Paul^{1,2}, Subimal Deb¹, Per Jönsson³, Jörgen Ekman³, Bhanu Pratap Das¹

¹ Centre for Quantum Engineering Research and Education,

TCG Centres for Research and Education in Science and Technology, Sector V, Salt Lake, Kolkata 700091, India

² Department of Physics, Indian Institute of Technology Tirupati, Yerpedu, Andhra Pradesh 517619, India

³ Department of Materials Science and Applied Mathematics, Malmö University, SE-20506 Malmö, Sweden

We report the first results of the magnetic dipole hyperfine structure (HFS) constants of neutral Li, Li-like Be, neutral Na, and Na-like Mg using a modified version of the Quantum Annealer Eigensolver (QAE) algorithm on D-Wave's quantum hardware. The results are benchmarked against relativistic configuration interaction with multiconfiguration Dirac Hartree-Fock (MCDHF) calculations using the General-purpose Relativistic Atomic Structure Package (GRASP), and simulated annealing. In our modified QAE, a zooming-and-sigma-annealing approach with a floating-point encoding scheme is adopted to estimate the ground-state eigenvalue and eigenvector of the relativistic Dirac-Coulomb Hamiltonian matrices (H_{DC}) constructed from 11 or fewer configuration state functions (CSFs). For calculations with extended correlation orbital sets, we applied a CSF truncation scheme, retaining only CSFs (up to 12) that make significant contributions to the ground-state wavefunction. Our modified QAE precision is kept limited to three decimal places (up to 10 qubits). Hardware demonstrations on the D-Wave quantum processing unit (QPU) yielded results that were completely consistent with GRASP (at the chosen precision) in determining the magnetic dipole HFS constants, with accuracy varying across systems and H_{DC} matrix dimensions.

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Simulating DOCI Nuclear Hamiltonians with Ising Systems

Emanuele Costa¹ and Alba Cervera-Lierta¹

¹*Barcelona Supercomputing Center, Barcelona, Spain*

The development of quantum technologies is providing new tools for the study of quantum many-body systems, such as molecules in quantum chemistry and nuclei in nuclear physics. Digital quantum computers offer several routes to simulate these systems, but the required gate complexity and sensitivity to noise make such simulations difficult to realize on near-term hardware. Analog quantum simulators, in contrast, are more resilient to noise and enable accurate state preparation, but their native interactions are too rigid to directly represent the Hamiltonians typically used to describe these systems. In this work we show how to encode a class of nuclear Hamiltonians – described within the doubly-occupied configuration interaction (DOCI) approximation, also well known in quantum chemistry – using Ising-type Hamiltonians. Following an approach similar to that used for catalyst terms in Ref. [1], we construct a gadget Ising Hamiltonian whose low-energy effective dynamics, obtained via Brillouin-Wigner perturbation theory, reproduces the same ground-state configuration as the target DOCI Hamiltonian. We introduce two gadget schemes: (1) a constraint enforcing pair conservation, where virtual-state transitions generate an approximate effective pair interaction; and (2) a first-quantization, one-hot-per-particle encoding, where a parametrized self-energy of the virtual states allows the pair interaction to be tuned exactly. Within this framework, we show that the ground-state fidelity of the DOCI Hamiltonian can be pushed to arbitrary accuracy using the parametrized self-energy correction, which removes the residual systematic bias present in the plain gadget construction, at the cost of a higher number of qubits. We describe both single- and multi-particle encodings, and discuss a minor-embedding strategy to reduce the connectivity requirements of the resulting gadget Hamiltonian.

Topics relevant to this contribution:

- Quantum annealing and coherent Ising machines
- Analog and digital quantum simulation
- Applications of quantum technologies

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Posters

Toward a Qubit-Based Simulation of Continuous-Time Soliton Dynamics and Resonant Kink–Meson Scattering

Kehinde Ogundipe

Alikhanian National Laboratory (Yerevan Physics Institute), Yerevan 0036, Armenia

Topological solitons provide a demanding setting for quantum simulation because their real-time dynamics combines a nonperturbative field configuration with interacting quantum fluctuations. We propose and are developing a qubit-based digital framework for simulating the scattering of an elementary meson from a kink in the $(1+1)$ -dimensional ϕ^4 double-well theory. In the proposed construction, space is discretized and the scalar-field amplitude at each lattice site is encoded in a finite qubit register. The kink sector is prepared through a digitized unitary displacement operator constructed from the classical kink profile, after which a localized meson wave packet is introduced in the fluctuation-mode basis. Real-time evolution under the interacting lattice Hamiltonian is approximated using product-formula circuits. The intended observables include reflection and transmission probabilities and the occupation of the kink’s localized shape mode, extracted from late-time field correlations and normal-mode projections.

The principal analytical benchmark is provided by Linearized Soliton Perturbation Theory. Although the classical ϕ^4 kink is reflectionless, the perturbative calculation predicts a leading one-loop elastic reflection amplitude. This amplitude displays resonant enhancement when the incoming meson energy equals twice the shape-mode energy, corresponding to an unstable twice-excited shape-mode configuration. Further nonanalytic structures arise at the meson–shape-mode and two-meson continuum thresholds. These established analytical predictions provide sensitive targets for testing field truncation, lattice discretization and circuit-approximation errors.

The poster will present the lattice-to-qubit mapping, state-preparation and measurement strategy, and preliminary resource and numerical analyses. The project aims to establish resonant kink–meson scattering as an analytically controlled benchmark for future digital and analog quantum simulators of non-equilibrium quantum field dynamics.

A Bayesian formulation of hybrid quantum-classical dynamics

Hilbert J. Kappen

Department of physics, Radboud University Nijmegen, the Netherlands

We develop a Bayesian formulation of diffusive quantum-classical dynamics by treating the wave function and classical variables as components of an ordinary stochastic process. The joint probability density $P(\psi, x, t)$ obeys a classical Fokker-Planck equation, while the quantum state appears as its second moment. Requiring this second moment to evolve linearly and autonomously yields the hybrid Lindblad equation and its stochastic unravelings. This construction makes positivity and unraveling freedom immediate and gives a unified description of quantum noise, classical noise, and their correlations through the covariance matrices (C, Γ, Q) .

The same stochastic representation turns quantum-classical state estimation into a classical hidden-state inference problem. Filtering and smoothing are Bayesian conditioning on the observed classical trajectory. We recover the stochastic master equation from the Kushner-Stratonovich equation with correlated noise and show how the quantum effect operator is related to the Bayesian backward message through the adjoint dynamics of the linear unraveling. The Bayesian posterior also defines a smoothed density matrix and, more generally, a posterior distribution over latent quantum-classical trajectories.

These quantities can be approximated with standard particle filtering and smoothing methods. Numerical examples show that smoothing improves reconstruction of a hidden quantum-classical trajectory and that the full trajectory posterior can retain structure, such as multimodality, that is absent from its density-matrix second moment. The resulting framework connects quantum filtering, retrodiction, and smoothing to the standard forward-backward machinery of Bayesian time-series inference.

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Exact Solution of Multi-Car Paint Shop Problem

K. Okisawa¹, M. Masayuki^{1,2,3,4}

¹*Graduate School of Information Sciences, Tohoku University, Sendai, Japan*

²*Department of Physics, Institute of Science Tokyo, Meguro, Japan*

³*Research and Education Institute for Semiconductors and Informatics, Kumamoto University,
Kumamoto, Japan*

⁴*Sigma-i Co., Ltd., Minato, Japan*

Various problems regarding the car body painting process in automotive manufacturing plants have been formulated depending on conditions such as car models and paint colors. One of these, the Multi-Car Paint Shop problem, involves applying two-tone painting to each of multiple car models.

Given a sequence of car bodies, this problem aims to minimize the number of color switches while satisfying the target production volume for each car model and color. This can be formulated as a binary combinatorial optimization problem. A previous study [1] presented a QUBO formulation and proposed an optimization method using quantum annealing.

In this study, we aim to derive an exact solution for the partition function of the Hamiltonian addressed in the prior work. This is expected to contribute to a comprehensive investigation of performance across various parameters such as car models and two-tone color assignments.

Focusing on the fact that the proposed Hamiltonian exhibits one-dimensional nearest-neighbor interactions, we attempt to transform it into the form of a one-dimensional Ising model by applying the Hubbard-Stratonovich transformation to a subset of interaction terms in the second term.

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Effect of Integer-to-Binary Encoding on the Performance of Factorization Machine with Quadratic-Optimization Annealing for Constrained Engineering Optimization

Eiji Kawase^{1,2}, Shuta. Kikuchi^{2,3}, Hideaki. Tamai¹, and Shu Tanaka^{2,3,4,5}

¹ Oki Electric Industry Co., Ltd., Saitama, Japan

² Graduate School of Science and Technology, Keio University, Kanagawa, Japan

³ Keio University Sustainable Quantum Artificial Intelligence Center (KSQAIC), Keio University, Tokyo, Japan

⁴ Department of Applied Physics and Physico-Informatics, Keio University, Kanagawa, Japan

⁵ Human Biology-Microbiome-Quantum Research Center (WPI-Bio2Q), Keio University, Tokyo, Japan

Abstract

Constrained engineering optimization problems are often formulated as black-box optimization problems because their objective functions are not available in explicit analytical forms and can only be evaluated through computationally expensive simulators. Factorization machine with quadratic-optimization annealing (FMQA) has been proposed as a sample-efficient approach for such problems [1, 2].

In FMQA, integer-valued or discretized continuous design variables are encoded into binary variables. A factorization machine is then trained as a surrogate model and optimized as a quadratic unconstrained binary optimization (QUBO) problem. Previous studies have reported that one-hot encoding and domain-wall encoding provide favorable optimization performance [3, 4]. However, the number of binary variables required by these one-hot and domain-wall encodings grows linearly with the number of representable states.

As a more compact alternative, binary encoding represents variables using significantly fewer bits. However, adjacent integer values may differ in multiple bits, making it difficult to preserve neighborhood relationships in the binary search space. In contrast, Gray code encoding requires the same number of bits as binary encoding while ensuring that adjacent integer values differ by only one bit [5].

In this study, we investigate the effect of integer-to-binary encoding schemes on FMQA performance by comparing binary encoding and Gray code encoding. Using the pressure vessel design problem as a benchmark, we evaluate the search performance based on the convergence of the objective value over the number of iterations. The experimental results demonstrate that Gray code encoding achieves faster convergence and yields better final objective values than binary encoding.

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Gadget Hamiltonians for an Implementation of Kitaev's History-State Hamiltonian

César Fernández Lamas¹, Javier Argüello Luengo³, Alba Cervera-Lierta¹, Emanuele Costa¹
and Antonio Rubio Abadal²

¹*Barcelona Supercomputing Centre, Barcelona, Spain*

²*Universitat de Barcelona, Barcelona, Spain*

³*Universitat Politècnica de Catalunya, Barcelona, Spain*

The equivalence between the circuit model and adiabatic quantum computation has long been established [1]. In this framework, Kitaev's local Hamiltonian has a ground state given by the history state, which encodes the evolution of a quantum circuit by coherently storing the state of the system at each computational step. This construction provides a way of preparing the history state through an adiabatic process with polynomial runtime.

However, translating this construction into a practical implementation requires interactions that may not be directly available in current quantum hardware. In this work, we explore the use of gadget Hamiltonians, following the formalism introduced in [2], to construct an effective 2-local implementation of Kitaev's history-state Hamiltonian. We consider a two-dimensional lattice in which one dimension represents the qubits and the other represents the computational time steps. In this representation, the propagation terms of the history-state Hamiltonian require an interaction that simultaneously advances all qubits from one time step to the next, which would generally correspond to an n -local interaction.

We show how a suitable gadget Hamiltonian can energetically penalize states in which the qubits are out of sync, while reproducing the desired collective propagation within the low-energy subspace. This provides an effective description based solely on 2-local interactions, offering a route towards an implementation of Kitaev's history-state construction using physically accessible interactions.

Topics relevant to this contribution:

- Quantum annealing and coherent Ising machines
- Analog and digital quantum simulation
- Applications of quantum technologies

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QUBO-Based Generation of LF Auxiliary Material Addition Candidates Using Transformer Prediction and Quantum Annealing

Takuma Yoshihara¹, Yuki Koshita², Kazuro Tsuda², Masayuki Ohzeki^{1,3,4,5}

¹*Graduate School of Information Sciences, Tohoku University, Sendai, Japan*

²*JFE Bars & Shapes Corporation, Tokyo, Japan*

³*Department of Physics, School of Science, Institute of Science Tokyo, Tokyo, Japan*

⁴*Research and Education Institute for Semiconductors and Informatics, Kumamoto University, Kumamoto, Japan*

⁵*Sigma-i Co., Ltd., Tokyo, Japan*

In ladle furnace operations, final steel quality is affected not only by the total amount of auxiliary materials but also by process conditions and the sequence of operations.

Previous work has applied long short-term memory (LSTM) networks to the prediction of alloying-element yield in steelmaking [1]. Zheng et al. developed an LSTM model whose hyperparameters were optimized using particle swarm optimization (PSO), considering different ferroalloy raw-material conditions, and combined its predictions with linear programming to support alloy additions. Although LSTM networks can capture temporal dependencies, their recurrent structure requires sequential processing across time steps and therefore restricts parallel computation along the sequence dimension.

Therefore, we propose a framework combining a Transformer-based forward model with QUBO sampling. The Transformer predicts final compositions and requires energy from stepwise process states and operation modes. Candidate operation sequences are then evaluated using material cost, composition deviation, and energy consumption. Their scores are aggregated for each pair of adjacent operation modes and converted into QUBO coefficients. Quantum annealing is used to sample multiple low-energy sequences. Unlike methods that merely resample existing candidates, this method can generate new, feasible operational procedures by combining effective operational patterns. Therefore, it is considered capable of presenting feasible and diverse solutions for formulating LF operational plans.

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Aircraft Loading Quantum Annealing Dataset

D. Headley¹, M. Babel², N. Chancellor¹, T. Groß¹, Alan Mott³, S. Sinno^{1,3}

¹*Newcastle University, Newcastle Upon Tyne, United Kingdom*

²*National Quantum Computing Centre, Harwell, United Kingdom*

³*Unisys, Milton Keynes, United Kingdom*

In this study, we investigate the performance of D-Wave devices relative to classical solvers for this real-world problem and compare a portfolio of different QUBO encodings including a qubit-efficient reformulation and the use of domain-wall-encoded variables for further compactness of representation. It therefore provides an ideal test application for annealing solvers. We compare standard embedding heuristics with a faster problem-aware approach, and investigate penalty-setting strategies and their synergy with our varying formulations.

In addition to the results of our analysis we provide the underlying data as a public dataset which is available to the community to perform reanalysis to understand the tradoffs of different strategies when using annealers and comparisons with classical solvers. This dataset can provide a valuable starting point for others to develop their own understanding on how annealing behaves on a prototypical minor-embedded optimisation problem, and therefore develop improved designs for their own experiments.

Quantum Evolution and Collaborative Self-Organizing Agents

Charles Zhou

Charles.zhou@quantumii.com

Quantum Intelligence, Inc. Salinas, CA 93907

Ying Zhao

yzhao@nps.edu

Naval Postgraduate School, Monterey, CA 93943

Quantum-mechanics-inspired unsupervised machine learning theory and practical solutions have attracted growing interest for addressing complex industrial challenges, particularly large-scale combinatorial optimization.

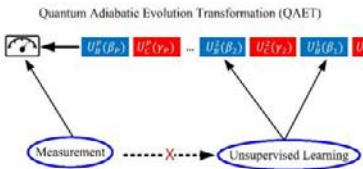
In this talk, we first review foundational concepts underlying this emerging direction, including quantum evolution, quantum spin, spin glasses, Ising models, and magnetic frustration. We then introduce the Quantum Adiabatic Evolution Theory–Quantum Intelligence Game (QAET–QIG) framework, which translates these physical principles into a decentralized architecture for learning, adaptation, and optimization. QAET–QIG-powered AI agents evaluate local information, interact with neighboring agents, and collectively evolve toward coherent solutions without requiring labeled ground truth or centralized control. This capability can help organizations anticipate risks and opportunities, uncover root causes, detect emerging trends, and improve the effectiveness and resilience of human–machine teaming. We illustrate the framework through three use cases: (1) Causal Mediation Coherence for evaluating quantum properties of condensed materials and identifying promising compounds; (2) scoring the potential impact of business news on publicly traded companies; and (3) constructing effect webs for cooperative wargaming and contested logistics, where distributed agents coordinate decisions under uncertainty, resource constraints, and adversarial pressure. Together, these examples demonstrate the potential of QAET–QIG to connect quantum-inspired theory with practical intelligence generation and robust, scalable decision support across scientific, commercial, and defense domains.

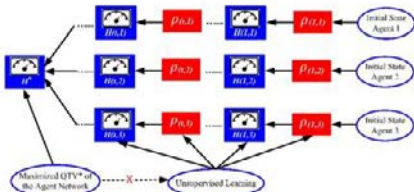


Background & Research Questions

- Are there unsupervised machine learning (ML) methods, related or interlocked to quantum mechanism theory?
- Can the Quantum Adiabatic Evolution Transformation and Quantum Intelligence Game (QAET-QIG or Q-Q) theory be applied to large-scale optimization?

Quantum Adiabatic Evolution Transformation (QAET)





$$H(t) = [1 - s(t)]H_B + s(t)H_C \quad (6)$$

where $s(t)$ is a smooth function, $0 \leq s(t) \leq 1$, $s(0) = 0$ and $s(T) = 1$. A QAET can play an essential role to generate robust quantum states for quantum computing [8]. We show that a measurement combined with a quantum intelligence game (QIG) forced by the environment can be an alternative method to the traditional QAET. $H_B = G$ and $H_C = H^*$ as shown in Fig. 2.

Collaborative Self-Organizing Agents (CSOAs) use the QAET-QIG framework:

- Update causal $H(t)$, e.g., directed acyclic graph(DAG)
- Measure /Maximize quantum theoretic value (QTV) periodically using $M_H = H^\dagger H$
- Two lemmas, seven theorems

Correlation-Based Spin-Pair Merging for Quantum Annealing with Global Spin-Flip Symmetry

Kazuki Abe¹, Tetsuro Abe¹, Shuta Kikuchi^{1,2}, Shu Tanaka^{1,2,3,4}

¹ Graduate School of Science and Technology, Keio University, Kanagawa, Japan

² Keio University Sustainable Quantum Artificial Intelligence Center (KSQAIC), Keio University, Tokyo, Japan

³ Department of Applied Physics and Physico-Informatics, Keio University, Kanagawa, Japan

⁴ Human Biology-Microbiome-Quantum Research Center (WPI-Bio2Q), Keio University, Tokyo, Japan

Dense Ising optimization problems require minor embedding when the logical interaction graph exceeds the connectivity of a quantum annealer. Minor embedding represents one logical spin by a chain of coupled physical qubits. Longer chains can increase embedding overhead and sensitivity to chain breaks, which reduce solution quality. One approach is to fix selected spins and solve the resulting reduced problem. Previous methods determine fixed spin values using sample means of individual spins [1] or time-averaged classical flux variables [2]. Correlation-based reduction, including the possibility of representing correlated variables by a single variable, has also been discussed [1]. For problems with global spin-flip symmetry, one-spin means vanish in a symmetry-preserving ensemble, whereas two-point correlations are invariant under global spin reversal and can characterize relative spin orientations.

Here, we investigate a specific scheme that greedily merges disjoint spin pairs without selecting a symmetry sector. We estimate the two-point correlations from a single preprocessing run of 1000 spin samples generated by a quantum annealer and use them to select pairs for merging. Among the spin pairs whose absolute correlation exceeds a threshold, we greedily select disjoint pairs in descending order of the absolute pair correlation and merge each selected pair into one logical variable. For an anticorrelated pair, we apply a local gauge transformation that converts the anti-alignment relation into an alignment relation before merging. We compare two variants, one using only positive correlations and the other also incorporating negative correlations via the gauge transformation. We evaluate the proposed method on a weighted Max-Cut instance with 100 spins. We adopt a complete graph and set the interactions to ± 1 randomly. In this study, we use the D-Wave Advantage2 as a quantum annealer.

Our results show that the proposed method reduced the number of variables at every threshold examined. The problem size was reduced to 51 variables at a threshold of 0.1, while the degree of reduction decreased monotonically with increasing threshold, leaving 64 variables at a threshold of 0.9.

At each threshold, the two variants reduced almost the same number of variables. In terms of the mean energy, both variants improved on the unreduced baseline. The improvement ranged from 2.5% to 3.3% over the two variants and all thresholds examined, with an average of approximately 3% and no monotonic dependence on the threshold. All energies were evaluated using the original logical Hamiltonian after mapping samples back to the original spin variables so that the constant offset introduced by merging does not affect the comparison. For the reduced problem and the unreduced baseline, we first averaged 1000 sample energies within each run and then averaged these means over 10 independent runs. The energy decrease relative to the unreduced baseline was normalized by the absolute value of the baseline average. For the tested weighted Max-Cut instance and hardware settings, correlation-based merging reduced the size of the logical problem and yielded a lower mean energy than the unreduced baseline.

Future work will examine extensions to problems with partial or approximate spin-flip symmetry.

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A local-field belief propagation decoder for the LHZ parity embedding

J. Bennett¹, W. Lechner¹²

¹*Insitut für Theoretische Physik, Universität Innsbruck, Technikerstraße 21A, 6020 Innsbruck, Austria*

²*Parity Quantum Computing GmbH, Rennweg 1/Top 314, 6020 Innsbruck, Austria*

The LHZ parity embedding is a popular method for implementing long-range interactions required for quantum optimization problems onto local graphs. In [1], a belief propagation (BP) error correcting decoder for the LHZ embedding was introduced. This decoder showed promise under independent and identically distributed noise but was later shown to be less effective under a noise model more representative of quantum annealing [2]. Despite these initial findings, methods based on BP decoding were found to be effective for LHZ embedded optimization problems in certain circumstances [3,4]. To improve effectiveness under a noise model closer to quantum annealing, we introduce a BP decoder which utilizes the local-field information of the qubits as well as parity information to influence its decisions.

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Robust Factorization-Machine Training for FMQA under Noisy Evaluations

Yosuke Mukasa¹, Shu Tanaka^{1,2,3}

¹*Graduate School of Science and Technology, Keio University, Yokohama, Japan*

²*Keio University Sustainable Quantum Artificial Intelligence Center (KSQAIC), Keio University, Tokyo, Japan*

³*Human Biology-Microbiome-Quantum Research Center (WPI-Bio2Q), Keio University, Tokyo, Japan*

Abstract

Factorization machine with quadratic-optimization annealing (FMQA)^[1] is a surrogate-based black-box optimization (BBO) method that models the objective function using a factorization machine (FM) and exploits its quadratic form with an annealing-based optimizer. Conventional FMQA uses squared-error loss^[2] to train the FM and does not explicitly account for noise, although BBO problems often involve noisy observations caused by measurement errors, equipment imperfections, and environmental fluctuations.

Even under Gaussian noise, the residuals of a surrogate are heavy-tailed, and squared-error loss lets a few large residuals dominate the learned quadratic coefficients. To improve robustness against such residuals, we replace squared-error loss with Huber loss^[3], which limits the influence of large residuals while retaining quadratic behavior near zero.

We evaluate the proposed method on TFBind10^[4], a ten-nucleotide DNA sequence-design benchmark for optimizing binding to the transcription factor Pho4. Since the reference landscape contains all 4^{10} possible sequences, the global optimum and noise-free objective values are known. Both the initial training data and subsequent evaluations are corrupted by additive Gaussian noise with a specified standard deviation. Optimization uses only noisy observations, while performance is assessed using the corresponding noise-free values. The quadratic optimization in FMQA is performed using an Ising machine^[5]. Under the same number of evaluations, the proposed method reduces the mean final optimality gap by approximately 20% compared with conventional FMQA and outperforms it in most independent runs.

These results suggest that modifying the loss function for FM training can mitigate FMQA performance degradation under noisy evaluations without additional objective-function evaluations. Future work will investigate other noise settings, including data with uncertainty estimates such as error bars, by incorporating both observed values and their variances into FM training.

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QBIQ: An Exact Hybrid Branch-and-Bound Solver for Binary Quadratic Optimization

R. Kužel¹, J. Povh^{1,2}, B. Zupanc¹

¹ *Rudolfovo - Science and Technology Centre Novo mesto, Novo mesto, Slovenia.*

² *Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia.*

We present QBIQ, an exact hybrid solver for Max-Cut, Quadratic Unconstrained Binary Optimization (QUBO) and linearly constrained Binary Quadratic Programs. QBIQ extends Biqbin [1], a parallel branch-and-bound (B&B) solver based on semidefinite programming relaxations, with a modular architecture for integrating classical, quantum-inspired, and quantum optimization methods.

QBIQ separates the branch-and-bound search from the algorithms used to compute primal solutions and relaxation bounds. Independent interfaces are provided for upper- and lower-bound computations at the root node and at subsequent nodes of the search tree. These components are exposed through Python and can be replaced or evaluated independently without modifying the underlying branch-and-bound routine. Heuristic methods can be used to obtain feasible solutions and improve the incumbent, while lower-bound solvers must provide valid bounds for pruning and certification of optimality. In this way, different methods can be integrated without compromising the exactness of the overall solver.

For quantum-assisted optimization, QBIQ can use remote quantum resources at the root node, where the full problem is available, and the overhead of accessing remote hardware is less disruptive to the overall computation.

QBIQ provides a modular framework for studying how different classical, quantum-inspired, and quantum methods affect bound quality and the overall performance of an exact branch-and-bound solver.

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A Quantum Algorithm for the Quantum Mpemba Effect: Application to the Lattice Schwinger Model

Keisuke Fujii^{1,2,3}, Harunobu Fujimura⁴, Masazumi Honda^{5,6}, Le Duc Truyen^{5,6}

¹*Graduate School of Engineering Science, The University of Osaka, Toyonaka, Japan*

²*Center for Quantum Information and Quantum Biology, The University of Osaka, Toyonaka, Japan*

³*Center for Quantum Computing, RIKEN, Wako, Japan*

⁴*Department of Physics, The University of Osaka, Toyonaka, Japan*

⁵*RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences (iTHEMS), RIKEN, Wako, Japan*

⁶*Graduate School of Science and Engineering, Saitama University, Saitama, Japan*

The quantum Mpemba effect describes anomalous relaxation in which a state initially farther from equilibrium can restore a symmetry faster than a state prepared closer to equilibrium. Investigating this phenomenon in interacting quantum field theories is challenging because real-time dynamics and symmetry-sensitive observables are difficult to access with conventional numerical methods. We develop a quantum-computing framework for probing nonequilibrium symmetry restoration through an entanglement-based diagnostic, together with a measurement strategy designed to remain practical for larger systems. We illustrate the approach in a representative lattice gauge-theory setting using numerical simulations of real-time dynamics. Across several classes of initial states, we observe crossings in the relaxation of the symmetry diagnostic that are consistent with quantum-Mpemba-like behavior, including cases in which states with stronger initial symmetry breaking relax more rapidly. We also examine the quantum resources needed to implement the approach across different hardware regimes. These results provide a practical route for studying nonequilibrium symmetry restoration in quantum many-body systems and lattice field theories, while motivating future implementation on quantum hardware.

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Jaikumar Assignment Linearization with Interaction Terms for the CVRP with Loading Incompatibilities: A QUBO Formulation and Its Evaluation

Haruya Kato¹, Masayuki Ohzeki^{1,2,3,4}

¹*GSIS Tohoku Univ, Sendai, Japan*

²*Science Tokyo Phys, Tokyo, Japan*

³*REI for Semiconductors and Informatics, Kumamoto, Japan*

⁴*Sigma-I, Tokyo, Japan*

The Capacitated Vehicle Routing Problem (CVRP) is a well-known combinatorial optimization problem in transportation. To reduce the size of the problem, it is common to use hybrid methods that split it into two steps: clustering the customers, and then deciding a route within each cluster. For the clustering step, geometric methods such as k-means or the sweep algorithm are often used. The Fisher–Jaikumar assignment linearization takes a different approach: it chooses a seed customer for each cluster and approximates the cost of adding a customer to a cluster, which turns the clustering step into a generalized assignment problem [1].

In this work we add interaction terms between pairs of customers to this linearization, so that it can handle the CVRP with loading incompatibilities. These deal with pairs that must not be carried on the same vehicle, such as two kinds of hazardous goods, which occur widely in real delivery operations. A feature of writing the requirement as interaction terms is that the same quadratic form can express not only hard prohibitions but also soft requirements, such as a preference for loading two customers together, simply through the choice of weights. The resulting objective function is in QUBO/Ising form, so it can be solved directly on annealing machines.

For the evaluation, we built a benchmark by giving labels to the customers of CVRPLIB instances and forbidding co-loading for selected pairs of labels. We compare a hybrid method based on k-means clustering, the Adaptive Large Neighborhood Search (ALNS) widely used in operations research, and the proposed formulation solved both by simulated annealing and exactly. By separating the gap obtained when the formulation is solved exactly from the gap obtained when the same formulation is solved by annealing, we distinguish the error that comes from the formulation from the error that comes from the solver, and show how much room there is for improved annealing methods to contribute.

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Topological edge states in a single flux qubit

P. Pérez-Fernández¹, M. Pino²

¹Universidad de Salamanca, E-37008 Salamanca, Spain

²Universidad de Salamanca IUFFyM, E-37008 Salamanca, Spain

We show that topological edge states appear in a minimal setup consisting of a single superconducting three-Josephson-junction flux qubit. For the parameters chosen, its low-energy physics is described by a massless Dirac model in an effectively infinite two-dimensional flux space, as in graphene. An effective termination is created by adding a quartic potential along one direction of flux space, obtained by shunting the qubit with two parallel arrays of Josephson junctions. The low-energy description of the circuit is then given by a finite Su-Schrieffer-Heeger (SSH) model, whose topological regime is selected electrically through a gate voltage.

Numerical diagonalization of the full circuit confirms the mapping and reveals a pair of edge states confined to one sublattice to within a few parts in a thousand, the signature of the chiral symmetry of the SSH model. Used as a qubit, this pair is protected against charge noise and relaxes slowly, with an estimated $T_1 \sim 1$ ms limited mainly by flux noise. Its degeneracy, however, removes the flux sweet spot and limits the dephasing time to about $0.1 \mu\text{s}$, whereas less sublattice-polarized pairs, which retain a finite splitting, reach microsecond dephasing times.

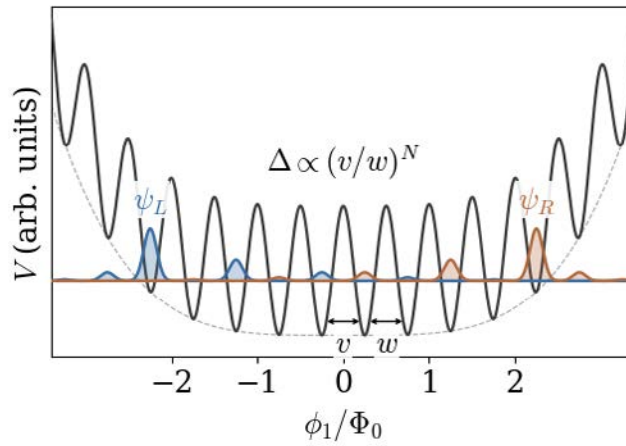


Figure 1: Sketch of the phenomenology expected from the SSH mapping. The washboard potential of the 3JJ loop is confined by the quartic potential (dashed grey). When $|w| > |v|$, a state within the gap emerges, localized at the boundary (ψ_L , ψ_R). The figure is only a schematic, in which the level splitting and the decay length of the edge states are exaggerated for clarity and the well spacing is drawn uniform, whereas the actual lattice alternates intracell and intercell separations.

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Construction of an Outlier Removal Algorithm Using Black-Box Optimization with Quantum Annealing

H. Toyoshima¹, Y. Koshita², K. Tsuda², M. Ohzeki^{1,3,4,5}

¹*GSIS Tohoku Univ, Sendai, Japan*

²*JFE Bars & Shapes Corporation, Tokyo, Japan*

³*Science Tokyo Phys, Tokyo, Japan*

⁴*REI for Semiconductors and Informatics, Kumamoto, Japan*

⁵*Sigma-i Co., Ltd., Tokyo, Japan*

In the construction of prediction models by machine learning, the quality of the data largely determines the prediction accuracy. In real datasets, however, the inclusion of outliers, values that deviate greatly from the rest of the data, is unavoidable. If they are kept in the dataset, the model is drawn toward them, deviates from the underlying trend of the data, and the regression accuracy degrades. In this study, in order to remove such outliers automatically and improve the regression accuracy, we have developed an algorithm that reduces the selection of data to a combinatorial optimization problem and searches for the optimal combination of data by black-box optimization with quantum annealing.

In the proposed method, all data are divided into training data, used to fit the model, and validation data, used to evaluate its accuracy. The problem is then formulated as that of selecting, out of an enormous number of combinations of which data to use, the most appropriate combination in terms of the validation error, and is solved by quantum annealing. On the basis of the combinations that are selected when the validation error is maximized and when it is minimized, outliers are then identified statistically and removed.

Because the choice of whether to use a sample is made for the validation data as well as the training data, outliers contained in the validation data can also be excluded within the search itself. The proposed method is therefore expected to be applicable to real industrial data, where outliers are not confined to the training data and clean reference data is not available.

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Principles of Constrained Quantum Optimization

Einar Gabbassov^{1,2,3}, Gurpahul Singh^{3,4}, and Achim Kempf^{1,2,3,4}

¹*Department of Applied Mathematics, University of Waterloo, Canada*

^{2,4}*Institute for Quantum Computing; Department of Physics and Astronomy, University of Waterloo, Canada*

³*Perimeter Institute for Theoretical Physics, Canada*

g75singh@uwaterloo.ca

Constrained combinatorial optimization underlies many industrial and technological decision problems. Ubiquitous form of constrained problems are the 0-1 integer programs:

$$\min_{\mathbf{x} \in \{0,1\}^n} \mathbf{c}^T \mathbf{x} \quad \text{subject to} \quad \mathbf{A} \mathbf{x} \geq \mathbf{b}$$

where $\mathbf{c}$ is a vector of coefficients and $\mathbf{A}$ and $\mathbf{b}$ encode linear inequality constraints. Classical algorithms exploit constraint geometry: the feasible region is a bounded polyhedron defined by the constraints and the candidate solutions lie on the corners of this polyhedron (Fig. 1, left). We ask how the same principle should guide quantum optimization.

Many quantum optimization algorithms are generated by the time dependent Hamiltonian

$$H(t) = [1 - s(t)]H_{\text{init}} + s(t)H_p, \quad s(0) = 0, \quad s(T) = 1$$

where the mixer H_{init} drives transitions between candidate solutions, the problem Hamiltonian H_p defines the energy landscape, whose ground state encodes the solution to the problem and $s(t)$ interpolates between them. By the adiabatic theorem, a system initialized in the ground state of the mixer follows the instantaneous ground state when the evolution is slow relative to the spectral gap. We show, however, that gap narrowing is a symptom rather than a fundamental bottleneck. At an avoided crossing, energy levels exchange eigenvectors. If those eigenvectors carry different entanglement structures, an adiabatic evolution forces rapid entanglement restructuring and computational slowdown [1] (Fig. 1, center).

Rather than encoding feasibility through energetic penalties, we modify the mixer:

$$H_{\text{init}}^{(\varepsilon)} = (\Pi_F + \varepsilon \Pi_Q) H_{\text{init}} (\Pi_F + \varepsilon \Pi_Q)$$

Here, the projectors (Π_F and Π_Q) select the feasible and infeasible subspaces, while ε controls leakage between them. At zero leakage the subspaces are invariant and the relevant levels cross exactly; small leakage opens narrow avoided crossings (Fig. 1, right). A fast diabatic passage jumps these crossings while preserving the feasible eigenvector and its entanglement structure. This fast-jump regime can reduce runtime by avoiding unnecessary restructuring; so a vanishing global gap need not be a computational bottleneck.

These insights also extend to circuit-based quantum computing because the adiabatic and circuit models are computationally equivalent up to polynomial overhead.

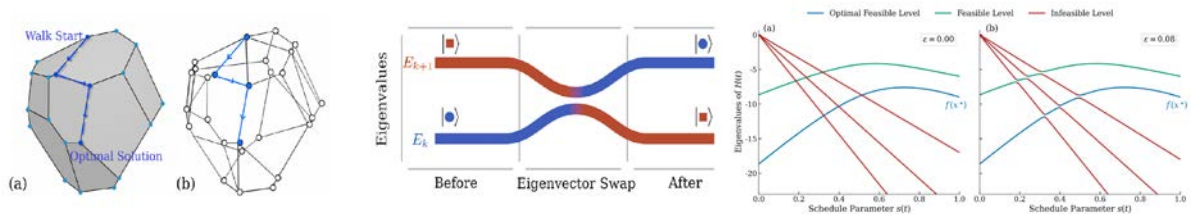


Figure 1. Left: simplex search algorithm in classical optimization. Center: an eigenvector swap close to an avoided level crossing. Right: Instantaneous eigenvalues of $H(t)$ showing exact invariant-subspace crossings at (a) zero leakage open under (b) small leakage.

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List of Participants

Abe Kazuki	Keio University, Japan
Babel Manav	National Quantum Computing Centre, UK
Baldwin Christopher	Michigan State University
Banks Robert	ParityQC Germany
Bennett Jemma	Universität Innsbruck
Braida Arthur	Université Paris Cité, IRIF (CNRS)
Chancellor Nicholas	Newcastle University
Chew Henry	Qilimanjaro Quantum Tech
Chowdhury Farhan Tanvir	University of Exeter
Chowdhury Ajmeri Amreen	University of Strathclyde
Colombo Ambrogio	D-Wave
Costa Emanuele	Barcelona Supercomputing Center
Deshpande Rahul	D-Wave Quantum
Feigel'man Mikhail	CENN Nanocenter, Jožef Stefan Institute
Feinstein Natasha	University College London
Fernández Lamas César	Barcelona Supercomputing Centre
Grabarits Andras	Department of Physics and Materials Science, University of Luxembourg
Guldentops Hans	RaGu Consulting
Hassan Syed Muhammad Ali	The Cyprus Institute
Hatomura Takuya	NTT, Inc.
Hattori Tomohiro	Keio Univ.
Hayashi Taiga	Department of Applied Physics and Physic- Informatics, Keio University
Headley David	Newcastle University

Humar Gregor	Jožef Stefan Institute
Ide Shunta	Keio University
Kappen Hilbert Johan	Radboud University
Katiyar Achit	South Asian University, New Delhi
Kato Haruya	Tohoku University
Kawase Eiji	Oki Electric Industry Co., Ltd.
Kikuchi Shuta	Keio University
Koniorczyk Mátyás	HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
Kuzel Roman	Rudolfovo Science and Technology Center
Le Duc-Truyen	Saitama University/iTHEMS/RIKEN
Marvian Mashhad Milad	University of New Mexico
Mendicelli Emanuele	University of Liverpool --> Jožef Stefan Institute
Mukasa Yosuke	Keio University
Ogundipe Kehinde	Alikhanian National Laboratory (Yerevan Physics Institute), Armenia
Okisawa Konosuke	Graduate School of Information Sciences, Tohoku University
Opariuc Cesar	RaGu Consulting
Palacios Ana	Qilimanjaro Quantum Tech
Passarelli Gianluca	Università di Napoli Federico II
Paul Boni	TCG Centres of Research and Education in Science and Technology
Pawłowski Jakub	Wrocław University of Science and Technology
Payandeh Fatemeh	Jožef Stefan Institute
Pérez Fernández Pablo	Universidad de Salamanca
Povh Janez	Rudolfovo Science and Technology Center
Rapas Camelia	RaGu Consulting

Rava Andrea Basilio	Forschungszentrum Jülich
Rich Chris	D-Wave Quantum
Riu Vicente Jordi	Qilimanjaro Quantum Tech
Sánchez-Beato Díaz-Hellín Miguel	Itecam
Seki Yuya	Keio University
Singh Gurpahul	Perimeter Institute/University of Waterloo
Tanaka Shu	Keio University
Teplitskiy Daniil	Jülich Supercomputing Centre (Forschungszentrum Jülich), University of Cologne, AIDAS
Toyoshima Hiroto	Tohoku University
Troncoso Gonzalo	Qilimanjaro Quantum Tech
Vodeb Jaka	Jožef Stefan Institute
Warburton Paul	UCL
Warkentin Daniel	Forschungszentrum Jülich
Werner Matthias	Qilimanjaro Quantum Tech, University of Barcelona
Willsch Madita	Forschungszentrum Jülich
Yamaki Shoh	Department of Physics, Institute of Science Tokyo
Yoshihara Takuma	Tohoku University
Zenesini Alessandro	CNR-INO and Università di Trento, Italy
ZHAO YING	Naval Postgraduate School
ZHOU CHARLES	Quantum Intelligence, Inc.
Zupanc Beno	Rudolfovo Science and Technology Center
Holubeu Yury	Student Faculty of mathematics and physics

