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Editorial: Advancing quantum computation: optimizing algorithms and error mitigation in NISQ devices

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Editorial on the Research Topic
Advancing quantum computation: optimizing algorithms and error mitigation in NISQ devices

For the moment, noisy intermediate-scale quantum (named NISQ) device is the best option for quantum computation and this quantum research with tools of optimization and error mitigation has achieved both many important milestones and overcome fundamental challenges over several years. While such NISQ devices have demonstrated prototype quantum algorithms that exploit uniquely quantum resources such as superposition and entanglement, their practical application remains constrained by gate errors, limited qubit counts, and algorithmic inefficiencies during coherence time. This Research Topic brings together recent advancements to address these challenges through the optimization of quantum algorithms, the design of resource-efficient encodings and architectures, and the exploration of new computational paradigms for NISQ platforms. Thus, the contributions outline viable routes towards near-term quantum utility while establishing the foundation for longer-term progress towards scalable, fault-tolerant quantum computation in the future.

A central theme is that progress in the NISQ era requires innovations in algorithmic design and problem representation, not solely hardware improvements. The article by Fuchs et al. exemplifies this by addressing the efficient mapping of the weighted MAX k-CUT problem onto quantum hardware. This combinatorial problem is a key benchmark, but simple encodings demand excessive qubits and circuit depth. Their work systematically examines alternative encoding strategies, including binary and constrained subspace representations, using numerical simulations. The authors demonstrate that balanced and subspace-restricted encodings significantly improve approximation quality while reducing circuit complexity, thereby enhancing the feasibility of implementing variational quantum algorithms on current NISQ devices.

Beyond encoding efficiency, the Research Topic highlights execution paradigms that exploit quantum hardware characteristics. The brief report by Osaba and Villar-Rodriguez revisits quantum annealing, specifically reverse annealing, as a relevant NISQ optimization strategy. Unlike conventional forward annealing, reverse annealing starts with a known candidate solution and performs a localised quantum search, making it suitable for hybrid and iterative optimization workflows. Through experiments on the well-known knapsack problem instances, the authors explored whether initialising reverse annealing with solutions from related problems enhanced performance. Their findings suggest that transferring solution information, particularly when problem instances are closely related in terms of Hamming distance, can improve success probabilities and robustness. This study establishes a conceptual bridge between transfer learning and quantum optimization, offering a promising direction for practical NISQ-era applications.

The intersection of quantum algorithms and data-driven methods is a critical area explored in contributions covering quantum machine learning. A consistent perspective across these works is the strategic adaptation of established classical machine learning techniques to align with the limitations and advantages of current NISQ hardware. For instance, Seong and Park recast centroid-based clustering, a fundamental unsupervised learning task, into a quantum-mechanical framework using a cost Hamiltonian. This approach provides a principled method for implementation on quantum devices, illustrating how classical techniques can be extended through quantum formulations, despite remaining challenges like noise sensitivity.

Complementing this, Lee et al. investigate the optimization of Quantum Convolutional Neural Network (QCNN) architectures. They show design strategies that balance QCNN's expressive power with hardware constraints like circuit depth and parameter count, which are crucial for mitigating noise impacts. Both studies demonstrate that careful algorithmic design and architectural choices are key to developing practical QML models suited for near-term quantum processors.

Taken together, the articles in this research area show that we need a complete, joined-up way to use NISQ quantum computing. This involves bringing together integrated ways of setting up problems, specific methods for running them, and mixing classical and quantum steps. Instead of relying on future fault-tolerant regimes, these contributions demonstrate how innovative algorithmic design and problem-specific insights can extract meaningful computational advantages from current NISQ technologies.

Therefore, the broader context reflects the transitional nature of the NISQ era. While noise and limited coherence time remains significant challenges for some years, targeted advances in algorithm optimization and error-mitigating quantum computation meaningfully extend the class of problems accessible today. Future quantum research will benefit from systematic benchmarking on larger instances, adaptive error-mitigation techniques, and the development of theoretical performance bounds under realistic noise models.

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