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Quantum Optimization

The key to the incredible speed of a quantum computer lies in its ability to fabricate and manipulate quantum bits, or qubits, typically artificial particles such as ions, superconducting oscillators or protons. Quantum properties allow qubits to form entanglement, a phenomenon that provides far more processing power than the binary bits that drive today's classical computers. Specially designed quantum algorithms, which are lists of operations — analogous to a cooking recipe — that tell a computer to do something can further speed up calculations to accelerate scientific advances.

Unfortunately, quantum machines have a significant drawback: they are more error-prone than classical computers. Qubits are extremely fragile and difficult to control, and the slightest environmental disturbance, referred to as "noise," such as a vibration or change in temperature, results in persistent and relatively high error rates when executing an algorithm. As a result, today's quantum computing devices and those of the foreseeable future are referred to as Noisy Intermediate Scale Quantum (NISQ) computers, because the noise inherent in the systems frequently produces incorrect results.

Yufei Ding, an assistant professor in UC Santa Barbara's Computer Science Department, has developed a plan to improve the efficiency and accuracy of quantum applications in the next generation of quantum devices. Her project, "A Top-Down Compilation Infrastructure for Optimization and Debugging in the Noisy Intermediate-Scale Quantum (NISQ) Era," has now garnered a prestigious Early CAREER Award from the National Science Foundation, which comes with $500,000

over five years to support her research.

“I am so excited to have the opportunity to deepen and widen my research on quantum computing with the NSF Early CAREER Award support,” said Ding, who joined UCSB in 2017 after completing her Ph.D. at North Carolina State. “My interest and passion in quantum computing date back to the first quantum mechanics course I had as a physics undergraduate. Its fundamental beauty and how it reveals the operating mechanism behind the physics world around us just intrigue me. It is my deep belief that quantum computing will revolutionize the way we solve problems and being a part of that revolution is a dream coming true.”

“We are extremely proud of Professor Yufei Ding for this tremendous recognition,” said Rod Alferness, dean of UCSB’s College of Engineering. “Professor Ding is a shining example of the high-quality junior faculty we have in the College of Engineering. Her work to address the existing challenges in programming and optimization will expand the frontiers of quantum research and impact future quantum computing applications.”

In her project, Ding seeks to design state-of-the-art architecture to improve the stability of quantum computing by focusing on compilation and optimization. Compilation is the process by which a computer program takes a source code, written in one programming language, and translates it into a second language to create an executable file or outcome. Presently, the longer a quantum algorithm runs or compiles, the more its performance degrades because of noise in quantum devices. As a result, minimizing runtime and maximizing efficiency are critical.

“Our approach is to focus on the optimization of high-level algorithms and low-level hardware, which are two key components in the quantum compilation process,” said Ding, who previously received an Early Career Researchers Award from the IEEE Computer Society’s Technical Consortium on High Performance Computing. “We believe that a compilation infrastructure is the key to bridging those two components, forming a full-stack NISQ system that moves devices closer to attaining quantum supremacy.”

Ding plans to create a new high-level programming language to optimize algorithms. A programming language provides a set of rules and principles to convert an algorithm’s mathematical description into an action that is executable on a physical computer. Most programmers prefer high-level languages because they are closer to

the spoken and written language of humans and easier to understand, write in and debug than low-level machine code, which is a series of binary numbers that tell a computer what to do. Ding intends for her language to also allow for autotuning, automatically selecting the best and most efficient implementation of a computation during the compilation process.

High-level languages allow programmers to operate quantum computers; however, the actual device-level control is performed via analog pulses, which stimulate the qubits to manipulate their state. Any operation that changes the state of a qubit to 0 and/or 1 is referred to as a quantum gate. In the second component of Ding's project, she and colleagues will focus on controlling pulses through low-level optimizations in order to improve efficiency and mitigate errors.

"We will leverage the fact that there are different pulse-level choices for implementing any particular gate and use them to improve their overall performance and mitigate errors," Ding explained.

The final thread of her research plan will develop advanced testing and debug support by creating runtime assertions and invariants. Assertions in programming language are conditions that must be true for a program to run correctly. If an assertion is false, then the code that follows will fail or result in an error to indicate the source of the defect. Invariants are conditions that must be true during the execution of a program, ensuring that a program is always in an expected state.

"The systematic projection-based runtime assertion and invariant generation will pave the way for automated quantum program analysis and bug detection at a much larger scale and benefit all quantum computing users and developers," said Ding, who added that the compilation stack created by this project could significantly impact the efficiency and accuracy of near-term quantum devices.

"Our work has the potential to benefit major quantum computing applications, such as quantum chemistry, and to expand to materials, finance and stochastic/numerical mathematics," said Ding. "The success of our agenda will enable a more complete and efficient software stack and support quantum applications on near-term devices."

About UC Santa Barbara

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