NTT-RIKEN workshop on photonics, neural networks, and solving combinatorial optimization problems using specialized hardware systems.

February 5 to 9. 2024

Venue: RIKEN, Main Research Building 3F, 345-347 Seminar room

***** Program*****

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Monday Febr. 5:

1:30 pm F. Nori. Welcome and opening remarks.

1:32 pm Timothee Leleu, NTT
Title: Optimizing Combinatorial Problem Solving in Specialized Hardware Systems

3:30 pm Saumil Bandyopadhyay, MIT-NTT
Title: Chip-scale photonics for deep neural networks

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Tuesday Febr. 6:

1:30 pm Sam Reifenstein, NTT
Title: New Parameter Tuning Method for Coherent Ising Machines

3:30 pm Masahito Kumagai, Tohoku University
Title: Coherent Ising Machines Operating in Single Photon Regimes for Constrained Optimization Problems

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Wednesday Febr. 7:

1:30 pm Zheng-Yang Zhou, RIKEN

Title: Frustration elimination for effective optical spins in coherent Ising machines

3:30 pm Farad Khoyratee, RIKEN

Title: High-performance computing for solving combinatorial optimization problems

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Thursday Febr 8:

1:30 pm. Sudeera Gunathilaka, Tokyo Institute of Technology.

Title: Coherent Compressed Sensor

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Friday Febr. 9:

3:30 pm Makoto Morishita, Graduate School of Informatics, Nagoya University

Title: Performance Evaluation of GPTune in CACm

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ABSTRACTS OF THE TALKS:

Monday Febr. 5:

1:32 pm Timothee Leleu, NTT

https://sites.google.com/view/timothee-leleu

https://ntt-research.com/phi-people/timothee-leleu-profile/

Title: Optimizing Combinatorial Problem Solving in Specialized Hardware Systems

Abstract: TBA

3:30 pm Saumil Bandyopadhyay, MIT-NTT

https://scholar.google.com/citations?user=oF8UGCkAAAAJ&hl=en&oi=ao

https://ntt-research.com/phi-people/bandyopadhyay-profile/

Title: Chip-scale photonics for deep neural networks

Abstract: Exponential scaling of the size of deep neural networks (DNNs) has motivated the development of in-memory computing architectures optimized for artificial intelligence models. At the same time, advances in the fabrication of large-scale integrated silicon photonics have sparked interest in optical systems as a platform for processing DNNs at high speeds with ultra-low energy consumption. Although mapping linear algebra to photonic hardware is relatively straightforward, implementing a fully integrated photonic platform for DNN processing, which performs both linear and nonlinear computation optically and on a single chip, has remained an outstanding challenge. In this talk, I will discuss our recent work towards realizing such a system in a commercial CMOS foundry process [1, 2].

This fully integrated coherent optical neural network, which monolithically integrates multiple photonic processor units for matrix algebra and nonlinear activation functions into a single silicon chip, eliminates optical-to-electrical conversions between layers and implements single-shot coherent processing of a DNN entirely in the optical domain and with sub-nanosecond latency. We demonstrate that this system can directly train DNNs in situ, obtaining accuracies comparable to that of a digital system. Our results open the path towards integrated, large-scale optical accelerators for low-latency DNN inference and training. I will close by discussing implications for scaling these systems, including our work on error correction algorithms for high-fidelity unitary matrix processing on optical modes in photonic mesh networks [3, 4].

[1] S. Bandyopadhyay, A. Sludds, S. Krastanov et al. "Single chip photonic deep neural network with accelerated training." arXiv:2208.01623 (2022).

[2] S. Bandyopadhyay, A. Sludds, S. Krastanov et al. "A Photonic Deep Neural Network on a Single Chip with Optically Accelerated Training." In Conference on Lasers and Electro-Optics (CLEO) 2023 SM2P.2 (2023).

[3] S. Bandyopadhyay, R. Hamerly, D. Englund. "Hardware error correction for programmable photonics." Optica 8 (10) 1247-55 (2021).

[4] R. Hamerly, S. Bandyopadhyay, D. Englund. "Asymptotically fault-tolerant programmable photonics." Nature Communications 13 6831 (2022).

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Tuesday Febr. 6:

1:30 pm Sam Reifenstein, NTT

https://ntt-research.com/phi-people/reifenstein-profile/

Title: New Parameter Tuning Method for Coherent Ising Machines

Abstract: Combinatorial optimization heuristics such as the CIM typically have many parameters which need to be tuned accurately in order for the solver to have good performance. In order to study an understand these heuristics solver in more detail, algorithms for automatic parameter tuning are necessary. Our new algorithm, called dynamic anistropic smoothing (DAS) can be used to efficeintly and accurately tune parameters for the CIM and other differential solvers. In this talk we will introduce this new tuning algorithm and how it can be applied in the future to the study of the CIM.

3:30 pm Masahito Kumagai, Tohoku University

https://scholar.google.com/citations?user=ola9Co0AAAAJ&hl=en

Title: Coherent Ising Machines Operating in Single Photon Regimes for Constrained Optimization Problems

Abstract: A Coherent Ising Machine (CIM) is an oscillator-network-based analog computing system to circumvent the bottleneck in von Neumann digital computing architectures. The CIM consists of a network of Degenerate Optical Parametric Oscillators (DOPOs) and is designed to find a ground state or perform Boltzmann sampling for all degenerate ground states and low-energy excited states in combinatorial optimization problems. A nonlinear measurement feedback scheme, called Chaotic Amplitude Control (CAC), has recently been proposed to correct pulse amplitudes' inhomogeneity and thereby faithfully map the Ising Hamiltonian to the loss landscape of the DOPO network. However, the quantum limit of the

CIM-CAC performance is not fully explored yet. This research clarifies how quantum noise squeezing improves the system's performance. From the numerical simulation on the Ising model with the Zeeman terms, obtained from combinatorial clustering problems formulated as constrained optimization problems, it is revealed that the CIM-CAC with squeezed vacuum noise operating in a single photon per pulse regime outperforms that with standard vacuum noise. Moreover, the CIM-CAC with squeezed vacuum noise is superior to the fictitious CIM-CAC with white noise and no noise. This is because the squeezed vacuum noise that changes its strength depending on the internal amplitudes helps escape from local minima or periodic trajectories. This fact could once again motivate the construction of a physical CIM rather than a classical CIM simulated on digital computers.

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Wednesday Febr. 7:

1:30 pm Zheng-Yang Zhou, RIKEN

Title: Frustration elimination for effective optical spins in coherent Ising machines

Abstract: Frustration, that is, the impossibility to satisfy the energetic preferences between all spin pairs simultaneously, underlies the complexity of many fundamental properties in spin systems, including the computational hardness to determine their ground states. Coherent Ising machines (CIM) have been proposed as a promising analog computational approach to efficiently find different degenerate ground states of large and complex Ising models. However, CIMs also face challenges in solving frustrated Ising models: Frustration not only reduces the probability to find good solutions, but it also prohibits to leverage quantum effects in doing so. To circumvent these detrimental effects of frustration, we show how frustrated Ising models can be mapped to frustration-free CIM configurations by including ancillary modes and modifying the coupling protocol used in current CIM designs. In our proposal, degenerate optical parametric oscillator (DOPO) modes encode the ground state candidates of the studied Ising model, while the ancillary modes enable the autonomous transformation to a frustration-free Ising model that preserves the ground states encoded in the DOPO modes. Such frustration elimination may empower current CIMs to improve precision and to benefit from quantum effects in dealing with frustrated Ising models.

3:30 pm Farad Khoyratee, RIKEN

https://scholar.google.com/citations?user=iG8IYRYAAAAJ&hl=en&oi=sra

Title: **High-performance computing for solving combinatorial optimization problems**

In recent years, the increasing complexity of problems has spurred the development of numerous algorithms and technologies for combinatorial optimization. Combinatorial optimization involves finding the best configuration of variables to achieve specific goals, with applications ranging from finance to traffic management. One class of such problems, Non-deterministic Polynomial (NP) problems, poses significant computational challenges due to their exponential growth in computation time on classical computers with the number of variables.

To address NP problems, hardware based on the Ising model, known as Ising machines, has been developed. These machines offer potential solutions to NP. While various types of Ising machine hardware, including those utilizing laser systems, have been explored, alternative technologies such as Field Programmable Gate Arrays (FPGAs) have shown promising performance in certain scenarios.

In this talk, we will provide an overview of combinatorial optimization, discuss the challenges posed by NP problems, and explore the potential of Ising machines and alternative technologies in addressing these challenges. We will highlight recent advancements and discuss future directions for research in this field.

Keywords: Combinatorial optimization, Ising machines, Non-deterministic Polynomial (NP) problems, Field Programmable Gate Arrays (FPGAs).

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Thursday Febr. 8:

1:30 pm. Sudeera Gunathilaka, Tokyo Institute of Technology.
https://scholar.google.com/citations?user=AoeGGVQAAAAJ&hl=en

Title: Coherent Compressed Sensor

Abstract: Increasingly, quantum-inspired machines have drawn significant attention because they have the potential to overcome the difficulties associated with solving large-scale combinatorial optimisation problems. The challenge, however, remains in bringing quantum-inspired machines to practical use and applying them to real-world problems.

To explore the practical applications of these machines, we focus on efficiently solving L0-norm compressed sensing (CS) problems. The CS method refers to the reconstruction of a high-dimensional signal or image using highly downscaled measurements. It has attracted significant interest from a wide range of fields and applications. Because L1-norm CS is a convex optimisation problem, many efficient algorithms have been developed that are widely used in real-world applications. The L0-norm CS, however, is believed to perform better than the L1-norm CS. However, optimisation of L0-norm CS is a challenging task since it involves combinatorial optimisation. It is our belief that a quantum-inspired machine

will be able to perform L0-norm CS efficiently and this will pave the way for their practical applications.

In this talk, I will be introducing our research with the coherent Ising machine (CIM), one of the most suitable machines for solving optimisation problems in L0-norm CS, since CIMs can construct a densely connected network. Using CIMs with chaotic amplitude control (CAC) feedback [3], we demonstrate that they can be used to solve L0-norm CS problems efficiently, outperforming both CIMs without CAC feedback and simulated annealing as well as other practical algorithms [1]. Furthermore, we show that the performance of CIM with CAC feedback approaches the theoretical limit of L0-norm CS compared to CIMs without CAC feedback [2]. For the real-world data, we have used 64×64 and 128×128 resized MRI images. Results have shown that reconstruction results with CIM with CAC feedback are relatively more accurate.

References

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

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Friday Febr. 9:

3:30 pm. Makoto Morishita, Graduate School of Informatics, Nagoya University, Japan
https://www.linkedin.com/in/makoto-morishita-aa1647250/

Title: Performance Evaluation of GPTune in CACm

Abstract:
In High Performance Computing (HPC), software often has many parameters that impact its performance. However, it is difficult to determine optimal values for such parameters in an impromptu way. The automatic tuning – autotuning – of parameters is therefore an area of great interest. GPTune is an autotuning framework developed by DOE's Exascale Computing Project, and use the framework in a set of applications of interest.

In this talk, I will introduce the autotuning parameters of CACm (Chaotic Amplitude Control with momentum). Chaotic Amplitude Control is an algorithm used to find the low-energy states of the Ising Hamiltonian. CACm has some parameters to be tuned, so I adapted GPTune to optimize such parameters. I will show the advantage of autotuning for optimizing parameters.