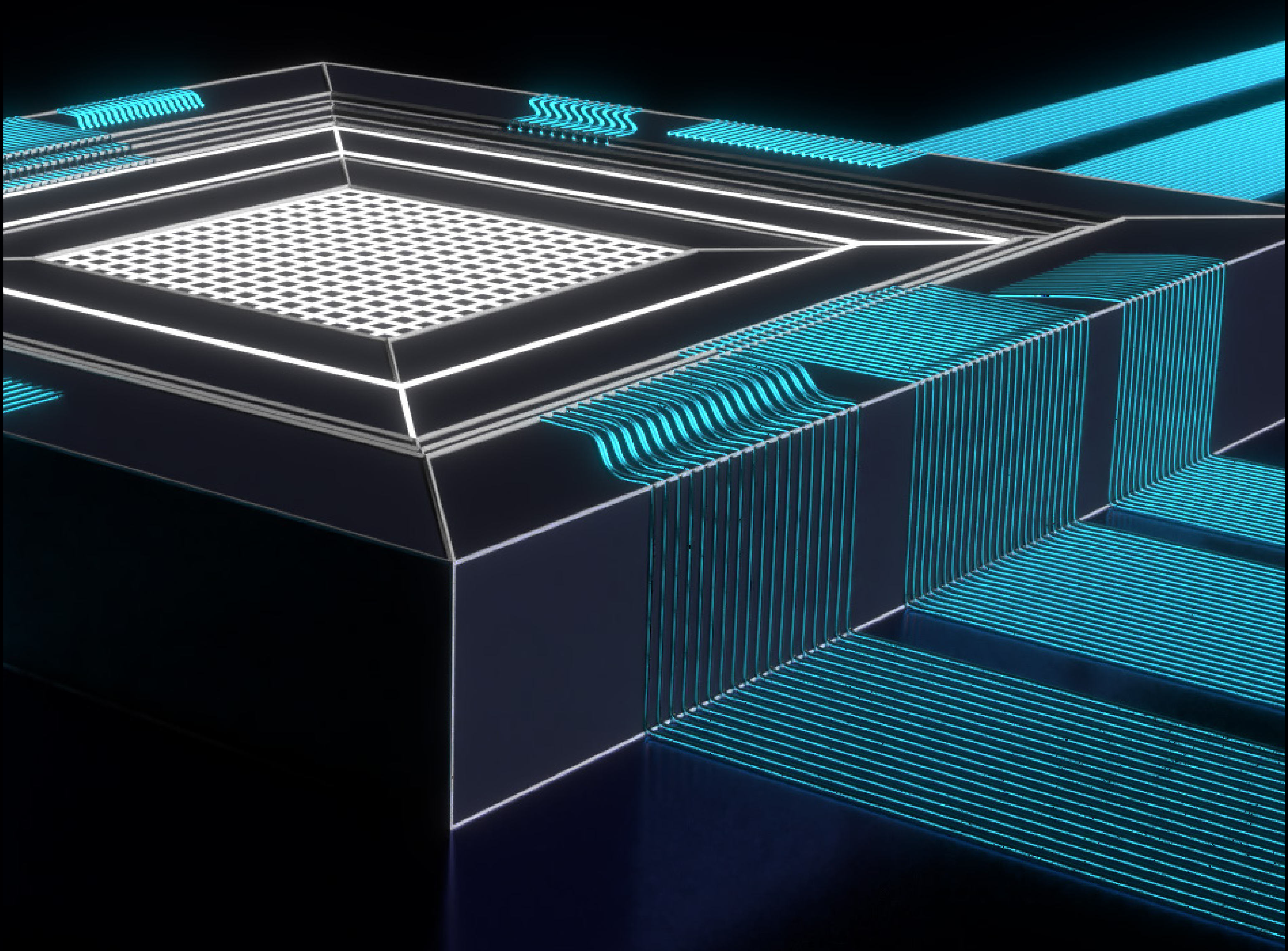


BASIC RESEARCH NEEDS IN

Quantum Computing and Networking

JULY 11–13, 2023

U.S. DEPARTMENT OF ENERGY | Office of Science

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY ADVANCED SCIENTIFIC COMPUTING RESEARCH

PRACTICAL ADVANTAGES FOR QUANTUM COMPUTING AND NETWORKING

Employing quantum mechanical resources in computing, information processing, and networking opens the door to potential exponential advantages over classical counterparts. However, quantifying and realizing such advantages poses extensive scientific and engineering challenges. Department of Energy (DOE) investments have driven steady progress in addressing such challenges. Recently developed quantum algorithms offer asymptotic exponential advantages in speed or accuracy for fundamental scientific problems. These problems include simulating physical systems, solving systems of linear equations, differential equations, and optimization problems. Empirical demonstrations on nascent quantum hardware suggest better performance on contrived computational tasks than classical analogs. However, the requirements for a quantum computer or network to demonstrate an end-to-end rigorously quantifiable performance improvement over classical analogs remains a grand challenge, especially for problems of practical value. In particular, what will be required for quantum technology to ultimately exhibit scalable, rigorous, and transformative performance advantages for practical applications?

In July 2023, DOE's Advanced Scientific Computing Research program in the Office of Science convened the Workshop on Basic Research Needs in Quantum Computing and Networking, where major opportunities and grand challenges were identified. The following five priority research directions (PRDs) were identified as a result of the workshop.

PRIORITY RESEARCH DIRECTIONS

1. End-to-end software toolchains to program and control quantum systems and networks at scale

Key Questions: How can we design expressive programming models and languages to attract a broad user base and facilitate quantum algorithm design and implementation? How can we incorporate these into end-to-end toolchains to produce resource-efficient quantum programs?

Quantum computing and networking systems continue to grow in scale and complexity and will place an increased burden on the software stack to program, control, and manage these systems effectively. Software toolchains will be needed that integrate programming models with hardware-level control systems to maximize the performance and fidelity of quantum systems and to facilitate codesign of hardware, control systems, and algorithms across different technology platforms. Integrating quantum networking systems with quantum computing systems will be critical in advancing the delivery of distributed distributed quantum computing services. This integration will require a quantum networking stack that is compatible with the quantum computing software stack, ensuring that the combined system can be efficiently managed, controlled, and programmed.

2. Efficient algorithms delivering quantum advantages

Key Questions: What classes of existing and understudied scientific applications admit substantial quantum advantages over conventional classical computing paradigms? How can we design novel algorithms and supporting mathematical models to realize such advantages? Are there any provable or empirical barriers for quantum advantages? What are the physical resource requirements of practical implementations of these algorithms, including numbers of physical qubits and quantum circuit depth?

Quantum computing is not expected to universally accelerate current computing tasks, and so identifying problems with special structure amenable to quantum advantages is a paramount goal. Taking a complementary perspective, broadening our understanding of foundational computational kernels admitting quantum advantages is equally important. While a variety of quantum advantages are currently known, they are subject to shortcomings such as a lack of known practical applications, near-term realization, rigorous provability of advantage, or efficient verifiability of advantage. In addition, quantum advantages have largely focused on improving execution time. Advantages with respect to other critical resources, such as quality/accuracy of solution, energy consumption, space/memory, or communication, are understudied, especially in the context of quantum networking.

3. Benchmarking, verification, and simulation methods to assess quantum advantages

Key Questions: How can we rigorously assess quantum advantage relative to classical capabilities as quantum computing and networking technologies evolve and scale? What metrics and evaluation methodologies faithfully reflect or enable the assessment of quantum advantage across the computing and networking stacks?

Assessing progress toward quantum advantage is a challenging and multi-faceted endeavor. Empirical evidence of advantages are expected to continue to rely on large-scale classical simulations of quantum systems as quantum technologies mature. A considerable hurdle is forecasting scalable quantum advantage based on limited results obtained from relatively small near-term quantum systems and classical simulations. On the one hand, while rigorous proofs of asymptotic quantum advantage are ultimately desirable and may be used to direct empirical studies, the former often rely on abstract or specialized models of quantum computing or otherwise impose additional restrictions. On the other hand, quantum advantage suggested by empirical assessments may not be sustainable as problems grow in scale or complexity, or as better classical algorithms are developed. Bridging this gap between theory and practice is essential for establishing sound and practical quantum advantages. Rigorous, informative, and efficiently verifiable performance metrics, at all levels of quantum computing and networking stacks need to be defined and developed. Ideally, such metrics should be integrated across the stack so that improvements can be quantified and predicted performance may be realized in practice.

4. Resilience through error detection, prevention, protection, mitigation, and correction

Key Questions: How can we enhance the resilience of quantum systems to noise and errors to relieve scalability and quantum advantage bottlenecks? What kinds of quantum algorithm codesign techniques can aid in yielding resilient quantum systems?

Scientists and engineers in national laboratories, academia, and industry continue to improve quantum computing and networking hardware, but despite these steady advances, these systems will be noisy and imperfect. In recent years, significant efforts characterizing errors and inserting error mitigation at various layers of the software stack have allowed the research community to cut through some of the noise and achieve reliable results in small-scale quantum experiments. To achieve reliable results with quantum systems at larger scale and complexity, more efficient and better methods characterizing, mitigating, preventing, or protecting against dynamical errors need to be integrated in the critical layers of the software stack. Steps are needed toward fault tolerance, codesign, and early demonstrations of quantum error correction that outperform the physical counterpart. Another approach would be to identify the error resistance mechanisms for quantum algorithms and codesign new hardware-aware algorithms and hardware controls that lead to error resistance.

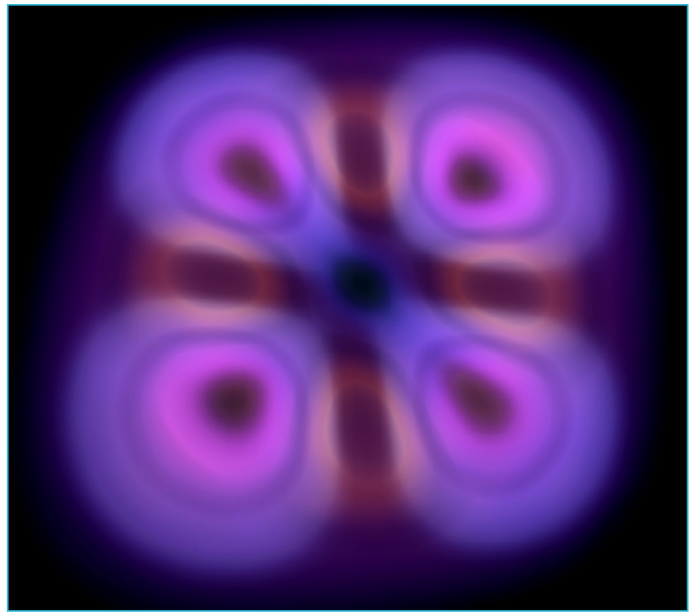
5. Hardware and protocols for next-generation quantum networks

Key Questions: Can quantum repeater hardware be built to achieve entanglement distribution rates higher than those of repeat-until-success direct transmission experiments? What software and hardware, besides the repeaters, is needed to build scalable quantum networks? What applications and advantages will those networks enable? What kinds of distributed quantum computing models will result in novel quantum applications and advantages?

To date, non-error-corrected quantum memories and entanglement distribution between them have been demonstrated with multiple qubit technologies. Moving forward and enabling scalable entanglement distribution networks will require progress in multiple directions. To create fault-tolerant quantum repeaters, it will be necessary to enhance quantum memories by integrating error detection and correction functionality during the design and implementation process. Photon sources, detectors, and time tagging hardware will need to improve to increase the fidelity of entanglement swapping operations. The quantum networking software stack will need to implement distributed error correction protocols and enable optimization across the stack. High-fidelity quantum information transduction methods and hardware need to be developed to enable the use of entanglement distribution networks in distributed quantum computing applications.

SUMMARY

With advancement toward quantum technology utility as an overarching goal, as well as the understanding of the requirements for the utility both on the application and technology side, the Workshop “Basic Research Needs in Quantum Computing and Networking” identified five PRDs. Over the last decade, DOE investments in quantum computing software and hardware have laid the groundwork for the type of basic research that will underpin key advances in the five PRDs. Collaborative relationships among computer scientists, mathematicians, and physicists, along with the establishment of common terminology, will be critical. This collaboration and shared understanding are essential for optimizing both the quantum computing/networking stacks as well as individual stack layers. These efforts are necessary to achieve the end-to-end demonstrations of disruptive quantum advantages in scientific applications.



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