Greater Quantum Efficiency by Breaking Abstractions

Research Statement

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My research goal is to build highly optimized and reliable quantum toolchains tailored for near-term quantum computing devices. Building the first generation of quantum computers is a great engineering challenge, whereas software/hardware co-design can provide an accelerated pathway that saves years of engineering efforts. Current quantum toolchains follow the vertically layered design similar to its classical counterpart: algorithms - programming languages - instruction sets - technology mapping - error correction/mitigation - physical implementation. The layered design philosophy hides details in lower level from the above, thus complexity is well maintained. However, this approach misses opportunities for optimizations. My past work explore ways of improving the computation efficiency and reliability, mainly by breaking abstractions between layers with numerical and analytical tools [ASPLOS'19, MICRO'19, NJP'19, ArXiv'19].

Current work

Break the ISA abstraction Optimizing the compilation process is crucial to the success of near-term quantum computing, but is also a notoriously hard problem. The common practise is to compile the quantum algorithms to circuits of elementary gates (quantum ISA), whose physical implementations are pre-calibrated, continuous microwave control pulses. We proposed a novel quantum compilation methodology that breaks the ISA abstraction and directly compiles sub-circuits down to control pulses [ASPLOS'19, MICRO'19]. Leveraging optimal optimal control theory, our compilation method achieves 5-100X improvement in circuit latency for near-term quantum algorithms. Our method is the core component of an NSF Expeditions in Computing project [EPiQC] and is considered to "boost the speed of quantum computers" [PhysNews].

Break the qubit abstraction Compared to classical bits, quantum bits are far more fragile and short-lived. Thus, it's important to extract error information from the phyiscal qubit implementation. Bosonic codes like the Gottesman-Kitaev-Preskill (GKP) qubit encoding provides such a qubit architecture that enables upper level software to monitor the internal correctness without destroying the qubit state, thus it is a promising candidate for future quantum information processing. In [NJP'19], we gave the definition of fault-tolerance for GKP codes and designed a protocol that fault-tolerantly prepares GKP states utilizing the measurement outcome. With deeper integration with the upper level error correction, we believe qubit architectures like the GKP qubit serve as strong alternatives for the existing qubit implementations like the transmon qubits.

Reliable quantum software The verification of quantum tool chains is a relatively unexplored area, but an important futre direction of near-term quantum computing. We designed and implemented CertiQ [ArXiv'19], the first verification framework for a real-world commercial quantum compiler (Qiskit-Terra). We introduced novel techniques such as contract-based design and founds bugs that are specific to quantum software. We believe the methods we developed in CertiQ can be extended to other quantum software components and pave the way to a truly reliable quantum tool chain.

Future Research Agenda

I will continue my current directions and further improve the efficiency, reliability, compilation time and noise adaptation of my previous work and demonstrate them experimentally. In addition, I will explore the following directions.

Algorithm level error correction I will explore methods to combine high level quantum algorithms with customized error correction scheme. A prominent example is the generalized superfast encoding for quantum chemistry algorithms. I will utilize classical coding theory to scale up the error correcting ability of such error correction schemes and design more noise-aware quantum algorithm implementations.

Noise-adaptive compilation Near-term quantum devices have errors from elementary operations like 1- and 2-qubit gates, but also emergent error modes like cross-talk. However, traditional methods only consider the errors in each operations and compose them, thus not able to completely characterize the errors for noisy devices. I will leverage tools in quantum information theory such as quantum channel twirling, semi-definite programming and tenor networks to estimate, bound system errors and design new optimizations with these error information.

References

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